

**FUNDAMENTAL CHARACTERISTICS OF LAMINAR AND
TURBULENT FLAMES IN CORNSTARCH DUST-AIR MIXTURES**

by

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ABSTRACT

This thesis is concerned with the experimental determination of the fundamental flame characteristics in a dust-air mixture and the influence of turbulence on flame propagation. Experiments were carried out in a tube having a 0.19 meter inside diameter and length of 0.93 meter, and 1.86 meter with both ends closed. A dispersion system was developed giving a good quality uniform dust suspension. A comparative method for the estimation of dust flame characteristics, based on well defined methane-air flame characteristics, was developed and employed to estimate the characteristics of a flame propagating in a cornstarch dust-air mixture. A systematic study of the influence of dispersion-induced turbulence on the dust flame propagation was carried out. The influence of obstacles on flame propagation also was investigated. Some mechanisms of flame propagation in a cornstarch dust-air mixture have been proposed and discussed. In the conclusion, general remarks concerning the dust flame characteristics and the influence of turbulence on flame propagation are made. The future direction of research is also indicated.

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RESUME

Le sujet de cette thèse est la détermination expérimentale des caractéristiques fondamentales d'une flamme dans un mélange poussière-air et de l'influence de la turbulence sur la propagation de la flamme. Les expériences ont été conduites dans deux tubes mesurant respectivement: 0.19 m. de diamètre intérieur et 0.93 m. de long, et 0.19 m. de diamètre intérieur et 1.86m. de long, chacun des deux tubes étant fermé à ses deux bouts. Un système de dispersion a été développé pour générer une poussière uniforme ayant des bonnes qualités de suspension. Une méthode comparative pour estimer les caractéristiques de la flamme, sur base des caractéristiques bien définies des flammes méthane-air, a été développée et utilisée pour estimer les caractéristiques d'une flamme se propageant dans un mélange air-poussière de maïs. Une étude systématique de l'influence de la turbulence induite par dispersion sur la propagation de la flamme a été conduite. L'influence d'obstacles sur la propagation de la flamme a été investiguée. Quelques mécanismes de propagation de la flamme dans des mélanges air-poussière de maïs ont été proposés et discutés. En conclusion, des remarques générales concernant les caractéristiques des flammes de poussière et l'influence de la turbulence sur la propagation de la flamme ont été faites. Des directions futures de recherches ont aussi été indiquées.

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LIST OF NOTATIONS

b	— coefficient
B	— mass transfer number
C_A	— burning rate constant
C_d	— mass concentration of the dust
C_g	— volume concentration of the gaseous fuel
C_i	— constant ($i = 1, 2, 3$ and 4)
c_p	— specific heat with constant pressure
D	— test tube diameter
D_q	— quenching distance
d	— dispersion pipe diameter, distance along the axis of jet
d_p	— dust particle diameter
$(dP/dt)_{\max}$	— maximum rate of pressure rise of explosion
K	— Karlovitz-Kovaszny criterion
K_{st}	— parameter, $(dP/dt)_{\max} V^{1/3}$, named K_{st} factor
k	— thermal conductivity
L	— tube length
l	— integral length scale of turbulence
Pr	— Prandtl number
P	— pressure
P_a	— initial pressure in the explosion vessel
P_f	— final explosion pressure in the explosion vessel
P_o	— pressure of the upstream flow in a dispersion pipe near the orifices
Q	— chemical energy of an explosion mixture per unit mass
q	— dimensionless extinction coefficient
Re	— Reynolds number
R	— test tube radius
r	— radius

S	— surface area of test tube
T	— fraction of light transmitted through a path length
t	— time
U	— internal energy of a volume V
u	— burning velocity
u_{eff}	— effective flame velocity relative to the gas
u_f	— velocity of a leading point of the flame relative to the wall of the tube
u_m	— maximum velocity in the mean velocity profile in the test tube
$\bar{u}$	— mean average flow velocity in the test tube
u'	— rms turbulent velocity
V	— volume
w	— relative velocity between the particles of dust and the molecules of air
W	— weight of dust
$\bar{W}$	— average propagation velocity of flame front
x	— variable distance
α	— thermal diffusivity
β	— density ratio across the flame
γ	— specific heat ratio
ΔP_{max}	— maximum pressure rise of explosion
δ	— flame thickness
ϵ	— eddy diffusivity
η	— Kolmogorov dissipative microscale of turbulence
λ	— Taylor microscale of turbulence
ν	— kinematic viscosity
ρ	— density
ϕ	— diameter of orifice in the dispersion pipe

$\phi_{\max}$ — diameter in the jet maximum area
 α — heat transfer coefficient

Subscripts

ch — chemical
d — dust
g — gas
i — ignition
j — jet
l — laminar, liquid
max — maximum
min — minimum
m — metal, mixing
p — particle
t — turbulent

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CHAPTER 1

INTRODUCTION

There are two essential problems in combustions and the study of explosions. The first is to find what is the total energy release when a given volume of an explosive mixture at given initial and boundary conditions undergoes combustion while the second is to find how fast the energy is being released. In gas phase combustion the first problem is relatively easy. If the thermodynamic path is specified (constant volume or constant pressure) then the final state of the combustion products can be determined from standard equilibrium thermodynamic calculations. The total energy released is then obtained by taking the difference between the enthalpies (or internal energies) of the products and reactants. The second problem of finding the energy release rate is much more difficult. In general, it requires a knowledge of the detailed chemical kinetic and gasdynamic transport processes. Apart from two limiting cases, namely, the lower limit of molecular diffusion controlled laminar flame and the upper limit of a Chapman-Jouguet detonation, it has not been possible to calculate from first principles the burning rate for a given gaseous mixture. Hence, the understanding of turbulent premixed gaseous flames is essentially based on various experimental modellings. Available results and analyses have demonstrated that for gaseous premixtures, burning velocities can be correlated in terms of dimensionless groups such as the ratio of turbulent burning velocity to laminar burning velocity, the ratio of rms turbulent velocity to laminar burning velocity, the turbulent Reynolds numbers (based on the integral scale of turbulence), the Lewis number and the dimensionless activation energy for the gaseous mixture. Therefore, the predictions of the role played by turbulence during combustion essentially depends on two kinds of comparisons. While one comparison is between the turbulent intensity and the laminar burning velocity, the other is between the turbulent eddies size and the laminar flame thickness.

What essentially distinguishes premixed gas explosion from dust explosion is that in the former there exists only one phase, therefore combustion is a homogeneous process, and thorough mixing of gaseous fuel with air is easily obtained and gravity effects are negligible. On the other hand, in a dust-air mixture, the dust particles are significantly larger than air molecules and are strongly influenced by the force of gravity. Uniformity of the dust suspension is difficult to achieve. The effects of dust concentration, particle size, shape and

size distribution on dust dispersion, suspension, and combustion must be taken into consideration. Finally, the existence of a solid phase, as well as a gas phase, complicates the combustion process. This process includes all or some of the following steps, as outlined by Swift [1].

- 1) Volatile evolution: volatile gases, which may not be combustible, are driven from the particle by heat from the ignition source or other burning particles.
- 2) Surface melting: the particle surrounds itself with a layer of combustible vapor as its surface softens, melts, vaporizes and boils.
- 3) Pyrolysis-decomposition products, which are generally combustible, are released as further heating pyrolyses the particle.
- 4) Gas phase ignition and burning: a diffusion flame stabilizes around the particle when the vapors surrounding the particle reach a flammable concentration and are ignited by either auto or pilot ignition.
- 5) Char burn-up: the particle undergoes heterogeneous combustion when the diffusion flame of step 4 extinguishes due to insufficient vapor evolution or oxygen diffusion into the vapor layer. In this step, surface oxidation converts the remaining solids to volatile oxides, leaving solid carbon and ash.

The initial investigation of Faraday and Lyell [2] in 1844 was the first serious study suggesting the active role of coal dust in coal mine explosions. It was suggested that coal dust magnified the violence of the methane-air deflagration. The active role of organic dust in explosions was first postulated in 1795, some fifty years before Faraday, by Count Morozzo [3]. He suggested that an explosion of a flour mill in Turin involved the flour dust itself rather than just a flammable gas given off by the flour. Therefore, danger from various dusts such as those of coal, grain, chemicals, and pharmaceuticals were overlooked for a long time. The interest in dust explosions was rejuvenated occasionally when a few major explosions occurred over a short time period. This most recently occurred in December of 1977 when five major agricultural dust explosions occurred within eight days, in the United States. A significant number of similar dust explosions still occur in facilities designed for handling and processing of grain and grain products, and in coal mines around the world every year. These explosions cause loss of human life, injury, property damage, and loss of business. Our current quantitative understanding of heterogeneous flame propagation is not adequate for accurate modelling and prediction.

The main impetus for dust explosion research came with the need of codes and procedures for suppressing the likelihood of accidental vapor and dust explosions. Extensive research has been carried out by the Department of Interior Bureau of Mines [4 -6] in the United States, and many groups in Europe [7] to index the explosive hazard of different dusts and in finding the influence of chemical and physical variables on the initiation of dust explosions. A considerable body of engineering data has been collected from Hartmanns' equipments [5 -9] and empirical knowledge has been compiled in monographs by Bartknecht [7]. This fact, as well as the appreciable differences among data from different test equipments used, can be traced to the lack of a consistent theoretical basis for doing the experiments and for understanding the mechanism of dust flame propagation.

Researchers who have investigated the mechanisms of dust flame propagation, especially for coal dusts, include Essenhigh [10], Krazinski et al. [11], Field et al. [12], Howard et al. [13], Smoot et al. [14, 15], Ballal [16, 17] and Slezak et al. [18], to name just a few. This interest is a consequence of the necessity to increase the efficiency of combustion processes in industry as well as the need to prevent accidental dust explosions. The major experimental results and numerical simulations are concentrated on studying the nature of laminar dust flames. The experiments are conducted in various open burners of different shapes and sizes. In view of several serious experimental difficulties, the laminar dust flame structure and the mechanisms of laminar flame propagation have not been studied as extensively as those of gas flames.

More attention has been recently devoted to turbulent rather than laminar combustion because the former is involved in nearly all cases of dust explosion. However, the research on turbulent dust explosions is much less than that on turbulent gas phase explosions. This can be attributed to the heterogeneous nature of dust-air mixtures and the difficulty of making turbulence measurements in such systems. Attempts to quantify turbulence effects in exploding dusts have only been made recently [19, 20, 21]. The investigation of the influence of turbulence on dust combustion is becoming an important area in combustion research.

The goal of the present investigation is to examine and understand the fundamental mechanisms of both laminar dust flame propagation and effects of turbulence. The author believes that only on this basis one may arrive at the meaningful assessment of the explosibility of dust-air mixtures and formulate guide-lines for the design of adequate venting

for installations handling combustible dusts.

A survey of the available literatures in both gas-air and dust-air mixture combustion and explosion is given in the next chapter, Chapter 2. Chapter 3 covers the basic considerations and thesis objectives. Chapter 4 describes the preliminary investigations for the selection of apparatus. Chapter 5 presents the description of the experimental details. Experimental results and discussion are included in Chapter 6. Concluding remarks are presented in the last chapter, Chapter 7.

CHAPTER 2

LITERATURE SURVEY

2.1 Synopsis of Available Experimental Investigations of Combustion in Dust-Air Mixtures

Currently, there are mainly two types of combustion experiments being carried out for dust-air mixtures: stabilized open flames and closed bomb experiments.

2.1.1 Stabilized open flame, constant pressure combustion

For most gases it has been observed that such fundamental quantities as i) laminar burning velocity, ii) laminar flame thickness, iii) quenching distance and iv) minimum ignition energy have unique values for a given mixture, and thus can be considered as the properties of a given gaseous mixture. The definition of each are as follows:

- The laminar burning velocity (u_l) is defined as the velocity of a laminar flame front, which travels in a direction normal to itself and with respect to the velocity of the unburned mixture.
- The laminar flame thickness (δ_l) is defined as the ratio of the maximum temperature difference ($T_b - T_o$) to the maximum temperature gradient (dT/dx) which occurs at the point of inflexion of the temperature profile, i.e. $\delta_l = (T_b - T_o) / (dT/dx)_{max}$.
- The quenching distance (D_q) is defined as the smallest gap between two solid walls through which a flame can freely propagate.
- The minimum ignition energy (E_{min}) is defined as the smallest quantity of the energy which can initiate a self-propagating flame.

The wide use of burners and vertical combustion tubes to measure flame speeds in dusty atmospheres has emulated the extensive work done with gas flame in similar devices. When care is taken to limit wall effects, it is possible to obtain good data on the structure and speed of steady, one dimensional laminar flames.

In past research, the nature of laminar premixed coal dust-air flames has been studied in various open burners and the general characteristics of those flames have been identified. However, the details of the processes in the flame have not been resolved. The influence of the general dust parameters (size of particle, volatile part, dust concentration, physical nature of the particle) and the processes (radiation, conduction, diffusion, heterogeneous reaction) on the fundamental characteristics of the flame (burning velocity, flame thickness, minimum ignition energy, quenching distance) are the subject of a continuing interest.

Numerous experiments reported in [13, 22 -33] have been carried out to measure the burning velocity and flame thickness on open burners. Experimental observations reveal that burning velocity and flame thickness depend not only on the coal dust characteristics, but also on the apparatus (scale, shape, dispersion and stabilizing system). The analysis presented in [18] shows that flame speeds from 3 to 200 m/s could be achieved, depending on the type of apparatus in which the investigation was conducted.

Measurements of minimum ignition energy in dust mixture have been reported recently by Ballal [17, 34] and Hertzberg et al. [35]. Ballal carried out his experiments in dust clouds of carbon, graphite, coal, aluminum and magnesium. He found a qualitative similarity between ignition and quenching of dust clouds and of liquid droplet sprays and mists. He modified the theory developed earlier [36] to predict the experimental results in dust-air flames, the quenching diameter in particular. Energy requirements for the spark ignition in air of polyethylene powder, lycopodium, and Pittsburgh coal dust have been determined by Hertzberg et al. [35]. The minimum ignition energies measured at room temperature for all three dusts studied occurred at relatively high concentrations of dust, which were several times higher than the stoichiometric concentration. The authors of [35] reported that the accurate determination of the minimum ignition energy of a dust involves extraordinary complications. The most important one involves the production of a quiescent dust-air mixture with reproducible concentration. They illustrated the complications with available data of minimum ignition energy for lycopodium which varied between different Bureau of Mine studies from 25 mJ to 50 mJ. In contrast a value of about 10 mJ was determined by Eckhoff using the optimum characteristics of the spark discharge [37]. They concluded that a reliable determination of a minimum ignition energy which reflects intrinsic flammability behaviour for dust mixtures is dubious. In [35] and [37], the experiments were performed in closed vessels. Since the measurements had been completed during the initial stage of the

combustion process, the process can still be considered as a constant pressure one.

Recently, quenching distances have been measured by Jarosinski et al. [38] in a relatively large scale apparatus ($D = 0.19$ meter, $L = 1.86$ meter) for freely propagating flames in dust-air mixtures of cornstarch, aluminum and coal. The authors of [38] considered that the quenching distance can be offered as the most fundamental quantity to identify the controlling processes in dust combustion. Such quantities as the burning velocity, the flame thickness, and the minimum ignition energy depend on the apparatus and therefore are not sufficiently fundamental in dust combustion. The quenching distance, linked directly with the flame thickness, determined by definition at the limit quenching conditions, if properly measured, should not be dependent on the apparatus. The minimum quenching distances for fine cornstarch ($d_p = 15\mu\text{m}$) and aluminum flake dust ($15\mu\text{m} \times 0.1\mu\text{m}$) with air were stated as 5.5mm and 10.4mm, respectively. These values are comparable with experimental data for gas flames. The quenching distance as determined in a methane-air mixtures is 2.0mm for the stoichiometric mixture, 9.2mm for the lean limit, and about 20.0mm for the rich limit [38].

Experimentally, it is very difficult to produce a uniform laminar flow in a dust-air mixture and to stabilize an adiabatic dust flame on a burner. Analysis of open burner and tube experiments in [18] shows large scatter of data depending on the type of apparatus in which the investigation was conducted. This is a result of various nonadiabatic conditions of dust flames stabilized on different burners and a poor reproducibility of the experimental conditions such as the physical and chemical properties of dusts, their suspension and agglomeration. Much more experimental data concerning flame characteristics are necessary to be measured for studying the nature of laminar dust flames. It is very difficult to measure the flame thickness and the laminar burning velocity by making direct optical observation of the dust flame structure. Hence emphases should be placed on the measurement of those fundamental characteristics which are linked directly with laminar flame thickness, such as minimum ignition energy and quenching distance.

2.1.2 Closed bomb experiments, constant volume combustion

Since the hazards of various dust clouds must be known for practical reasons, an empirical explosibility index was developed by Hartmann and his colleagues [4-6, 39], using closed bomb tests to classify the relative hazard of dusts. The index of explosibility is related

to its ease of ignition (ignition sensitivity) and the severity of the explosion (explosion severity). Ignition sensitivity is assumed to be a function of ignition temperature, minimum ignition energy, and minimum explosion concentration. Explosion severity is assumed to be a function of the maximum explosion pressure and the maximum rate of pressure rise. The ignition sensitivity, explosion severity, and explosibility index are defined as unity for a dust having ignition and explosion characteristics similar to that of Pittsburgh coal dust [40]. Because of the scaling problem, the volumes of the Hartmann bombs [41] are too small (range from 1.3 to 8 liters) to allow the dust flame to fully develop. Bartknecht [42] and U.S. Bureau of Mines [43] then developed two different kinds of 20-liter explosibility test chamber and Barthnecht [7, 44] developed 1m³ to 10m³ chambers. Barthnecht [7,44] also compiled the empirical knowledge in monographs, which are valuable in engineering practice.

The standard diagnostic used in constant volume bomb explosion studies is the pressure-time history of the combustion processes. From the $P(t)$ curve one can deduce two explosion characteristics. While $\Delta P_{\max}$ is related to the energetics of the mixture, $(dP/dt)_{\max}$ is proportional to the burning rate. Therefore $\Delta P_{\max}$ and $(dP/dt)_{\max}$ are two important parameters to characterize the strength of the hazards in an explosion.

From the maximum rate of pressure rise, a useful parameter called the K_{st} factor can be obtained ($K_{st} = (dP/dt)_{\max} V^{1/3}$). The K_{st} factor is in essence a scaled $(dP/dt)_{\max}$ based on the volume V of the vessel used. Such scaling permits the $(dP/dt)_{\max}$ from different sizes of explosion chambers to be compared. The work of Bartknecht [7] suggests that K_{st} = constant (the so-called cubic law) for a given dust. Other investigators [45] question the general validity of the cubic law.

The maximum pressure developed by a gas or dust explosion in a closed vessel is independent of the vessel size and shape if heat lost to the vessel is disregarded. In ducts in which the cross-sectional area is small relative to the length and in vessels having one or more walls near the ignition source, significant heat loss will occur and result in a decrease of maximum pressure. Experiments by Kratz and Rosecrans [46] show a decrease of maximum pressure for gas explosions in hemispherical, cylindrical, conical, and L-shaped vessels.

The maximum rate of pressure rise is affected by vessel volume and shape. Experimental data obtained by Nagy et al. [6] are from non-initially turbulent gas phase explosions (9.5% methane) in a closed vessel. The vessels ranged from 1.2 to 25000 liters in volume, and are cylindrical, cubical, rectilinear, and spherical in shape. Experimental results demonstrate that the rates of pressure rise, obtained from the pressure-time curves at several values of explosion pressure when plotted against S/V (the ratio of surface area to volume for an apparatus), fall on a straight line. The data for the 25000 liter spherical vessel deviate because of induced turbulence during flame propagation.

In the case of dust explosions in closed vessels, due to the injection system for dust dispersion, some degree of turbulence will always be present in the test apparatus before the dust cloud is ignited. Initial turbulence levels are usually expressed qualitatively in terms of the delay time between dispersion and ignition or the pressure required for injection. Thus they are varied with injection system and ignition delay time. It is hardly surprising that all the combustion data obtained from closed vessel are dependent on the apparatus used and test procedure. Table.1 shows a large scatter in the data of dust explosion in closed vessels [5, 7, 8, 20, 21, 47].

Unlike gas mixtures, turbulence effects on the flame propagations and combustion rates in dust-air mixtures are not easily conducted by the open flame methods because dust particles cannot follow the air flow exactly, especially at high Reynolds numbers. Therefore, attempts made to quantify turbulence effects in exploding dusts are mainly conducted by using closed-bomb experiments.

2.1.3 Other experimental investigations

Attempts have also been made to study the acceleration of dust flame propagation by turbulence in open tubes and channels [18, 48-55]. The acceleration of flame propagation by turbulence in dust explosions was demonstrated by Cassel et al. [48] by inserting a grid close to the ignition point in a 5cm diameter tube which was filled with a flammable aluminum dust-air mixture. Flame speeds of the order of 100m/s were obtained, as compared with flame speeds of the order of 5 to 10m/s in the absence of the grid. Increased flame speeds due to turbulence were also experienced in the work of Essenhigh and Woodhead [49] and Essenhigh [10].

In [50, 51] an experimental program for measuring the turbulent burning velocity of coal dust clouds is described. The dust-air mixture flowed down a 14.3cm diameter tube and was ignited and stabilized within the tube by a small, constantly burning pilot gas flame. The concentration of dust and the flow velocity were uniform across the duct, and the level of turbulence in the flow was controlled by a grid placed upstream of the flame. The flame in the dust cloud assumed a conical shape immediately downstream of the pilot flame, and the turbulent burning velocity was calculated as the product of the flow velocity of the dust-air mixture and the sine of the angle that the flame front presented to the flow. As an example of the results obtained, the turbulent burning velocity was more than four times the laminar value, at a constant level of turbulence and a dust concentration of 0.35kg/m^3 . It is this author's opinion that the turbulence promotes better mixing of the volatiles released from the coal with the oxygen in the surrounding air.

In a recent modelling experiment, Pickles [52] recognized the importance of turbulence in determining the flame propagation rate in a coal dust duct with one open end. In particular, he attempted to simulate the situation in an actual mine where a coal dust explosion is usually initiated by a primary explosion of a methane accumulation. He assumed that the initial flow and turbulent mixing, thus created, control the rate of combustion in the explosion.

The propagation of dust flames studied in large long open tubes [18, 53] and in full-scale experimental underground explosion test facilities [54, 55] were conducted under conditions approaching those found in an actual mine. In experiments of [55], a satisfactory correlation was developed in the testing gallery between measured flow parameters and dust flame front velocity, and it was observed that the velocity of the flame front was increased significantly by the rough wall induced-turbulence. Nevertheless, it is still not possible to predict the flame front velocity itself in terms of the initial conditions and to link flame propagation to the relevant fundamental properties of dust (burning velocity, flame thickness, dust concentration and the fraction of dust actually burned).

It was demonstrated in [56 -59] that obstacles in the path of an advancing gaseous flame front can greatly accelerate the progress of the flame. Similar considerations applied for dust deflagrations, are illustrated by Wolanski [19]. He states that obstacles can cause a rapid transition of combustion from deflagrative to detonative during a dust explosion. From this we can infer that even if a detonation does not occur, the process of deflagration is

enhanced by turbulence generated by obstacles.

2.2 Techniques of Dust Dispersion

In a dust-air mixture the dust particles are significantly larger than the air molecules and are strongly influenced by the force of gravity. Therefore, to achieve a uniform dust suspension is a major concern to experimenters in this field. One can distinguish two general methods of dust dispersion, namely, the free fall system [18, 60-64] and the pressure system [41-44, 65-68].

The free fall system used by Palmer and his co-workers [60, 61], consisting of a hopper and a screw device to feed the dust at the top of a long combustion tube, can serve as an example of this kind of system (for example [62]). The creation of dust-air mixtures in the free-fall system is followed by sedimentation, agglomeration and recirculation phenomena which will affect of the flame propagation after the mixture is ignited. Greene and O'Donnell investigated those phenomena and evaluated their effects on dust suspensions [63]. The free-fall system which can give satisfactory uniformity of dispersion is usually used to study the concentration limits and the effect of addition of inert materials to a flammable dust. It does not, however, lead to the determination of the rate of pressure rise due to the difficulty of sealing.

The system utilized by Ishihama and Enomoto [64] is a special modification of a free-fall system, which recently was used in a large horizontal combustion tube [18]. In this system, dust suspension is generated inside the combustion tube by discrete wall protuberances when the entire tube is rotated about its central axis. As the tube rotates, the dust, which is carried by protuberances, falls throughout the interior volume of the tube. The system was used to study the concentration limit and characteristic of a freely propagating flame.

One of the best known air pressure system is that used in the Hartmann tube. It consists of a mushroom deflector and a dispersion cup developed by the Bureau of Mines [41]. There are also other widespread pressure systems: an 8 liter device with the dispersion cone system, 5, 10, and 20 liter spherical devices with dispersion nozzles or a dispersion cone system [41,43]; Kauffman's 950 liter spherical vessel which uses the technique of a jet

stirred reactor [21]; Bartknecht's annular dust dispersion nozzle (sometimes called spray ring or sprinkler system) [42, 65, 66]; Procker and Gamble's two flow system [67] and Fenwal and Dow's whipping hose dispersion system [68].

On the whole, the free-fall system is used in long open combustion tubes while the air pressure systems traditionally disperse dust in different spherical bombs or cylindrical vessels with a small ratio of the length to diameter ($L/D = 1$, L and D is the length and the diameter of the cylindrical vessel, respectively). No one dispersion system is exclusively superior to the others, each of them should satisfy their experimental requirements. Therefore, a good dispersion system is a system satisfying vessel configuration, ignition timing, turbulence, the aims of the particular research program and the dust to be tested.

Another area, in which a knowledge of the dust-air mixture is employed, involves the fluidized bed. Initially pioneered in the 1950s by the European chemical industry for various thermochemical processes, a fluidized bed employs an upward moving gas stream to partially suspend a bed of small particles that tend otherwise to settle under gravity forces. The work of Proust and Veyssiere [69] is an example of fluidized beds in a combustion application, in which pulverized dust in particle form is concurrently fed into the bed within a square section (20cm x 20cm) vertical glass tube (2 meters long). Although the use of fluidized beds probably is one of the solutions to obtain the flame propagation in quiescent flow without turbulence due to dispersion system, the determination of particle concentrations and its variation along the tube length is not easy. Also, there are certain limited particle concentrations applicable to the techniques of fluidized beds. The best uniformity of dust-air mixture probably was obtained by Cassel et al. [48, 70] in Mache-Hebre nozzles and by Ballal [16] in his zero-gravity study, in which a free fall apparatus was used to simulate an environment of zero gravity. The limitation of this method is that the period for flame propagation remain less than 1.4 seconds.

2.3 Laminar Dust Flame Studies

A considerable amount of experimental and theoretical work has been done on the study of laminar dust flames, most of which has concentrated on pulverized coal. An up-to-date account of flame propagation through dust clouds of coal with extensive references may be found in the reviews by Essenhigh [10], Smoot et al. [15] and Krazinski

et al. [11].

2.3.1 The importance and difficulty of laminar dust flame studies

A knowledge of the processes controlling the laminar flame in premixed dust-air mixtures is crucial to the understanding of the mechanisms of turbulent dust flames. For the most part, these mechanisms are responsible for the severe explosion hazards in industry and serve as a source of basic information about the processes controlling laminar dust flames. Despite the theoretical and practical importance of the fundamental studies of flame propagation through various laminar dust-air mixtures, only a few attempts have been made to determine the properties of such flames.

The lack of reliable data on laminar flame properties is not surprising in view of the many difficulties, complexities and contradictory requirements associated with experimental conditions. One of the most serious difficulties is that of creating uniform mixtures with reproducible concentrations of dust, but without turbulence caused by the dispersion system itself. Pure laminar flames propagating in uniform premixed dust-air mixtures do not exist. Real mixtures in experiments are neither laminar nor uniform, nonuniformly distributed, but keep some residual turbulent motion superimposed on the flow. This mixture can only locally satisfy the conditions of uniformity and the flow contains certain intensity of turbulence. Thus, real laminar flames in dust-air mixtures are usually examined as some approximation to "ideal" laminar dust flames.

Most of the available knowledge of laminar dust flames has been obtained with various burners producing standing flames [22, 23]. A common feature of the burners is the use of some sort of flame stabilizing device that is required to generate a standing flame. The difficulty in stabilizing the relatively thick dust flames on a burner gives rise to non-adiabatic conditions. The other difficulties of obtaining reliable data for dust flame on burners include the measurements of particle size, particle-size distribution, fuel-air ratio, and fuel composition. Another major problem is the influence of earth's gravity, which induces the upward buoyant motion to burnt gases and the downward settling of the fuel particles relative to the flame front.

In view of the above difficulties and along with the difficulty of making direct optical observation of the dust flame structure, laminar dust flame structure and mechanism of

laminar flame propagation have not been studied as extensively as those of gas flames.

2.3.2 Similarities and differences between dust and gas laminar flames

Most of the experiments for studying laminar dust flames were patterned after those successfully used to study premixed gaseous flames. Experimental results in Smoot, et al. [15] and Ballal [16, 34, 36] demonstrate that a heterogeneous mixture will produce a flat, laminar flame. Such a flame can be established over a range of concentrations with the rich flammability limit occurring at very high concentrations. The flame velocity as a function of fuel concentration is similar to such curves for gaseous hydrocarbons burning in air. The peak velocity is about 0.25m/s and is increased by a finer coal-dust particle size or a higher volatile content. The measured flame temperature is about (1000-1700)°K and a flame thickness is in the order of 10mm. Measurements in [38] showed that the quenching distance in cornstarch dust-air mixtures is 5.5mm. The careful recent studies of Eckhoff [37] have indicated that the minimum ignition energies of dust mixtures can be as low as a millijoule. When these values are compared with the corresponding ones for homogeneous gas-air mixtures, they are seen to be rather similar. Typical burning velocities for lean methane-air gaseous flames are about 0.15m/s, adiabatic flame temperatures are about 1700°K and minimum ignition energies are in the region of millijoules with a flame thickness of approximately 3mm.

More recent work [71] has emphasized that many of the features of gaseous flames, such as species diffusion and gas phase chemical reaction, are also found in dust-air flames. Thus, many similarities are recognized between propagating premixed gaseous flames and dust flames. However, the dust flames discussed here are those in which the solid particles emit appreciable amounts of "volatile" gases when heated and the remaining char burns comparatively slowly in hot oxygen.

In homogeneous gaseous mixtures, numerous works have been devoted to the study of the structure of premixed flames and to the systematic experimental determination of such flame characteristics as the laminar burning velocity, the flame thickness, the quenching distance and minimum ignition energy, which are properties of the mixture. Unfortunately, this is not the case in heterogeneous mixtures. The development of experiments in which the same parameters are measured in sprays or dust mixtures (recent studies in this field can be

found in [30, 72, 73]) is based on the assumption that heterogeneous mixtures have properties similar to those of gas mixtures and hence the laminar burning velocity is a property of the mixture. However, in contrast with gaseous flame which are characterized by a one-valued dependence of the burning velocity on the mixture composition, the burning velocity in heterogeneous mixtures of dust or droplet with air depend not only on the concentration of particles in the mixture but also on the size of the particles, and the amount of volatile parts.

One of the most remarkable differences in flame characteristics of dust and gaseous flames is a long afterburning zone in some dust flames and its absence in gas flames. In a gas-air mixture, the heat is released in a thin flame front. In a dust-air mixture, one can precisely measure a propagating flame front boundary, but is unable to determine where the end of the burning zone is. Part of the heat is released at the flame front and the remaining part in the solid char burning zone. The solid char burning region can somewhat influence the flame propagation velocity of the flame front. There is very high discrepancy in the estimated thickness of dust flames. For instance, Smoot et al. [15] estimated the thickness of premixed laminar coal-dust flames, on the basis of their own experiments, as between 0.5cm and 4.0cm while Slezak et al. [18] are of the opinion that the thickness of the premixed laminar coal-dust flame is very high and may even reach 1 meter. This difference of opinion on the flame thickness shows clearly the importance of precise definition in the measurements. In the first case, the estimation of the thickness is based on the measurement of temperature profile of the flame front, the sampling of the flame and the results of computation of the flame parameters, in which the combustion processes are controlled by conduction and diffusion, while in the other case the flame thickness was estimated from the glowing region, in which the radiation during a flame propagation process was taken into account. The main difficulty in defining the dust flame thickness is that of defining the rear boundary of the flame. By this boundary we understand that at the real equilibrium boundary, at which the chemical processes are complete to such a degree that the temperature reaches a value approaching the maximum value and the flame front thus formed and contained between the fore and rear boundary. This flame front is considered to be capable of self-propagation in the fresh mixture. Numerous experiments [16, 49, 63, 70, 74-76] show that the flame thickness thus defined for a dust flame is comparable with that of the thickness of a gas flame. The existence of afterburning zone characterized by the glowing of dust particles behind the flame front is of no significant meaning for self-propagation.

2.3.3 The mechanisms of laminar dust flame propagation

The mechanisms of propagation of dust flames are impossible to understand without the knowledge of some of the flame characteristics. There is considerable discrepancy in those characteristics due to the data measured being dependent on the apparatus and the experimental procedure. This discrepancy of experimental data is a source of difference in the estimation of the role of particular processes in the control of the propagation of a dust flame. Incorrect estimation of the flame characteristics which are properties of the dust-air mixtures, makes it impossible to assess the role of various factors in more complicated turbulent flames, such as the influence of the physical properties of the mixture and the turbulence parameters on the propagation mechanisms of turbulent dust flame. The investigation into the characteristics of laminar dust flames, which have been performed in the course of the last decades, are briefly shown in Table 2.

The mechanism of flame propagation in dust-air mixture is very complex. From past researches and analyses [10-18, 22-38, 77-80], some general characteristics and features of laminar dust flames have been identified. As the air containing dust enters the flame, the particles are heated to the onset of volatilization or ignition. Therefore, the exothermic reaction of the particles and/or liberated volatiles further increases the temperature until reaction is complete and the flame front is passed. Yet the details of this complex set of processes have not been resolved and even simple questions remain unanswered. Included is a consideration of several relevant questions: are the incoming particles heated mostly by radiation or conduction; is the reaction of the particles heterogeneous or homogeneous; what is the burning velocity; how thick is the flame zone and what are the combustion products; how do processes vary with the dust particle size, concentration, or volatiles content; how are those various phenomena modeled and to what extent are the required approximations realistic and consistent with experimental observations?

Several investigators including the early work by Nusselt [77], Essenhigh [10], through to the more recent work by Krazinski et al. [11] investigating the theory of premixed dust flames, focused on flames dominated by radiative heat transfer. They suggested that the flame propagation mechanism is mainly controlled by radiation, and the large observed values for flame thickness (10cm-100cm) agree with the calculated values [13]. Thermal radiation was considered to play an important role to supplement heat transfer by thermal diffusion forward from the burning region. For graphite dust, radiation is reported by Cassel

et al [70] to account for 60% of this heat transfer while for aluminum powder the value is 35%. The role of thermal radiation in heating a dust cloud does not appear to be adequately understood, but would seem to be susceptible to fundamental analysis. Experimentally, it has been observed by Lecuschke [78] that radiation from one burning dust cloud can ignite another when the two are physically separated. Modelling efforts show that radiation, in general, increases the burning velocity and the flame thickness. This model is thus, at best, applicable to low-volatile coals and to thick flames.

While most of the previous work has been based mainly on particulate radiation, a few have investigated the influence of streamwise molecular diffusion and conduction in these flames. Smoot and co-workers [71] have recently described the development of a generalized model for predicating flame propagation in laminar, dust-air flames, as illustrated in Fig.1. Most of this approach has been patterned after previous solutions for propagating gaseous flames, using the numerical techniques of Spalding et al. [79, 80], but generalized to include particle effects. Radiative effects which were included in the model formulation, were set equal to zero in the first set of computations. For concentrations of 0.3kg/m^3 of $30\mu\text{m}$ Pittsburgh bituminous coal in air, the flames are approximately computed to be 10mm in thickness, which agrees well with thicknesses determined from measured temperature and species profiles. A series of nine additional predictions were made in the absence of radiative effects for coal-air flames in order to identify mechanisms, which according to the model, control the rates of propagation. From these computations, the rate of hydrocarbon oxidation in the gas phase and the rate of heterogeneous reaction of the carbon (char) were not rate-limiting. The rate of gas-phase reaction (other than hydro-carbon oxidation) and the rate of coal pyrolysis were significant, while the rate of conduction and molecular diffusion in the gas phase and conduction between the particle and gas phase were of major importance. In the model formulation, in which radiative heat transfer effect were included, the flame was divided into three areas:

- i) a preheat region with no reaction but with radiative absorption and heat loss effects;
- ii) the flame region where the chemical reaction is occurring; and
- iii) the post-flame region with no reaction but with radiation and heat loss effects.

With these radiation effects being considered, the computed results demonstrate the following. First, radiative effects, while not dominant, increase the propagation velocity somewhat; in this case the increase is only 13%. Second, the apparent overall thickness of the flame is increased by 63% due to the gradual heatup in the preheat region. Third, the

radiative effects of the post-flame region on the preheat temperature are actually greater than radiative effects from the hotter but very thin flame region. Fourth, the maximum flame temperature is increased by about 10% due to radiative effects. These radiative results do not alter the conclusions regarding the importance of molecular transport effects in determining the structure of propagating flames. These transport effects include diffusion of gaseous fuels, together with thermal conduction between the hot gas and the incoming particles. These molecular effects are responsible for the very thin flames and the steep profiles that are characteristic of these laminar coal-air flames. Rates of pyrolysis and gas-phase reaction also have an impact on propagation of coal-air flames. Radiation is an additional process that does not dominate, but can apparently have some influence on the rate of propagation. Smoot and co-workers suggest that propagation in laminar pulverized coal-flames is influenced by several competing processes, including conductive particle heating, coal pyrolysis, molecular diffusion upstream in the gas phase, gas phase reaction, and radiative effects. Results also suggest that for coals with at least 18% approximate volatile matter, heterogeneous char reaction is not an important rate-limiting process. But, so far, Smoot's model predicts temperatures being (400-700) °K higher than the measured values, in the range of (1100-1300) °K. While the measured temperature values were thought to be somewhat low, the predicted values were thought to be high. The most likely case of high temperature predictions seems to be the omission of radiative and conductive heat losses to the wall of the burner. Also, these models cannot be trusted for predicting the burning velocities for specific dust clouds in general. It was suggested that this difficulty was probably due to both a lack of understanding of the underlying physical mechanisms like swelling, internal burning, and chemical kinetics, and a lack of a complete knowledge of the dust constituents for many dusts of interest [10].

In contrast to Smoot's opinion, Slezak [18] suggested that a smaller apparatus tends to limit the radiative transport downstream of the flame front. By limiting this heat transport mechanism the reaction zone structure is fixed by conduction and convection transports.

Modelling of dust-air flame has been attempted only for very restrictive situations by Smoot [71], Ballal [16, 17], Slezak [18], and Krazinski [11], respectively. Accurate predictive quantitative theories, however, do not yet exist, neither is it yet possible to predict satisfactorily whether a flame can propagate in a given dust-air system and what would be the characteristics of its propagation. Effective research is still in the data-gathering and

mechanism-determining stages.

2.4 Effects of Turbulence on Gas and Dust Combustions

Turbulence discussed in the following may be defined as three dimensional vortical fluid motion of finite intensity involving random macroscopic mixing with a large range of length and time scales [81]. Before reviewing the effects of turbulence on the various combustion processes, it is necessary to briefly examine ways in which turbulence can arise during an explosion. It is also not surprising that reviews of turbulence effects on gas-phase combustion and explosion are also included in this section and given wide coverage. The reason is not only due to the numerous investigations of gas phase explosions that are conducted throughout the world and to an abundance of literature that pertain to turbulence effects in such explosions, but also because much of the knowledge acquired for dust combustion has come from an understanding of the processes involved in combustion of gaseous fuel-air mixtures. Indeed, an understanding of turbulent dust flames is very difficult without the help from the knowledge of gaseous turbulent flames.

2.4.1 Source of turbulence

1) Mechanical agitation

Prior to ignition, turbulence may exist in an explosive mixture due to movement created by external means such as fans or rotating machinery. This is particularly important in the handling of grain dusts in areas such as baghouses where space velocities are high [1]. In coal mines, a common practice is to carry the coal dust away from the operating face by ventilating air [82]. In this manner, some degree of turbulence is created in the dust cloud before the dust is deposited on surfaces away from the face.

2) Flow-induced turbulence

As noted by Eckhoff [83], the length to diameter ratio of cylindrical enclosures is an important consideration in assessing the possibility of flow-induced turbulence. If this ratio is larger than a value of four, wall friction may induce turbulence in the unburned cloud ahead of the flame during a dust explosion.

Venting is an accepted method of preventing an enclosure holding a fuel-air mixture

from rupturing in the event of an explosion within the enclosure. The venting process, however, is known to cause flame distortion and create turbulence, which also can be considered to be of the flow-induced type. When the vent cover ruptures, unburned fuel is exhausted through the vent, causing wall-friction-induced turbulence within the enclosure. In the case of an initially uncovered vent, turbulence is generated from the onset of deflagration, since venting also begins at this time.

3) Obstacles-induced turbulence

Once an explosion has been initiated, the presence of obstacles in the path of the propagating flame can create high level of turbulence in the unburned mixture being pushed ahead of the flame front. This is an entirely realistic situation in a mine gallery or processing area where machinery and even personnel may be considered as obstacles should an explosion occur. In office areas as well, such items as desks and file cabinets are potential turbulence generators.

4) Dispersion-induced turbulence

Every pneumatic dispersion system in closed combustion vessels are essentially a turbulence generator. The turbulence parameters created by dispersion systems are not analogous to the natural conditions. The importance of studying the features of dispersion-induced turbulence and their effects on dust combustion is due to the fact that all dust combustion data in closed vessels are dispersion systems dependent.

2.4.2 Effects of turbulence on gas phase combustion

The qualitative effects of a turbulent flow field on flame propagation in a combustible gas mixture have been known for at least a century. The large majority of the existing researches on turbulent gas phase combustion can be divided into two categories. The first category is comprised of studies of various aspects of flame propagation, flame structure and dynamics of flame-turbulence interactions in idealized simple situations. The objective of these studies was to give a better understanding of the phenomenon of turbulent combustion. The other category of works focused on deriving various computer modelling techniques which can be employed for quantitative studies of turbulent combustion problems of engineering interest. The rapid development of numerical modelling capabilities in recent years caused this direction of research to become a dominating one. The fundamental difficulty in the numerical treatment of turbulent combustion arises from the nonlinearities in

the fluid dynamic and chemical reaction equations as a consequence of which the equations pertaining to the statistical moments of turbulent fluctuations of different orders are coupled with each other. New numerical methods, which are taking into account all the details of vortex dynamics and flame-turbulence interactions are needed either to advance the understanding of turbulent combustion or to achieve reliable results. The present review puts emphasis on the first category.

The fundamental theories of turbulent combustion were developed by Damkohler [84] and Shchelkin [85] almost fifty years ago. It is considered to be the first significant effort at modelling turbulent flames. Although many models developed since this time have been based on Damkohler's work, no adequate comprehensive theory has yet evolved. Classification of existing theories is based on either the ratio of the turbulent macroscale to the laminar flame thickness or, more frequently by employing the following physical models: the wrinkled flame model; the entrainment model, and the turbulent diffusivity model. This classification is very broad and depends on qualitative arguments that group wrinkled flame models corresponding to large scale, low intensity turbulence, and diffusivity models corresponding to small scale, high intensity turbulence. Other models, suggested by Ballal and Lefebvre [86], use the turbulent intensity and scale as a classification scheme. The review paper by Andrews, et al. [87], summarizes all the current theories of turbulence that are relevant to the structure of turbulent flames. It is suggested there that $Re_\lambda (= u' \lambda / \nu)$, the turbulent Reynolds number based on the Taylor microscale of turbulence, for the reactants, is an important controlling parameter and it could be used to correlate the ratio of turbulent burning velocity to laminar burning velocity.

2.4.2.1 Unconfined turbulent flames in premixed gases

The study of turbulent flame propagation was begun by Mallard and LeChatelier [88] in 1883. It was known that flow becomes turbulent and flame velocity rises rapidly at a Reynolds number (based on the diameter of the testing tube) of about 2000, since the laminar burning velocity is independent of flow velocity at low Reynolds numbers. Damkohler [84] investigated the flame formed on a bunsen burner, both experimentally and theoretically. He suggested that U_t / u_l , where U_t is the turbulent burning velocity and u_l is the laminar burning velocity, should be proportional to $Re^{0.5}$ at a low Reynolds number and proportional to $Re^{1.0}$ at a higher Reynolds number. He also realized that the mechanism through which turbulence

affects flame propagation is quite different according to whether the scale of turbulence is small or large as compared to the thickness of the combustion waves. He expressed the turbulent burning velocity by the formula

$$u_t/u_l = (\epsilon/\nu)^{0.5}, \quad (2.1)$$

for small-scale turbulence ($l/\delta_l \ll 1$), where ν is the kinematic viscosity, and ϵ is the eddy diffusivity, l is the integral scale of turbulence and δ_l is the flame thickness, and

$$u_t \approx u', \quad (2.2)$$

for large-scale turbulence ($l/\delta_l \gg 1$), where u' is the rms turbulent velocity. Damkohler proposed, according to Eq.(2.2), that the flame will be wrinkled but that the laminar transport processes will remain virtually unaffected.

Shchelkin [85] extended Damkohler's theoretical considerations further, and expressed

$$u_t/u_l = (1 + \epsilon/\nu)^{0.5}, \quad (2.3)$$

for small-scale turbulence ($l/\delta_l \ll 1$), while

$$u_t \approx u', \quad (2.4)$$

for strong, large-scale turbulence ($u'/u_l \gg 1$ and $l/\delta_l \gg 1$), and

$$u_t/u_l = (1 + b(u'/u_l)^2)^{0.5}, \quad (2.5)$$

for weak, large-scale turbulence ($u'/u_l \ll 1$), where b is a coefficient of magnitude of 1. For strong turbulence, Eq.(2.5) reduces to Eq.(2.4). Therefore, Eq.(2.5) can be considered as the general formula for large-scale turbulence given by Shchelkin.

From Damkohler's and Shchelkin's work [84, 85], small and large scale turbulent flame models have been proposed. One model is based on a molecular transport process (the wrinkled laminar flame model) and the other on turbulent transport processes (small-scale eddy model). The wrinkled laminar flame model is a turbulent flame brush which consists of a thin laminar reaction front, fluctuating in shape and location. The small-scale eddy model uses the same theoretical approach as laminar flames, but the

molecular transport coefficients are replaced by the equivalent turbulent ones.

Furthermore, Ballal and Lefebvre [86] proposed a three-region model for premixed turbulent gaseous flame, in which turbulence was generated by grids : a "wrinkled-pulsating" behavior of region 1, featured with $u' < 2u_1$ and $\eta > \delta_1$, the "jet-like" characteristics of region 2, $u' = 2u_1$ and $\eta = \delta_1$, and the "eddy entrainment-combustion in depth" mechanism of region 3, $u' > 2u_1$ and $\eta < \delta_1$, where η is Kolmogorov microscale of turbulence. With this model, the results from the relation for each region are in good agreement with experiments [86].

It is understandable that turbulence does not always play the role to increase the rate of combustion. If quenching can be regarded as the extinction or retardation of a flame due, in part, to excessive heat losses from the combustion zone, then flame quenching by excessive turbulence has been observed by Sokolik et al. [89]. They found that in a closed vessel the burning velocity peaked at a certain turbulence intensity and then decreased with a further increase in turbulence. In the work of Abdel-Gayed and Bradley [90], the flattening of their turbulent burning velocity curves with increasing turbulence suggests a limiting value for turbulent burning velocities. Ballal and Lefebvre [91, 92] defined the concept of quenching distance as the smallest diameter of a tube or the shortest distance between two long parallel plates, which will quench the passage of a flame through it. They found that the quenching distance increased with an increase in turbulence intensity and was independent of changes in turbulence scale. One of the most comprehensive reviews of flame quenching by turbulence is provided by Chomiak and Jarosinski [93]. They found that premixed gaseous flames are quenched by turbulence when the chemical reaction time is seven to twenty times longer than the eddy lifetime. Qualitatively, this was explained by excessive stretch of the local combustion regions.

The acceleration of a propagating flame by obstacles placed in its path has received considerable attention by various researchers. In their work on gaseous explosion in vented ducts, Rasbash and Rogowski [94] caution that the flame speeds they measured would have been significantly higher had turbulence-inducing obstacles been located in the duct.

Moen et al. [56] investigated the influence of turbulence-inducing obstacles on freely

propagating methane-air flames and measured flame speeds well in excess of those obtainable with no obstacles in the path of the flame. They also found that without repeated obstacles to provide flow field distortions and turbulence continuously, the flame was unable to maintain its high turbulent flame speed. The degree of turbulence was not quantified in this work.

Extension of the work of Moen et al. [56] to a large-scale apparatus [57] led to similar results. The importance of considering obstacle-induced turbulence when calculating venting requirements has been stressed by Moen [56], and the possibility of such turbulence causing a transition from deflagration to detonation is discussed by Lee and Moen [95], Lee et al. [96], and Andrews and Herath [97].

The phenomenon of turbulence created by an obstacle in the path of an advancing flame and the subsequent flame distortion is explained by Moen et al. [56] as follows. The obstacle creates a wake pattern in the flow of unburned gases ahead of the flame; this wake pattern contains large and possible small scale turbulent eddies. When the flame enters the turbulent flow region established by the obstacle, it becomes wrinkled and folded as the hot combustion zone is distorted and entrained into the wakes by the action of the large-scale eddies. An enhanced rate of burning results from the increase in flame surface area. Any small-scale eddies present in the wake further intensify the combustion process by contributing to the heat and mass transport across the wrinkle and fold surfaces. A simple feedback mechanism for gas flame acceleration by repeated obstacles was proposed based on the assumption that increase in the rate of burning of the flame fold due to the turbulence produced by the obstacles controls the acceleration process. The model assumed by Moen et al. in [59] was that a flame fold (which does not continue to grow) has already been established, and that the rate of burning of this flame fold is determined by the turbulence field which the flame propagates into. In this model the details of the turbulent combustion or the nature of the combustion zone are not considered.

The acceleration process of gas flames propagating in a tube is also considered by Chomiak [98]. There are three groups of effects, which are of essential importance: pressure and temperature effects, flame shape and turbulence effects, and flame instability effects. In general, the pressure and temperature dependences are weak. An analysis demonstrated by Chomiak is based on the Zeldovich-Shchelkin model [99] for a flame accelerating at a closed-end of a tube and employs flame shape and turbulence effects. If we apply this analysis to the obstacle case, the mechanism of gas acceleration can be explained

mainly by the effects of nonuniformity of mean velocity and not by turbulence which is contrary to the common interpretation of flame acceleration. Chomiak demonstrated in [98] that in fully developed turbulent pipe flows the flame acceleration caused by the effects of turbulence are only about 1/3, on the average, of the effect of mean velocity.

Quenching of propagating flames by obstacle-induced turbulence has been discussed by Lee et al. [96]. In their work with long tubes, they were able to obtain an upper bound for the deflagration speed in gaseous mixtures near the flammability limits. At these limits, where the rate of combustion is relatively slow, it was observed that an increase in turbulence intensity led to quenching rather than enhancement of flame propagation.

The basic physics of unconfined turbulent flames propagating in premixed gases are discussed and reviewed by Chomiak in [100]. The following subjects are considered in greater detail: stability of laminar flame in turbulent flow, shear wave-flame interaction, flame generated turbulence, influence of small scale turbulence on flame propagation and structure of turbulent flame at high Reynolds numbers.

2.4.2.2 Constant volume explosions in gas phases

The constant volume bomb has been considered as the best apparatus for measuring the burning velocity in both laminar and turbulent conditions [101]. It has been successfully applied for determining of the burning velocity in several studies [89, 102].

The classical theory of constant volume explosions studied by Fiock et al. [103], Lewis and Elbe [104], and Bensen and Burgoyne [105] shows that the burning velocity u , the pressure P and the rate of pressure rise dP/dt are related to each other in a simple manner:

$$u = (dP/dt) / \{ 3/r [P/P_a]^{1/\gamma} [P_f - P_a] [1 - (P_a/P)^{1/\gamma} (P_f - P)/(P_f P_a)^{2/3}] \}, \quad (2.6)$$

where r is the radius of the spherical propagating flame front, P_a is an explosion pressure at the initial instant, P_f is the final explosion pressure in the explosion vessel and γ is the specific heat ratio. It is useful to relate the results of pressure measurements to the burning velocity, since direct measurements of burning velocity is much more difficult than pressure measurements. Also, the quantity, u , can serve as a basis for comparing data among a variety of experimental set-ups. Bradley and Mitcheson [106] have recently reviewed the basic

equations and associated assumptions for flame propagation and previous solutions for central ignition of premixed gases in closed spherical vessels, and presented three categories of solutions. Theoretical pressure rise, predicted by those solutions, is in good agreement with accurate experimental values of the pressure-time relationships. This model is derived with the help of a few simplifying assumptions. They are the following :

- i) regular, spherical flame propagation occurs without heat loss,
- ii) the burned and unburned mixtures behave as perfect gases,
- iii) the unburned mixture is being compressed isentropically by the propagating flame, and
- iv) the pressure rise is directly proportional to the mass fraction burned.

In the analyses of Nagy et al. [6], turbulence effects have been taken into account by the introduction of a constant α . Thus, the turbulent burning velocity was α times the laminar burning velocity. These analyses were based on the assumption that the flame will be influenced by wrinkling but laminar transport processes will remain unaffected.

Wheeler [107] was one of the first researchers to study the effect of fan-stirred turbulence on ethane-air mixture explosions. Andrews et al. [108] used the double ignition technique along with a fan-stirred reactor in which a uniform, isotropic turbulence was created. They found that the flame speed, flame thickness and turbulent burning velocity increased with the fan speed, but that the gas velocity ahead of the flame showed little change with fan speed. The laminar and turbulent burning velocities of the gas-air mixture, determined by the experiments in [108], were compared with those data from several other methods.

Andrews et al. [108] suggested that the ratio of turbulent to laminar burning velocity (u_t/u_l) is correlated as a function of turbulent Reynolds number $Re_\lambda (=u'\lambda/\nu)$, which is based on the Taylor microscale of turbulence, in the unburned gas. This correlation predicts an approximate linear increase of u_t/u_l with Re_λ . They found that when Re_λ is greater than 100 [87], a wrinkled laminar flame structure is unlikely and the turbulent flame propagation is probably associated with small dissipative eddies. Although Sokolik et al. [89] also drew the same conclusion in their work, Williams [109] had a different opinion. His criterion for the existence of wrinkled laminar flame structure of turbulent premixed flames is that the

laminar flame thickness must be smaller than the Kolmogorov microscale η of turbulence. An equivalent statement is that the turbulent Reynolds number Re_η , which is based on the Kolmogorov scale of turbulence, must be larger than the ratio of the turbulence intensity u' to the laminar burning velocity u_l . In Williams' theory, neither of these conclusions involve the Reynolds number Re_λ . Andrews et al. [110] responded to Williams' comment with:

- i) A Reynolds number based on the Kolmogorov scale might be more fundamental, but this scale cannot be measured directly.
- ii) The Kolmogorov scale (η) may be expressed as:

$$\eta = 24.72(Re_\lambda^{-3/2}) l, \quad (2.7)$$

in an isotropic turbulent flow field [84], where l is the integral scale of the turbulence.

Since most practical flames seem to have a range of l/δ_l values extending from 1 to 20, the $\eta/\delta_l > 1$ leads to $Re_\lambda < 8.5$ for $l/\delta_l = 1$ and $Re_\lambda < 62.5$ for $l/\delta_l = 20$. These values compare with $Re_\lambda < 100$ and thus meet the criterion proposed by Andrews et al. [110].

Abdel-Gayed and Bradley [111] proposed that the correlation of u_t/u_l with Re_η (the turbulent Reynolds number based on the integral scale of the turbulence), is independent of mixture composition, while the curve of u_t/u_l vs. u_l/u' is flattened in their experiments for u_l/u' greater than 20. Since u_t/u_l is well-correlated with both Re_λ and u_l/u' in their experiments, they suggested that a wrinkled laminar flame structure is evident at high values of the ratio of u_l/u' , but a small scale eddy structure seems to be dominant at lower values ($u_l/u' < 1$) since, around this limit, a large eddy will decay before it has been consumed by a laminar flame propagation. They also gave a qualitative explanation about the transition between a small scale eddy and a wrinkled laminar flame mechanism at constant Re_η (turbulent Reynolds number based on integral scale). From this argument, they proposed a relationship for small scale eddy structure:

$$u_t/u_l = (Pr \ \epsilon/\nu)^{0.5}, \quad (2.8)$$

where Pr is Prandtl number. Since, ϵ/ν cannot be obtained theoretically, a relation for this number :

$$\epsilon/\nu = 20.5 Re_1^{0.476} , \quad (2.9)$$

is suggested from their experiment for an isotropic turbulence when $Re_1 > 100$.

Substituting Eq.(2.9) into Eq.(2.8), and using $Pr = 0.7$:

$$u_t/u_1 = 3.788 Re_1^{0.238} , \quad (2.10)$$

is obtained.

Abdel-Gayed et al. [112] proved the correlations of u_t/u_1 with Re_1 by high-speed Schlieren pictures. They suggested that the variation of u_t/u_1 with Re_1 appears to be mainly due to the u' factor in Re_1 . The evidence concerning variation of u_t/u_1 with length scale of turbulence is contradictory. They then combined the result from Libby et al. [113] who state that no consistent Reynolds number trend is apparent in Abdel-Gayeds' [111,112] experiments, and concluded that no unique relationship has yet been found between u_t and quantities such as u' , u_1 , and the turbulent Reynolds number Re_λ [114].

From the turbulence structure suggested by Tennekes [115] and Kuo and Corrsin [116], in which dissipative eddies consist of vortex tubes with a diameter of the order of η (Kolmogorov length scale) and a spacing of the order of λ (Taylor microscale), Abdel-Gayed et al. [112] proposed a two-eddy theory of turbulent combustion in which all the matter in large eddies (average life time $1/u'$) is used in the formation of dissipative (small-scale) eddies (average life time $t_\eta = 1.681 1/(u'Re_1^{0.5})$).

The study of initial turbulence effects on gas phase explosion in closed vessels has special meaning for dust explosions. It can help to explore the role of dispersion-induced turbulence on dust explosions, if the initial turbulence is produced by the same dispersion system used in the dust dispersion. In the study of initial turbulence effects, ΔP_{max} and

$(dP/dt)_{\max}$ were used to characterize the severity of an explosion. Wheeler [107] used a fan to induce turbulence in an ethane-air mixture and observed that $\Delta P_{\max}$ increased only slightly above the value for a quiescent mixture but caused a significant increase in $(dP/dt)_{\max}$. The work of Harris [117] demonstrated that $\Delta P_{\max}$ was increased only slightly by initial turbulence when the pentane-air mixture was prepared near its stoichiometric concentration and was more pronounced at the lower flammability limit. Experiments with turbulent mixtures near the stoichiometric concentration showed that $(dP/dt)_{\max}$ at the maximum fan speed of 2000 rpm was approximately five times the value measured at zero turbulence. Similar results were obtained by Nagy et al. [6]. It was observed that $\Delta P_{\max}$ with initial turbulence was approximately 30% greater than that in zero turbulence, for methane-air mixtures near the low flammability limit; the $(dP/dt)_{\max}$ was approximately five times the value measured at zero turbulence for methane concentrations ranging from 8-12%, and eight times near the lower flammability limit. The initial turbulence in the experiments of Nagy et al. [6] was produced by the dispersing blast in gas injected system. Turbulence was increased with the initial pressure in an explosion vessel unless precautions, such as partially evacuating the vessel before ignition, are taken. Therefore, the initial turbulence in Nagy's experiments can be considered as a dispersion-induced turbulence. The gas combustion data of $(dP/dt)_{\max}$, which are proportional to the intensities of initial turbulence, can be used as an indirect measure to determine the characteristic of dispersion-induced turbulence in dust combustion.

2.4.3 Effects of turbulence on dust explosions.

Turbulence effects on dust explosions can be essentially classified as two types. One is the dispersion-induced turbulence. There is always some degree of initial turbulence existing in the test apparatus before the dust cloud is ignited. Another is the flow-induced turbulence during flame propagation. In the case of dust explosions, it is difficult to avoid initial turbulence in a closed vessel, if a pneumatic dispersion system is employed. The maximum intensity of this initial turbulence depends on the structure of the dispersion process. Turbulence decays with time and the longer the ignition delay time in relation to the beginning of dispersion, the lower the intensity of turbulence. Thus, Swift [1] and Cross and Farrer [118] have suggested that dusts should be tested for $K_{st} (= (dP/dt)_{\max} V^{1/3})$ values

with the highest possible degree of dispersion-induced turbulence, presumably to simulate a worst possible case. Kauffman et al. [21], using a 950 liter premixed turbulent combustion bomb, determined a marked increase in the burning velocity of grain dust with an increase in turbulence intensity. The turbulence level inside the reactor was controlled by the difference between the pressure in the reservoir holding the dispersing air and the original pressure in the explosion vessel. The turbulence intensities were measured by hot wire anemometers in the cold flow without dust particles and was verified using a Laser Doppler Anemometer. It appeared to be the first time that turbulence levels existing prior to a dust explosion have been measured. Experimental results in [21] demonstrated the strong influence of turbulence on $\Delta P_{\max}$ and $(dP/dt)_{\max}$, that $\Delta P_{\max}$ is increased by more than 50% and $(dP/dt)_{\max}$ is more than doubled by an increase in turbulence intensity from 1.5 to 4.2 m/s, with a concentration of 0.5 kg/m³ of 74 μ m cornstarch.

Experiments of Bond et al. [20] have been carried out in a 0.333 m³ closed spherical vessel to assess the influence of turbulence on the burning rate of cornstarch dust-air explosions. Turbulence in [20] was induced by the dispersion process only or superimposed on an existing turbulence which was created by an additional air supply through a perforated torus. Experimental results demonstrated that the maximum overpressure remained practically constant as the intensity of the turbulence was varied, while the maximum rates of pressure rise increased by a factor as high as eight. The relative burning rate increases brought about by turbulence in cornstarch dust-air explosions were equal to those observed in methane-air explosions (7% methane concentration) performed under identical conditions of turbulent flow.

Since dispersion-induced turbulence is inherent in dust explosion experiments, it not only increases the rate of energy release in the explosion process; but also effects the flammability limits and the minimum ignition energy of the dust-air mixture. Lovachev [119] suggested that perhaps the only way of obtaining reliable results on flammability limits and minimum ignition energies for dusts is to conduct the tests in space, where the effects of gravity and therefore the problem of dust dispersal are alleviated. Until such time, the problem of obtaining realistic data within the confines of the earth's atmosphere has to be faced.

Work similar to that using fan-induced turbulence in gas-phase explosions has been

carried out for wheat flour dust by Hayes et al. [120]. They observed a twofold increase in the measured flame speed, when the speed of fan varied from (1000-1500) rpm. This increase in flame speed was explained in terms of increased efficiency of heat transport. Fan-induced turbulence is rarely used in experiments of dust explosions because the uniformity of dust suspension is affected by the motion of the fan.

The experimental studies of flow-induced turbulence effects on dust flame propagation have been reviewed in Chapter 2, section 2.1.3. Essenhigh [10] distinguished three mechanisms of coal dust flame propagation according to the rates of heating of particles that ranges from 10°C/s for slow flames to $(10^4-10^6)^{\circ}\text{C/s}$ for fast flames. He suggested that in explosion flames where the flame speeds are high, propagation occurs by turbulent exchange, probably with heterogeneous ignition.

Clark and Smoot [121] provided a global model for calculation of accelerating coal-dust flame. The general macroscopic equations of change for particulate systems is used as the foundation for this model, along with appropriate auxiliary relationships. Clark and Smoot predicted that a deflagrating coal-dust flame can accelerate to high velocity and pressure, increasing turbulence being a major cause of the acceleration. A parametric study was made to determine effects of key variables on the accelerating coal-dust flame. Key variables included the duct diameter, coal particle size and the ratio of air to coal. A correlation of turbulent gaseous flame was applied to this dust flame. The turbulent coal-dust flame velocity was considered as a function of the laminar flame velocity and the turbulent Reynolds number (based on the Taylor microscale of turbulence), which was reported by Andrews et al. [87] for turbulent gaseous flames.

It can be presumed that the presence of turbulence will accelerate streamwise diffusion, thicken the flame, and increase radiative heat transfer. But what are the rates and controlling processes for turbulent premixed dust flame propagation? Very little about turbulent dust flame is presently known.

In this chapter, a detailed literature review concerning gas-air and dust-air mixture combustion and explosion has been presented. One may draw a clear conclusion of where we are and what we should do now in dust research studies. Drawing upon this information the basic considerations and thesis objectives are described in the next chapter, Chapter 3.

CHAPTER 3

BASIC CONSIDERATIONS AND THESIS OBJECTIVES

3.1 A Brief Recap

The mechanisms of flame propagation in dust-air mixtures are very complex. In previous research, some general characteristics and features of laminar dust flames have been identified, and the effect of turbulence on dust explosions was quantified. However, in both laminar and turbulent combustion, there is a scatter in the reported experimental data, and there are divergent opinions of the dominant process in dust flame propagation. Hence, neither simple and approximate nor complex methods have been put forward to estimate which is the dominant mechanism and what are the characteristics of its propagation in a given dust-air mixture. Furthermore, there is even less knowledge of the basic mechanisms associated with turbulent dust flames than those of laminar flames.

In brief, from the current state of investigation of dust flames it can be concluded that effective research is still in the data-gathering and mechanism-determining stage. Qualitative mechanisms are being elucidated by quantitative investigation and many gaps are surfacing in the scientific understanding of the basic phenomena. Clearly, part of the difficulty implied in this investigation stems from the dearth of good experimental data, which prevents one from making realistic assumptions or discarding terms of secondary importance or developing relations between key parameters. Hence the acquirement of reliable experimental data remains a priority.

3.2 Basic Considerations

3.2.1 The importance and the reliability of a comparative method in the examination of a dust flame

The wide variety of materials that may cause dust explosions in air include natural organic compounds (starch, cellulose, sugar, etc.), synthetic organic compounds (polyethylene, polystyrene, etc.), coals, and metals (Mg, Al, a number of alloys, etc.). It

seems highly unlikely that flames in dust clouds of all those materials can be described by one single model of dust flame propagation. However, it seems realistic to consider one flame propagation mechanism applicable to a group of dusts characterized by a certain amount of volatiles. Self-propagating coal dust flames, for example, appear to be controlled by processes occurring in the gaseous phase and are similar to those occurring in gas flames [16, 71, 122]. This opinion would suggest that for those natural and synthetic organic materials as well as lignites and bituminous coals of very small particle sizes and with completed dust dispersion, the flame characteristics are comparable to those of gas flames. In all these dusts, it is probable that the rate of flame propagation is principally controlled by the rate of streamwise molecular diffusion of oxygen and volatiles, together with heat conduction from the resultant hot gas to the particles [71]. These dust flames are most likely to fit a model of the "gas-flame type".

The method of comparative studies of dust and gas flames has already been used in various problems by Smoot et al. [30, 71], Jarosinski et al. [38, 123], Strehlow et al. [72, 124], Nagy [9] and Bond [20]. The similarity between flame propagation in "gas-flame type" dust-air mixture and premixed gas-air mixture is roughly recognized [16, 38, 71, 125]. For homogeneous gases the flame characteristics such as the laminar burning velocity, the flame thickness, the quenching distance and the minimum ignition energy are well known. The effects of turbulence on the propagation of a premixed gaseous flame are also well established.

The flame characteristics of dust mixtures are known incompletely. Hence, it is worth while to compare in detail all the available flame characteristics (including the burning velocity, the flame thickness, the quenching distance and the minimum ignition energy) and the explosion characteristics (including the maximum pressure rise, the maximum rate of pressure rise and the entire combustion time) in gas and in dust mixtures, to reveal similarities and differences between both flames. The reliability of this comparative method in the examination of dust flames is based on the gas explosions in comparison with dust explosions in the same apparatus, and under the same experimental conditions. This procedure follows the discussion of the validity of the cubic law shown in Appendix A. The analysis in Appendix A demonstrates that the similarity of explosion characteristics in various vessels depends not only on the property of the mixture but also on the level and the length scale of the dispersion-induced turbulence, which are related to the technique of the dispersion system and the procedure used.

In the present work, methane and cornstarch are used as comparative fuels. The behavior of a flame is examined by the pressure history of the combustion process $P(t)$ and the location of the flame front along the tube as a function of time $L(t)$, which is related to the flame propagation velocity. Comparison of the maximum pressure rise, the maximum rate of pressure rise, the flame propagation velocity and their mutual relations, for gas and dust flames, makes it possible to find similarities and differences. The agreement or deviation of dust explosion characteristics from that of gas, treated as a reference will enable us to form an opinion on a physical model for dust flames and the mechanisms associated with its propagation.

3.2.2 The necessity and the possibility of examining the mechanisms of dust flame propagation during constant volume combustion

Self-sustained flame propagation can be established not only in a gas-air mixture but in a fine dust-air mixture (with particle diameters of less than $50\mu\text{m}$). The formation of a laminar flame capable of propagating in a flammable mixture means the existence of a laminar burning velocity (u_l), a flame thickness (δ_l), the associated quenching distance (D_q) and the minimum ignition energy (E_{min}). The measurement of those flame characteristics and also the analysis of partial processes occurring in the flame, gives insight into the mechanism of its propagation. Unlike a homogeneous gas-air mixture, the flame characteristics such as the laminar burning velocity or the flame thickness are not well established for dust mixtures. In a gas-air mixture those characteristics are a property of that mixture. The processes in dust-air mixture are more complex. The results of experiments with a multidroplet mist [73] or dust cloud [16] have shown that, in addition to fuel/air mass ratio, the physical properties of the fuel, the size of particles (or droplets) or the amount of volatile matter have a significant effect on the burning velocity and the flame thickness. Thus, the laminar burning velocity and the flame thickness are also properties of heterogeneous mixtures, but they must be characterized by at least three parameters, the fuel/air mass ratio, the size of particles and the amount of volatiles.

The laminar burning velocity is the most important parameter characterizing the controlling processes in a flame, therefore estimation of its proper value becomes critical for flame diagnostics. The laminar burning velocity of gas-air flames is usually measured in various types of open burners, tubes and closed vessels. It is interesting to find that the closed vessel method used by Andrews and Bradley [102] to determine flame characteristics

in a methane-air mixture offers very reliable data, much better than those determined by other methods. A similar method was successfully used by Sokolik and Karpov in their measurements of turbulent burning velocity in several gas-air mixtures [126].

The laminar burning velocity of dust flames is usually measured in flames stabilized on various open burners. The serious disadvantage of this method lies in most cases, in the fact that the stabilized flame is under direct influence of the burner (heat transfer and stabilizing effects), which changes its characteristics. The propagation of dust flames in open or half-open tubes is not promising since it is very difficult to take into account the effects of buoyancy and the acoustic vibration phenomena on flame propagation, especially in large diameter tubes. Usually laminar burning velocity is one order of magnitude lower than the buoyancy velocity, which implies that the accuracy of the calculation for determining the laminar burning velocity is poor.

The relatively good results obtained by the method developed by Ballal, for a flat flame in a tube, are limited to zero gravity experiments [16]. In employing this technique under natural gravity conditions, in which burning velocity are slower than the settling velocities of dust particles, the local dust concentration would change too fast.

The closed vessel method has rarely been used for investigating dust flame characteristics. Usually, closed vessel explosions are used for indexing the relative dust explosion hazard. The most important explosion characteristics are the maximum pressure and the maximum rate of pressure rise. The relationship between the pressure history and the flame propagation has, as yet, not been explored experimentally in closed tube explosions. In view of the deficiencies in open burner and open tube methods for laminar dust flame studies, it is reasonable to complement them by another method. The study of "one-dimensional" flame propagation in a closed tube can thereby serve as a correlation of explosion characteristics with flame characteristics, when a comparative method for examining dust and gas flames are used.

The advantage of studying the flame propagation in a closed tube lies in the adiabatic conditions of the first stage of flame propagation (see Appendix B), high accuracy of pressure measurements linked directly with the heat release, and in a short time scale of combustion which makes it possible to keep a relatively uniform dust concentration (the suspension of dust is transient) during the experiments. The time scale of combustion in closed tube experiments is approximately one order of magnitude shorter than that in an open

tube. This is due to the role played by the expansion of hot combustion gases in flame propagation. The advantages of closed tube experiments are highly helpful in improving the reliability of measurements.

Although the phenomena of flame propagation under constant volume conditions is rather complicated, the combustion of premixed gases, in particular, their gas dynamics in a closed tube has been well understood, (see [127-130] and Appendix B). Employing what we know about the characteristics of gas flame, and further correlating these flame characteristics with their explosion characteristics in a closed tube as our reference, we are able in a comparative manner to correlate the explosion characteristics of dust-air mixtures in the same closed tube (under identical initial turbulent conditions induced by dispersion system as those of gas-air mixtures) to their flame characteristics. The behavior of both flames is examined carefully by the pressure history and the flame propagation history. The comparison of $P(t)$ and $L(t)$ curves for methane and cornstarch dust flames makes it possible to identify the similarity of explosion characteristics for some corresponding mixture concentrations. Comparison of the gas and dust flame characteristics from some of previous experiments shows that dust-air flames and lean methane-air flames (5.0% -6.0% methane) have similar values of the burning velocity, the flame thickness, the quenching distance and the minimum ignition energy (see Table 2). The similarity of the flame characteristics between dust-air and gas-air mixtures can be verified by comparison of the explosion characteristics, which describe globally the combustion processes in closed vessel. If it is shown, by closed tube experiments, that the explosion characteristics are also similar, for corresponding mixture concentrations, one can assume that the gas and dust flame propagation is controlled by the same or similar processes. Thus, it is possible to use this method to verify those not well established characteristics of dust flames, especially the burning velocity and the flame thickness determined by other methods.

3.2.3 Investigation into the effect of turbulence on dust flame propagation by the proposed method

The interest in the turbulent combustion of dust-air mixtures is self-evident from the point of view of the almost total lack of data related to turbulent premixed flames propagating in many mixtures [71]. In most experiments performed in dust-air mixtures, the real state of the medium before ignition is unknown, since the concentration gradient in the dust cloud and the variance of concentration with time is influenced by the turbulent vortical fluid motion. The influence of turbulence on dust combustion in these experiments is usually

estimated in qualitative terms. The unsatisfactory level of knowledge about the parameters in dust-air mixtures is a result of the lack of experimental data on the turbulence in a two-phase mixture, due to the difficulty of making turbulence measurements in such a system. In the present study the influence of dust on the dispersion-induced turbulence has been examined, in accordance with the global effects of combustion. Two kinds of experiments were employed. In one of the tests, the gas-air mixture premixed in the air reservoir, with the same composition as that in the test tube, was dispersed prior to ignition. In another test, the same gas-air mixture in the air reservoir was used to disperse inert dust (Al_2O_3). Small difference in pressure histories and flame front locations along the test tube between these two experiments showed that the influence of dust on the dispersion-induced turbulence parameters would not be significant (see Fig.2). It was assumed on the basis of this conclusion, that turbulence measurements in air are not much different from those in a two-phase mixture. Thus, it was decided to estimate the turbulence parameters in a two-phase mixture on the basis of turbulence measurements in pure air. A realistic philosophy to understand the role played by turbulence and to conjecture the mechanism, through which turbulence takes part in the combustion of a gas-particles system, has been proposed by Bradley and Lee [125] and is put into practice in the present study. This requires a knowledge of the laminar burning velocity u_l , the flame thickness δ_l , the rms turbulent velocity u' and the integral length scale l . The comparison of the rms turbulent velocity u' with the laminar burning velocity of dust flame $u_{l,d}$ and three length scales of turbulence l , λ and η with laminar dust flame thickness $\delta_{l,d}$ are employed in the present study as a major means to figure out the mechanism of turbulent combustion. One can expect that these comparisons should help to model the interaction of a turbulent flow with a laminar flame and to elucidate the structure of a turbulent gas and dust flame.

3.3 Thesis Objectives and Outline of Present Undertaking

1) Development of a dispersion system for investigating dust flame propagation

To enable the investigation of dust flames it was necessary to prepare a good quality dust dispersion system for distributing the dust over the entire volume of the tube without giving rise to an axial flow during dispersion. The investigation into the influence of the dispersion-induced turbulence and the uniformity of the dust distribution on the explosion characteristics were an important part of this research work. The results are described in

Chapter 4. Chapter 5 describes the details of the apparatus, the measurement techniques, the experimental procedures, and the properties of combustible mixtures.

2) Acquisition of a "quasi-laminar" flame in constant volume combustion

The similarity between flame characteristics of a dust-air mixture and that of a gas-air mixture can be verified by comparison of the explosion characteristics of those mixtures as determined for laminar flame propagation. However, pure laminar dust or gas flames cannot exist in the present test tube, because of the instability phenomena and a cellular structure on their surface, and because they are influenced by turbulence produced by the dispersion system. Laminar premixed dust flames need a uniform dust-air mixture. Such uniformity is carried into effect by the pressurized dispersion system characterized by a high level of initial turbulence. It is demonstrated by experimental results that dispersion-induced turbulence decays very fast and the conditions inside the test tube approach asymptotically the laminar conditions. Unfortunately, the turbulence decay is accompanied by dust being attracted to the wall of the test tube and its associated agglomeration and settling down. To compromise the influence of the dust settling down, it was found from experimental results that 300ms ignition delay time is optimum from the point of view of low turbulence level at the moment of ignition and an acceptable amount of dust participating in suspension. Starting from this ignition delay time (300ms), the flame can be considered to approach the laminar conditions, and named "quasi-laminar" flame, for convenience. The concept of quasi-laminar flames is presented in Chapter 6, section 6.1.

3) Quantitative estimation of the flame characteristics and the controlling processes of flame propagation in cornstarch dust-air mixtures

The explosion characteristics of a cornstarch dust-air mixture are studied by comparing them to those of a methane-air mixture, making use of our present understanding of gas flames. Using a flame propagating in methane-air mixture as a reference [102] we can compare the characteristics of the dust flames with those of gas flames. Thus, the similarities and the differences between the behavior of both flames and their characteristics, which are studied under the same experimental conditions, may facilitate the understanding of the combustion processes involved in the dust flame. Finally, it is possible to make a quantitative estimation of the burning velocity, the flame thickness and controlling process of flame propagation in cornstarch dust-air mixture by this comparative method. Detailed experimental results and discussion of this part of research are presented also in Chapter 6, section 6.1.

4) Estimation of the influence of dispersion-induced and obstacle-induced turbulence on the flame propagation in dust-air mixtures

To enable the investigation of the influence of turbulence on flame propagation in a cornstarch dust-air mixture, it was necessary to use a well-defined gas flame as a reference. Two markedly different kinds of turbulence studied in the present experiments: turbulence induced by the dispersion system and by obstacles. The experimental results and discussion of this part of research are presented in Chapter 6, section 6.2 and 6.3.

5) Elucidation of the structure and the mechanism of laminar and turbulent flame propagation in dust-air mixtures

The elucidation of the structure and the mechanism of laminar flame propagation in cornstarch dust-air mixtures are discussed in Chapter 6, section 6.1, the turbulent flame part being the subject matter of Chapter 6, section 6.4 and 6.5. Finally, the concluding remarks and the indication of the future research are the subject matter of Chapter 7.

In brief, the contribution of the present thesis is based on a series of detailed experimental investigations of the explosion characteristics (such as the maximum rate of pressure rise or the K_{st} factor, the maximum pressure rise and the entire combustion time), in a premixed cornstarch dust-air mixture, both laminar and turbulent, and to correlate them with the flame characteristics (such as the burning velocity, the flame thickness and the quenching distance).

CHAPTER 4

PRELIMINARY EXPERIMENTAL INVESTIGATIONS

4.1 Basic Consideration of Apparatus Selection

4.1.1 General description

The majority of dust-air explosion test devices consists of a chamber for combustion, an ignition source and a means of dispersion. The combustion chamber influences explosion characteristics, such as the ratio of the heat release rate to the heat loss rate, by its specific size and shape. The ignitor directly influences the ignition energy level. The dispersion system influences the explosion characteristics by its specific type of dispersion-induced turbulence and the degree of non-uniformity of the dust-air mixture, which is dispersed by this system.

4.1.2 Combustion tube

Usually, the experiments of dust-air explosion are carried out in spherical bombs or small L/D ratio cylindrical vessels, ($L/D < 2.5$, where L is the length and D is the diameter of the cylindrical vessel). An explosion in a closed tube shows considerable differences in comparison with one in either a spherical or a small L/D ratio vessel. The flame in a tube generates a distinct axial flow and the flame propagation can be roughly considered as "one-dimensional". The tube can model most of the industrial elongated vessels which are, according to [7], vessels with a ratio $L/D > 5$. In such vessels as in pipelines or in silos, an explosion initiated at one of its ends causes displacement of the unburned mixture ahead of the flame front as a result of the expansion of hot combustion gases. Under these conditions, any roughness or obstacles present in the tube accelerates the flame. The resulting flame propagates much faster than that in a spherical vessel. However, heat losses in a tube are higher than in a spherical vessel. Where a flame propagates along a tube with a large L/D ratio, the influence of heat loss to the walls on the explosion characteristics becomes significant. The heat loss is proportional to the ratio of the surface area S to the tube volume V . To decrease the value of S/V , a large tube diameter is necessary. The selection of the diameter also can be examined by the ratio of the tube diameter to the quenching distance

(D/D_q). The value of this ratio in a standard test tube for flammability limit study of gaseous flames [131] is about 10. Table 2 shows that experimentally determined quenching distance for several dust flames is in the range of 0.5 -2.5 cm. Hence, in the present study, if a tube with a 0.19 meter diameter is used, the ratio of D/D_q is in the range of 8-40. It is of the same order of magnitude (or even higher) than that in [131]. Therefore, in the present study, a middle size test tube, $D = 0.19$ meter in diameter, $L = 0.93$ and 1.86 meters long, with two closed ends is considered as an appropriate geometric scale for investigating dust flame propagation.

Obtaining a uniform dust dispersion along a vertical tube involves many difficulties. The experiments not only require a uniform spatial distribution of dust concentration along the tube axis but also a steady suspension of particles during the combustion process. In order to obtain a uniform axial dust concentration distribution and suspension, a 1.86 meters test tube is cascaded in two segments, in which each segment contains its own dust dispersion system and has the same construction as the other. With this configuration the global non-uniformity along the length of the tube is minimized.

4.1.3 Dispersion system

Based on the review of the techniques of dust dispersion (see Chapter 2, section 2.2), the dispersion system developed in the present study is essentially a linear version of the circular perforated pipe used by Bartknecht [7] in his standard 20 liter sphere or the 1m^3 vessel. For distributing the dust over the entire volume of the tube without giving rise to an axial flow during dispersion, this linear dispersion pipe should be taken the same length (0.93 meter) as the test tube. Experimental observations show that the inside diameter of the channel in the whole dispersion system should be kept the same along the entire path of the dust charge, to eliminate the amount of dust left in the dispersion system during the discharge process. Since the maximum available inside diameter of solenoid valve is 14 mm, the inside diameter of the dust vessel and of the dispersion pipe were determined by this size. To obtain a uniform distribution of dust along the test tube, a large number of small diameter dispersion holes along the dispersion pipe is required. The minimum size of the hole diameter is considered to be 1mm for reasons of convenience but also to prevent them from being plugged by the residual of the dust combustion. Experimental results demonstrated that in order to permit more even dust distribution along the tube, the diameter of the dispersion holes in the middle has to enlarge to 2mm compared to 1mm at the ends (detailed

results are shown in Appendix C, Fig. C-1).

The volume of the dust chamber is determined by the necessary room (10cm^3) for storage of the maximum amount of dust (0.04kg) before dispersion, which corresponds to the dust concentration of 1.5kg/m^3 . The inside diameter of the dust chamber should also take the same size in diameter as the solenoid valve and the dispersion pipe.

The selection of the volume of air reservoir (230cm^3) has to satisfy two requirements. First it has to store the initial energy in the reservoir in order to disperse the entire amount of dust. This energy is proportional to the product of overpressure and volume of the air reservoir. The second is to keep the small ratio of the volume of reservoir to the volume of test tube for reducing the increase of the initial pressure in the test tube after dispersion.

4.2 Examination of Suspension of Dust Particles during Dispersion Process

There is an important difference between a gas and dust mixture. The concentration of a gas-air mixture is constant in time while that of a dust-air mixture is variable due to the variable suspension of dust particles. Even if a uniform initial distribution of dust concentration has been acquired by a proper dispersion system, it is deformed during the period between dispersion and ignition by the effect of sedimentation and agglomeration of the dust particles. It may also be deformed after ignition, during the combustion process, by the flow field in front of the flame induced by the flame propagation. Therefore, it is very important and necessary to examine the suspension of the dust particles during dispersion process in a designed dispersion system via preliminary experimental investigations.

Experiments show that for a 0.23 liter air reservoir, 1MPa initial pressure inside is required to carry 10-20 grams of cornstarch dust from the dust vessel through a 0.93 meter long pipe to disperse it into the test tube. Figure 3 presents the measurement of light transmission in which the dust concentration in the test tube decreases to a level less than 20% of the initial concentration at the ignition delay time of 50ms. The average flow velocity in the test tube estimated from light transmission measurements is around 10 m/s, as shown in Fig.4. These results show that while the dust particles are dispersed into the test tube, their momentum is too high to maintain a good suspension of dust particles. Very high momentum leads to most of the dust particles passing through the cross section of the test tube with very high velocities until impinging on the opposite tube wall. Some stick to the

tube wall, others fall down along the wall and only a very few particles remain in suspension. To overcome these difficulties a bar was located in front of the orifices to decrease the momentum of the dust jets. After the interaction with the bar, the jets are broken down and a flow in a cross-section along the wall of the test tube in two opposite directions is created. Systematic investigations were carried out to determine the optimum action of the bar. Experiments included the shape and the size of the bar as well as the distance between the bar and the dispersion pipe. Figure 4 shows the variations of the mean flow velocities in the direction of the jet axis as a function of distance in the direction of the jet axis. These velocities are the result of the interaction of jets with the bar and are estimated on the basis of the experimental data of light transmission measurements. The detailed description of the light transmission measurement technique is contained in Chapter 5, section 5.2. Experimental results show that a 9.5mm diameter circular cross-section bar located at 4 mm distance from the orifices creates the best conditions from the point of view of dust suspension. For this optimum location of the bar, the mean flow velocity between the bar and the tube wall is below 2m/s. Experiments shown in Fig.5 prove that under these conditions dust particles stay in suspension about 500ms or even a little longer. However, the momentum of dust jets remains slightly over the necessary level for suspension since around 10-20% of all the dust particles are stuck to the tube wall after dispersion.

In the present study, the sedimentation effect on the suspension of dust particles is evaluated on the basis of the Green and O'Donnell report [63]. The sedimentation velocity of 15 μ m diameter cornstarch dust particles is 2cm/s. With this velocity, the settling of dust particles can be ignored, since flame propagation velocities are the order of meters per second under the conditions in which when the ignition delay time being 300ms the entire combustion time is 500ms. The agglomeration effect cannot be tested by direct measurement. A rough estimation of this effect, which is obtained from the light transmission measurements, shows that agglomeration may not increase the size of dust particles significantly since the agglomerates still remain suspended within 500ms after dispersion.

4.3 Determination of Dispersion-Induced Turbulence Decay Features in the Closed Tube

A certain degree of turbulence must exist in any dispersion system for dust dispersion, mixing and suspension to occur. From this point of view, every pressure dispersion system essentially is a turbulence generator.

There is lack of data on the influence of dust on the turbulence parameters in two phase media. It is assumed in the present study that the influence of dust on the structure of dispersion-induced turbulence is of secondary importance. The validity of this assumption has been demonstrated by the experimental results and described in Chapter 3, section 3.2.3.

The transient flow field produced by the dispersion pipe, shown in Fig.6, corresponding to 0.5MPa of initial pressure drop from the pipe, through the orifices into test tube, can be characterized by the following two consecutive processes. Detailed description and analysis of this transient flow field produced by dispersion pipe are demonstrated in Appendix B. Detailed descriptions of the measurements of the turbulence parameters are presented in Chapter 5, section 5.3.8. At the start of the dispersion process there is the generation of supersonic jet flows by the orifices in the dispersion pipe. The jets interact with the bar and breaks down to result in a mean flow with superimposed rms turbulent velocity along the walls of the tube in two opposite directions. Starting from 200ms after the solenoid valve activation, the jet flows generated by the orifices become subsonic. From this instant, the mean flow and rms turbulent velocity decrease very quickly and decay. Interaction of either supersonic or subsonic jets with the bar results in a nonsymmetrical flow field. A steady choked flow of pure air from the dispersion pipe, corresponding to 0.25MPa of pressure drop in the orifices was used to simulate the basic features of the flow field in the test tube. The measurements of the mean velocity and rms turbulent velocity in this steady flow correspond to those values characteristic of a delay time after solenoid valve activation of about 85ms in the transient process. The distribution of the measured mean velocity and rms turbulence velocity across the test tube are shown in Fig.7 and Fig.8. The integral length scales were measured at the points A, B, C (see Fig. 8) being 4.03, 3.96 and 8.43 mm, respectively. The measurements in these three points show some irregularity in the distribution of the turbulence parameters across the tube section. However, observation of the regular flame shape in Schlieren pictures in combustion experiments with gas flames, shown in Fig.9, indicated that this distribution of the turbulence parameters is satisfactory.

The decay feature of the dispersion-induced turbulence in the 0.93 meter test tube was examined by two different methods. While one concerns the decay feature of mean flow velocity versus time measured during the transient process of air flow without dust particles; the other involves combustion data concerning the maximum rate of pressure rise (or K_{st} factor) versus the ignition delay time in 9.5% methane-air mixture. In the first series of measurements, assuming the ratio of rms turbulent velocity to the mean flow velocity, which

has been determined from the measurement in the steady flow, as constant during the entire transient process, the decay feature of rms turbulent velocity in the transient process can be estimated by the measured data of the decay feature of the mean flow velocity. Figure 5 shows the decay feature of mean velocity in the duration of 1000ms after the solenoid valve activation, measured at point A. In the second series of measurements, the maximum rate of pressure rise (or K_{st} factor) in a 9.5% methane-air mixture versus the ignition delay time can indicate the decay feature of the intensity of dispersion-induced turbulence as a function of time. Figure 10(a) shows explosion data of the maximum rate of pressure rise in 9.5% methane-air mixture versus the ignition delay time. Experimental results of Fig.5 and Fig.10(a) demonstrated that the tendency of the decay feature in dispersion-induced turbulence indicated by above two methods are similar, in which the turbulence decay occurs mainly between 35ms and 300ms after the instant of activation of the solenoid valve.

The influence of ignition delay time on the maximum rate of pressure rise and the maximum pressure rise in the 0.93 meter test tube for cornstarch dust-air mixtures in a wide range of concentrations with the same dispersion conditions as in the 9.5% methane-air mixture, is shown in Fig.11 and 12, respectively. The maximum rate of pressure rise approaches the peak value when the ignition delay time is 50ms. It is equal to about 130% of its reference value when the ignition delay time is 300ms. The reference value corresponds to the ignition delay time of 700ms, which is considered to be close to quiescent conditions, (see Fig.11). Because the data of maximum pressure rise reflects the quantity of dust particles participating in the combustion, the influence of turbulence decay feature on the dust suspension may be inferred from Fig.12. Measurements show that the maximum pressure rise approaches its peak values in the range of the ignition delay time from 50 to 100ms, decreasing slowly thereafter. With the ignition delay time being 300ms, the peak pressure is at the level of 80% as compared to its maximum value. It can be inferred that 80% of dust particles are still in suspension and the settling dust particles can be ignored.

4.4 Distribution of Initial Dust Concentration along a Vertical Tube (0.93 meter long)

The variation of initial distribution of dust concentration along the tube axis during the combustion process is almost unknown, since all measurements of dust concentration [131,132] are only able to examine their variation before the combustion starts. Furthermore, it is also not known if it is necessary or enough to maintain a uniform initial dust concentration along the axis of the test tube. Nevertheless, in the present study, it is

attempted to examine the influence of the initial axial distribution of dust concentration on the quality of the combustion process. Four different types of initial axial distributions of dust concentration are tested, and the estimation of that influence is based on the comparison of explosion characteristics such as the maximum rate of pressure rise and the maximum overpressure. The initial distribution of dust along the tube axis is dominated by the location of the dispersion orifices of the corresponding sizes along the dispersion pipe.

The initial distribution of dust concentration along the test tube in four various dispersion systems is shown in Fig. 10(b). The explosion characteristics of the dispersion systems under investigation are compared in Fig. 10(a) in the form of the maximum rate of pressure rise as a function of the ignition delay time for a 9.5% methane-air mixture. Experimental data show that the intensity of the dispersion-induced turbulence, which is defined as rms turbulent velocity and is taken to be proportional to the maximum rate of pressure rise in the explosion process, is strongly dependent on the total cross-sectional area of the orifices and only slightly dependent on the distribution of the dust concentration along the test tube. The explosion characteristics for cornstarch dust-air mixtures determined by means of the same dispersion systems as above, shown in the form of the maximum rate of pressure rise and the maximum pressure rise as a function of the ignition delay time, are presented in Fig. 13. Since the combustion rates are influenced not only by the nature of the dispersion system but also by the different quantity of the dust participating in the combustion, as shown in Table 1, the parameter $(dP/dt)_{\max}/\Delta P_{\max}$ is used to make the comparison among the different dispersion systems more meaningful. The parameter $(dP/dt)_{\max}/\Delta P_{\max}$ is proportional to the burning rate for the unit quantity of dust participating in the combustion. Figure 14 shows the variation of the parameter $(dP/dt)_{\max}/\Delta P_{\max}$ with the ignition delay time. Experiments show that the dispersion system with a uniform distribution of dust along the tube keeps the highest value of the parameter $(dP/dt)_{\max}/\Delta P_{\max}$ almost over the whole range of the ignition delay time, except for the value below 50 ms. For a very short ignition delay time, dispersion systems with a nonuniform distribution of dust seems to get a faster combustion rate and higher pressure rise than those with a uniform distribution of dust. This can be explained by a high local dust concentration near the ignitor.

The pressure history of combustion of a dust dispersed by different dispersion systems is shown in Fig. 15. The pressure curve which represents combustion in a mixture

with uniform axial distribution of dust is regular and smooth. However, global explosion characteristics such as the maximum pressure rise, the maximum rate of pressure rise and the entire combustion time are not influenced strongly by the uniformity of the initial dust concentration along the tube length.

4.5 Determination of Actual Dust Concentration in the Present Experiments

Dust concentration is an important quantity to serve as a basis for correlating the explosion characteristics and the flame characteristics, within a variety of experimental set-ups. In a closed vessel the amount of dust, introduced into the dispersion system before combustion, is fixed. The nominal dust concentration is traditionally defined by this fixed amount of dust divided by the volume of apparatus. From a theoretical point of view, the explosion characteristics (the maximum overpressure, the maximum rate of pressure rise) in a closed vessel should be an intrinsic property of the nominal dust concentration. However, the actual concentration of dust participating in combustion is different than the nominal one. This difference depends on the characteristics of the combustion chamber and the dispersion system. Therefore, the same nominal dust concentration can correspond to several different actual dust concentrations in various apparatuses and can result in different explosion characteristics from those apparatuses. This phenomena is responsible for the dependence of the dust explosion characteristics on the apparatus. If the nominal dust concentration is used to correlate dust explosion characteristics, a large scatter of data should occur within a variety of apparatus. The above discussion indicates the importance of determination of actual dust concentration in experiments. Two main errors in the determination of the actual dust concentration in the present dispersion system are caused by the amount of dust left in the dispersion system and by the amount that adhered to the tube wall. Both factors can be determined by direct measurements. The dispersed amount of dust is the difference between the entire amount of dust located into the dust reservoir and that left in the dispersion system after dispersion. The amount of dust that adhered to the tube wall can be estimated by the difference between the amount of dust dispersed and suspended. The suspended amount of dust is determined as the amount of dust collected from the bottom flange of the tube after dispersion. For a fixed pressure in the air reservoir at 1 MPa and a fixed amount of dust in the dust vessel ranging from 10-20 grams, the amount of dust left is between 1 gram and 2 grams, depending on the characteristics of the dispersion system (dispersion orifice diameters, number of orifices and their distribution). The amount of dust stuck to the wall strongly depends on the ratio of the surface to the volume of the tube. This ratio in the

present tube with $L/D = 5$ and $D = 0.19$ meter is 1.65 times larger than in a spherical vessel of the same volume. The amount of measured dust stuck to the wall in the present tube is between 2 grams to 3 grams, depending on the properties of the dispersion system. The detailed results of measurements are shown in Table 3.

Observations show that the amount of dust adhering to the wall after combustion strongly depends on the ignition delay time. It was found that for an ignition delay time less than 100ms, very few dust particles stick to the wall. The phenomenon of an increased quantity of dust deposit on the wall with an increase of ignition delay time is interrelated with the contact of the particles with the wall. The longer the time in which the dust particles have a chance to contact with the wall, the bigger the dust deposit. The time of arrival of dust particles from the dispersion system to the tube wall, determined by the light transmission measurements, is 50-100 ms (see Fig. 6). From the point of view of the amount of dust deposited on the wall, this arrival time becomes a critical ignition delay time. Figure 16 shows an experimentally determined relation of the deposit of dust on the tube wall and on the bottom flange versus the ignition delay time. In these experiments the quantity of dust stuck to the wall and to the bottom flange was carefully collected and weighed after every test.

The decreased amount of dust participating in combustion caused by sticking to the wall has a strong effect on the pressure of explosion. The influence of ignition delay time on the maximum pressure rise for different nominal dust concentrations, shown in Fig. 17, indicates that in the broad range of dust concentrations the maximum overpressure approaches its peak value for an ignition delay time in the range from 50-100 ms, decreasing thereafter. This decrease is steep for the ignition delay time in the range from 100-200 ms. After an analysis of Figs. 11, 14 and 15, one can conclude that for the ignition delay time less than 100ms, most of the dispersed dust participates in combustion. For the ignition delay time more than 300ms, when about 20% of the dispersed dust is stuck to the wall, then 80% of the dispersed dust goes into combustion.

In brief, a correction of nominal dust concentration in the present closed tube is demonstrated in Table 3, which includes the actual dust concentration and the fluctuation of the actual dust concentration caused by the difference of ignition delay time.

A comparison of the present results obtained for the K_{st} factor and the maximum pressure rise in cornstarch dust-air mixtures as a function of cornstarch concentration with

the previous results of other researchers is shown in Fig. 18(a) and (b).

CHAPTER 5

EXPERIMENTAL DETAILS

5.1 Apparatus

A test tube with 0.19 meter in diameter, 0.93 and 1.86 meter long, and with two ends closed is employed for investigating dust flame propagation in the present study. A 1.86 meter test tube is cascaded in two segments. Each segment, as is shown in Fig.19, contains its own dust dispersion system and has the same construction as the other. Figure 20 shows the structure of one segment. It consists of a test tube that is 0.19 meter in diameter and 0.93 meter long, and a dispersion pipe.

The dispersion system consists of a dispersion pipe, a dust chamber, a solenoid valve and an air reservoir. The dispersion pipe is connected with a small dust chamber (14mm in diameter, 10cm³ volume) then, via a solenoid valve (14mm inside diameter), with a high pressure air reservoir of 230cm³ capacity. The air reservoir is pressurized to an overpressure ranging from 1 to 2.5MPa. When the solenoid valve is activated, the dust is conveyed along with the air flow and the dust-air mixture is discharged into the test tube through the linear array of holes. To suppress the directed momentum of the dispersion jets, a circular rod 9.5mm in diameter is placed 4mm away from the holes running parallel along the length of the dispersion pipe thereby preventing the dust-air jets from impacting on the opposite wall. Detailed investigations of the size and shape of rod, and the distance between the rod and the dispersion pipe have been demonstrated in Chapter 4, Section 4.2. It was found that the dispersion was more effective when a rod was used, resulting in a more uniform distribution of dust inside the test tube. It was also found experimentally that the dispersion is improved when the dust container is placed at the top of the test section, so that the dust-air mixture would flow down along the dispersion pipe to be discharged into the test tube.

5.2 Measurement Techniques

5.2.1 The estimation of the initial distribution of dust concentration

The initial distribution of dust concentration along the test tube is determined by a calibration of the dispersion system. For this calibration, the whole length of the dispersion pipe is divided into six equal sections. The dust from every section is then dispersed 20 times in separate containers and its quantity is measured. For a given distribution of the orifices, the measured amount of dust is taken from the average value. Therefore, the accuracy of dust weight measured by a balance is satisfactory. Three independent calibrations revealed the scatter of the distribution of dust concentration along the test tube to be within the range of 5%.

The initial distribution of dust concentration across the tube is roughly examined by observing the distribution of the thickness of the dust layer on the bottom flange of the tube after dispersion.

5.2.2 Light transmission measurement

A light transmission measurement, shown in Fig. 21(a), operates on the principle of light attenuation. When a light beam crosses a homogeneously dispersed cloud of uniform dust particles, the beam intensity is attenuated. The attenuation of light is defined by Bouguer laws :

$$T = \exp \left(- 3qC_d l_m / 2l \cdot \rho_d d_p \right) , \quad (5.1)$$

where T is the fraction of light transmitted through a path length l_m , q is a dimensionless extinction coefficient, C_d is the mass concentration of the dust cloud, ρ_d is the density of an individual particle, and d_p is the mean particle diameter. In Eq.(5.1) since the combination of $\rho_d d_p / q$ is a constant depending only on the dust, the concentration of a given dust can be determined by the direct measurement of the light attenuation (T), as shown in Fig. 21(a).

In the present study, the qualitative evaluation of the suspension is monitored using light transmission measurements, through the 0.19 meter inside diameter of the test tube at two heights, as shown in Fig.6.

Assuming the slip velocity between particles and air is negligible, the mean flow velocities of the jets, as a function of the distance between the exit of the jets and the location of the measurement, can be estimated by the ratio of the distance to the time arrival of dust

particles. This estimation is acquired using light transmission measurements through the 0.33 meter inside wall length of a dispersion box at two-heights at various positions. The setup is shown in Fig. 21(b). In this measurement, the distance between the location of the light beam to the orifices in the dispersion pipe is known, and the time of arrival of dust particles can be determined by the starting point in the curve of light transmission (T) versus time (t) (see Fig. 6).

5.2.3 Pressure measurement

A piezoelectric transducer PCB 113A24 is used to determine the pressure history inside the vessel. The sensitivity of this transducer is approximately 207mv/MPa. The maximum rate of pressure rise is calculated from the slope of the tangent to the pressure-time curve through its inflection point. The transducer is installed flush to the wall surface. Since the propagation velocity of the flame front is only 0.025 times the speed of sound, the pressure in every location of the test tube is practically the same at any moment during the combustion process.

5.2.4 Flame arrival measurement

The flame arrival is detected at the axis of the test tube by ionization probes, biased at a 400 VDC potential. Eight ionization probes are located on the axis of the test tube. The locations of ionization probe along the tube length are demonstrated in Fig. 22(a) and (b). The ionization probe signals are recorded on two oscilloscopes.

5.2.5 Measurements of surface temperature rise on the tube wall

The outset of heat transfer into the wall along the length of the test tube is estimated from the measurements of surface temperature rise on the tube wall by a Pt-foil gauge, see Fig. 23(a). The parameters of Pt-foil gauge used are as following:

- i) 1mmx5mm of the size,
- ii) 0.1 μ m of the thickness,
- iii) 40 $\pm$ 10 Ω of the resistance,
- iv) 400 μ s of the time response, and
- v) (2.5-2.9) $\times 10^{-3}$ / $^{\circ}$ C of the sensitivity of minimum heat flux ((R-R₀)/R₀(T-T₀)).

The signals of surface temperature rise on the tube wall are recorded on an oscilloscope, see Fig. 23(b).

5.2.6 Visualizations of flame propagation

Visualizations of the flame propagation, from the closed to the open end of a one meter long, 0.18x0.18 meter square plexiglas tube, are recorded on both Schlieren picture and colour film by a fast speed camera at 1000 frames per second. The same dispersion system as used in the two ends closed tube is fixed in this square plexiglas tube.

5.2.7 Flame temperature measurement

Flame temperatures are measured by unshielded thermocouples which are made of 25 μ m diameter Pt -Pt 10% Rh wire, with a relatively fast time-response. The time constant of a junction in thermocouples can be determined on the basis of [134] from equation:

$$1/t = 2\alpha / C_1 \rho_m r, \quad (5.2)$$

where α is the heat-transfer coefficient, C_1 is the specific heat of metal, ρ_m is the density of metal, and r is the radius of the sensing element.

5.2.8 Turbulence measurements

Steady flow from a dispersion system without dispersion of dust is employed for the measurement of the turbulence parameters (the rms turbulent velocity and the integral length scale). This steady flow is produced by a constant pressure of 0.25MPa in the dispersion pipe, and is discharged continuously into the test tube with two open ends.

The unsteady discharge of air from the dispersion system without dispersion of dust is employed for the measurement of the decay feature of the mean flow. This unsteady flow is produced by an initial pressure of 1MPa in an air reservoir, and is discharged instantaneously into a test tube with two open ends. The decay feature of the rms turbulence velocity can be estimated on the basis of the relative intensity of turbulence (the ratio of the rms turbulence velocity to the velocity of the mean flow), the average value of which is about 10% which has been obtained by measurements in several cases of steady state conditions.

The turbulence measurement is accomplished by means of DISA 55 P11 hot wire sensors, a DISA 55M01 constant temperature anemometer with a DISA 55M10 standard bridge, a DISA 55D10 linearizer, DISA 55D26 filters, a DISA 55D70 correlator, a DISA 52B01 sweep drive unit and a x-y recorder. The DISA 55P11 hot wire sensor is a fine Pt-plated tungsten wire which is 5 μm in diameter and 3 mm long. The DISA 55M01 constant temperature anemometer consists of a DISA 55M10 standard bridge and a servo amplifier. The DISA 55M system measures flow fluctuations in gaseous media up to approximately 12 MHz. The upper frequency limit of the sensor used in anemometry is approximately 500 Hz. A very special feature of the DISA 55D10 linearizer is that logarithmic amplifiers are used in order to provide optimum linearization throughout the range. The accuracy of linearization is in the order of (0.5 - 3)%, which depends on the conditions of measurements. The frequency range is 0-100 kHz at an output voltage of 5 volts. The DISA 55D70 Analog Correlator is a true analog computer which is capable of performing all the calculations required for a correlation analysis. From the terminal "output correlation function", the output voltage is available which is proportional to the correlation coefficient $R_{AB}(x)$, x is the distance between two hot wire sensors A and B. From the curve of $R_{AB}(x)$, the integral length scale of turbulence is obtained. The DISA 55D26 filter serves the purpose of converting an anemometer output signal so that the parameters become desirable. The filter circuit comprises one lowpass filter and one highpass filter both of which are switchable in steps of 1/3 octave. The lowpass filter permits altering the upper frequency limit between 10 Hz and 1 MHz, and the lower frequency limit between 0.1 Hz and 100 kHz by means of the highpass filter. The DISA 52B01 Sweep Drive Unit is a generator which produces a (stepwise) increasing or decreasing DC voltage. This DC voltage is used for a DISA TCA System to control the 55 D75 Time Delay Unit, which can be used for the measurement of the correlation function.

The DISA thermoanemometer set for measuring the mean flow velocity and the rms turbulent velocity is shown in Fig. 24. The relationship between signal output of hot wire sensors and velocity measured was calibrated in a wind tunnel with atmospheric air and velocity range from 0-10 m/s. The DISA thermoanemometer set for measuring the integral scale of turbulence is shown in Fig. 25(a). The correlation curves measured in one selected cross-section at point A, B and C are shown in Figs. 25(b), (c) and (d), respectively:

5.3 Preparation of the Combustible Mixtures

Methane-air mixtures from lean (5.5% methane) to stoichiometric (9.5% methane) composition are used for comparison with dust-air mixtures. The properties of flame propagation in a methane-air mixture are well known [102, 131].

Cornstarch, used as dust in dust-air mixture, is a natural polymer of dextrose, with the chemical formula ($C_6H_{10}O_5$). Peraldi [135] has measured its heat of combustion and heat of formation. Lewis [136] has investigated the explosion characteristics of 28 kinds of green dust and has shown that cornstarch has a very high volatile content (above 90%). Commercially available starch usually contains about 10% moisture by weight. To eliminate the moisture and thus help produce a uniform dispersion, the cornstarch was placed in an oven at 70°C for about 18 hours prior to the experiment. Also a fluidizing agent (cab-o-sil, which is a fumed silica used in a wide range of products from low viscosity coatings to high consistence elastomers) was mixed with the cornstarch in the proportion of 0.5% of the fluidizing agent per unit mass of mixture, to prevent agglomeration. A particle size analysis obtained via direct imaging with an optical image analyzer showed the average size of the particles to be 14.7 μm with a standard deviation of 5.1 μm . A scanning electron micrograph shown in Fig. 26 indicates the particles to be remarkably spheroidal in shape.

The following table summarizes the properties of cornstarch that are relevant to its combustion characteristics:

Chemical formula :	$(C_6H_{10}O_5)_n$
Mole weight of monomer :	162
Density :	$1.5 \times 10^3 \text{ kg/m}^3$
Stoichiometric concentration (theoretical) :	253.7 kg/m^3
Heat of combustion :	$2.64 \times 10^3 \text{ kJ/mole}$
Heat of formation :	$0.928 \times 10^3 \text{ kJ/mole}$
Volatile content :	~ 90% or above

5.4 Procedure

Prior to dispersion, a measured quantity of dust is loaded into the dust vessel. The air reservoir is pressurized to 1MPa overpressure. When the solenoid valve is opened, the dust is conveyed from the cavity through the dispersion pipe. The impulsive jets emerging from the dispersion holes blow the dust against the rod and disperse it throughout the test tube. The delay time between dispersion and ignition is controlled by means of an electronic or mechanical timer. Both are used, but in different situations. Ignition of the dust-air mixture at the centre of the bottom end of the tube is achieved by a black powder ignitor. Typically, a 0.6 grams charge of black powder, contained inside a paper capsule, is "blow up" via a thin fuse wire connected directly to a 110 VAC line, producing approximately 1.7 kJ of ignition energy. A black powder ignitor is used because of its long combustion duration (25ms).

CHAPTER 6

EXPERIMENTAL RESULTS AND DISCUSSIONS

6.1 Laminar Flame Propagation in Premixed Gas-Air and Dust-Air Mixture

6.1.1 Acquisition of a quasi-laminar flame in the closed tube

A physical picture of a flame propagating in quiescent methane-air mixtures has been discussed in Appendix B. It demonstrates that a pure laminar flame propagation in a closed tube is unattainable. The flame is unstable due to the critical value of the Reynolds number and cellular structure on its surface. However, it has been found that there is a very reliable experimental correlation between the laminar burning velocity (which is determined in [102] as a mixture property) and the velocity of flame propagating in the tube, in an initially quiescent methane-air mixture (Fig.27(a)). Both velocities are linear functions of methane concentration. A similar correlation has been found between the laminar burning velocity and the velocity of a flame propagating in the same tube, in a turbulent mixture (Fig. 27(b)). Thus, it has been demonstrated that it is possible to estimate the laminar burning velocity on the basis of the velocity of a flame propagating under condition other than laminar. These results are very important from the point of view of the investigation of dust flame characteristics.

A laminar premixed dust flame requires a uniform dust-air mixture. Uniform mixture is created by a pressurized dispersion system with a high level of initial turbulence in the present study. During investigation of laminar flame characteristics, turbulence is detrimental. Experiments show that dispersion-induced turbulence decays very fast approaching asymptotically laminar conditions (see Figs.5, 10(a), 11). However, turbulence decay is followed by sedimentation and agglomeration of dust particles, which decrease the local dust concentration. To overcome the influence of dust settling, the dust and gas explosion characteristics have to be compared at some level of decaying turbulence. Experiments in Figs. 11, 12 showed that a 300ms ignition delay time is optimal, from the point of view of a low turbulence level at the instant of ignition and an acceptable amount of dust remaining in suspension (about 80% of its maximum value). For a 300ms ignition delay time, the time of combustion is about 1000ms. Table 4 shows that 300ms after the solenoid valve activation, the rms turbulence velocity is at a level of 20cm/s and continually

decays. Since the integral scale of turbulence ($\approx 4\text{mm}$) is of the same order of magnitude as the flame thickness (the flame thickness in a cornstarch dust-air mixture and in a 5.5% methane-air mixture are estimated to be approximately 3mm), turbulence cannot wrinkle the flame surface but intensifies the heat and mass transfer within the flame front. The decaying dispersion-induced turbulence increases slightly only the burning velocity 300ms after the solenoid valve activation. Hence in the present study, the flame starting from this instant is named quasi-laminar, for convenience.

6.1.2 Examination of dust flame behavior in the closed tube

The behavior of flame propagating in dust-air mixtures is examined by the measurement of pressure as a function of time and of flame front location along the test tube, and the results are compared with those in the gas-air mixture. In order to be sure that this comparison is meaningful, it is necessary to investigate the nature of the flame front in the dust-air mixture.

It is possible to model the flame behavior by visualization of the instant of ignition and the initial time development in a substitute tube with one end open, because in a closed tube the pressure rise in the first stage of flame propagation is about 10% of the pressure rise in the entire combustion process. One can neglect this small pressure rise and consider the flame propagating in both tubes as not being influenced by pressure. A tube made from plexiglass was used for visualization. Flame propagation from the closed to the open end of the tube was recorded on colour film by means of a high speed camera. The film speed was 1000 frames per second. The flame propagating in cornstarch dust-air mixtures with two concentrations of 400 and 560 g/m^3 and three different ignition delay times of 100, 300, and 430 ms was investigated. It was found that the flame front moved forward, that its surface was continuous although its shape was sometimes irregular. Figure 28 shows some successive tracings of the flame front taken from a film. While the flame front is not as sharply delineated in comparison to gas flame propagation, careful examination of the film makes it possible to determine that the particles start to burn virtually at the level of the flame front and they continue burning far behind it. This observation suggests that the burning time of the solid phase of particles is much longer than the burning time of the gas phase (consisting of volatile matter).

The temperature measurements made it possible to determine the thermal structure of the flame front. Figure 29 demonstrates typical temperature profiles of flame fronts in

methane-air and dust-air mixtures. The measurements exhibit smooth and continuous temperature profiles on the flame front typical also for a dust laminar-like flame. None of the temperature records showed the flame as a zone disrupted into diversified and separately reacting regions.

The measurements of surface temperature rise of the wall of the test tube in Figs. 30 (a) and (b) show that in a closed tube the physical picture of two stages of flame propagation does exist in a quasi-laminar dust-air mixture, which is similar to that in a quasi-laminar gas-air mixture, see Appendix B. A cornstarch-dust flame propagating in a closed tube also can be considered to remain uninfluenced by heat losses at the first stage of propagation.

6.1.3 Experimental results of flame propagation in the closed tube

To determine the basic characteristics of gas and dust flames in the same apparatus under the comparable conditions it was necessary to use the same experimental procedure typical for dust, in experiments with gas and dust. The only difference between them was that the gas-air mixture was premixed in advance in the test tube and in the air reservoir. Thus, there was no premixing in the chamber before dispersion as in the case of the heterogeneous cornstarch dust-air mixture.

Figures 31 (a), (b) and (c) reflect the maximum rate of pressure rise in the first stage, the maximum pressure rise and the entire time of combustion as a function of the ignition delay time for gas and dust mixtures in a 0.93 meter test tube. Within the range of low turbulence, corresponding to the ignition delay time of more than 300ms, the maximum pressure rise and the maximum rate of pressure rise in the dust flame are the same for the methane-air mixture with a concentration of methane less than 6.2%. The entire time of combustion is longer than for methane-air mixture with a concentration of 6.2% methane, and corresponding to the concentration of 5.5% methane. The same conclusions can be drawn from Figs. 32(a), (b) and (c), presenting analogous curves determined in a 1.86 meter test tube. Although the maximum pressure rise and the maximum rate of pressure rise are slightly lower in a 1.86 meter test tube and the time of combustion longer than that in a 0.93 meter test tube, the character of the curve and the relation between the gas and dust parameters are similar.

The maximum rate of pressure rise in a cornstarch dust-air mixture in comparison to a 7.3% methane-air mixture is the same in present tube as in Bond's 0.9 meter inside diameter

spherical vessel [20] ; the ratio for both being 0.3. This comparison indicates that the similarity of cornstarch dust-air flame to lean methane-air flame is independent of the apparatus.

It is worth while to examine in detail the influence of the concentration of fuel in the mixture on flame behavior. Figure 33 shows the pressure rise and the location of the flame front along the tube as a function of time in 0.93 meter and 1.86 meter test tubes for 5.5% and 6.2% methane-air mixtures for the ignition delay time of 319ms. Two different modes of combustion were observed in the 1.86 meter test tube for this particular ignition delay time. The shorter of the two times of combustion is probably as a result of some instability phenomena accompanying the combustion process.

Figure 34 presents the pressure rise and the location of the flame front along the tube as a function of time for dust flames of different concentration. The analysis of the figure shows that the propagation velocity does not significantly depend on the mixture concentration. Although the relatively rich mixture concentration changes from 260g/m^3 to 710g/m^3 the slope of $L=f(t)$ curves is nearly the same. The maximum pressure rise in the test tube is influenced mainly by the processes in the second stage of combustion. Similar conclusions related to the propagation velocity can be drawn from Fig. 35 illustrating the influence of dust concentration on the combustion process in the 1.86 meter test tube. The propagation velocities in this tube are higher than that in the 0.93 meter test tube. As a result, the time of combustion is only slightly longer. Figure 36 shows that the length of the first stage of flame propagation in the 1.86 meter test tube is longer for dust than for gas. Figures 36 and 37 compare the combustion in gas and dust mixtures in the 0.93 meter and 1.86 meter test tubes. The relation between the propagation velocity, the pressure rise and the time of combustion can be analyzed from these figures for gas and dust flames.

In the light of the data so far presented, it is worthwhile to analyze in some detail the experimental results related to the flame propagation velocity in gas and dust mixtures. It is known that the propagation velocity in the gas mixture in the first stage of combustion is an intrinsic function of gas concentration. Because the mixture is ignited at the closed end of the tube, the propagation velocity is determined by the burning velocity and the expansion of the hot combustion gases, which are, for a laminar flame, functions of mixture concentration. In experiments, in which the flame is influenced by the turbulence from the dispersion system, the laminar burning velocity is replaced by the turbulent burning velocity, and the propagation velocity varies with varying ignition delay time (Fig.38). The propagation

velocities determined in gas experiments for various ignition delay times are expressed by regular and smooth curves which depend on the mixture concentration and the ignition delay time. Figure 39 demonstrates the propagation velocities determined in experiments with dust flames. They are lower than those of lean limit methane-air flame, shown in Fig. 40, 41. Their dependence on mixture composition and ignition delay time are very weak. Measured values of ignition delay time and propagation velocity in dust mixtures are different from experiment to experiment resulting in large scatter in the data. Figures 22(a) and 40 present experimentally determined propagation velocities as a function of ignition delay time for gas and dust flames in the first and the second stages of combustion of the 0.93 meter test tube. Figures 22(b) and 41 show similar data determined for the 1.86 meter test tube. It is evident from these figures that the mean propagation velocity of the dust flame is, for a long ignition delay time of more than 300ms, at a level of the lean limit methane-air mixture. It is significant to examine the mean value of the gradient $\Delta P_{\max}/\Delta t_{\max}$ as a measure of the overall burning in the entire combustion process. The mean value of this gradient is calculated from the experimental data for gas and dust flames within the range of ignition delay time 454-1280 ms in the 0.93 meter and 1.86 meter test tube (Fig. 42). Also in this case the mean values of the rate of pressure rise for dust flames are at the level of the analogous values for a lean limit methane-air flame.

6.1.4 Experimental results of flame propagation in a tube with one open end

It is important to verify whether the similarity existing between dust and gas flames found in the closed tube experiments also exists in the case of free propagation.

The flame behavior in a near limit methane-air mixture was investigated in a standard flammability tube by Jarosinski [137] both for upward and downward propagating flames. The flammability limits were found to be at 5.25% methane for upward propagation and 5.85% methane for downward propagation. The flame behavior at the limit was observed to be different. The upward propagating flame, which is influenced by buoyancy, is convex and its propagation velocity agrees with that calculated on the basis of the Davis and Taylor equation [138]. The downward propagating flame is flat and its propagation velocity is approximately equal to the burning velocity. It was also found that the flammability limit of a pushed flame is the same as that of freely upward propagating flames and that its value is independent of the direction of flame propagation. For tube diameters large than the 5cm standard tube, cellular instability disturbs the steady and axisymmetric propagation that is

observed in a small tube. When pressure waves resulting from instability of the combustion process couple with the acoustic modes of the tube, thus satisfying the Rayleigh criterion [139], pressure oscillations are generated. Strong vibrations of this kind were observed in the present apparatus at the beginning of experiments in which the quenching distance was measured for a freely propagating flame [38]. The velocity of an upward propagating limit flame measured under conditions of damped vibrations was usually higher than the value determined on the basis of the Davis-Taylor equation which is equal to $w = 0.328gD = 45\text{cm/s}$, where g is the acceleration due to gravity and D is the tube diameter.

The measurements carried out in the present work show that the flammability limit is 5.2% methane for upward propagation, the limit propagation velocity being contained within the range of 50-100 cm/s. Experiments also show that 6.0% methane is the lean limit for downward propagation. With a concentration of 5.8%-5.9% methane the flame propagates in only part of the tube length and subsequently dies. It is only at a concentration of 6.0% methane that the flame propagates the entire length of the tube, with a non-uniform propagation velocity. The mean value of the downward propagation velocity is, at the limit, approximately 20cm/s.

The lean flammability limit for cornstarch dust-air mixtures determined under constant pressure conditions is approximately 240g/m^3 based on the real amount of dust in suspension. The upward propagation velocity at the limit concentration was found to be 60-120cm/s. It was also found that there is no flammability limit for a downward propagating flame in cornstarch dust-air mixtures. No flame, in a dust-air mixture in the range of cornstarch concentration from 240g/m^3 to 1000g/m^3 could pass the entire length of the tube. The behavior of the downward propagating flame in the cornstarch dust-air mixture just before extinction was recorded on film, Fig.43.

The above results demonstrate that cornstarch dust-air flames are similar to lean limit methane-air flames under constant pressure conditions. This comparison shows that a flame cannot propagate downward in cornstarch dust-air mixtures because its propagation velocity is too low. The highest value of burning velocity of dust flame is equivalent to that of the methane-air limit flame which is about 15cm/s (adiabatic value).

6.1.5 A physical model of a laminar flame propagating in premixed dust-air mixture

Reliable and reproducible data on the nature of a laminar dust flames are necessary to

verify the physical model of that flame. The experimental data obtained from different burners of various shapes and sizes reveal, over a wide variation in the measured parameters in gas and in dust flames, that the processes controlling flame propagation in these flames are similar. The similarity of the processes controlling laminar gas and dust flames has recently been emphasized by Bradley and Lee [125] and Smoot et al. [71].

In light of present work, laminar cornstarch-dust flames are similar to lean limit methane flame, this similarity being surprisingly complete. All the most important characteristics of a cornstarch-dust flame correspond to those of a methane flame with volume concentration of methane equal to 5.5% -6.0%.

The similarities and differences between a gas flame and a dust flame will now be listed. It has been found that, for comparable gas and dust flames, the numerical values of the maximum rate of pressure rise and the temperature in the first stage are the same (see Figs. 29, 31(a), 40, 41). The value of mean rate of pressure rise, characterizing the burning rate of the entire combustion process, is also the same (see Fig. 42). In recent research [38], the maximum quenching distance of dust flames in cornstarch-air mixture has been measured as exactly equal to that of gas flame in methane-air mixtures with volumetric concentrations of methane equal to 5.5%, (Fig.44). The D_q -curve in Fig. 44 is very flat within the concentration range 500g/m^3 to 1100g/m^3 , thus making it possible to consider the quenching distance to be constant ($D_q=6\text{ mm}$) within this range of dust concentrations. It is known that quenching distance in gas flames is linked directly with the thickness of laminar flames by the relation $\delta_l \approx D_q/2$, where δ_l is flame thickness and D_q is quenching distance. If one applies this relation to dust flames, the flame thickness in a cornstarch dust-air mixture must be of the order of magnitude of 3mm. This value is less than that to be expected because the burning time of the solid phase of particles observed on the film records was at least one order of magnitude longer than the burning time of the gas phase.

The reliable analysis of the structure of the laminar dust flame must be based on the understanding of the behavior of the oxidation of solid char, which occurs in dust combustion. Bradley et al. [140] have studied the behavior of the oxidation of solid char by dispersing a few fine graphite particles, less than $4.3\text{ }\mu\text{m}$ in diameter into the flame of a 6.5% methane-air mixture. They have reported that:

- i) three species (O, OH, H) are dominating over the solid char burning;

- ii) high concentration, fast reaction rate of these species occur only in the early flame zone of the methane-air mixture;
- iii) the maximum values of burning rate and the heat release of solid char are located almost at the same position as the maximum concentrations of the three species (O, OH, H).

Thus, the behavior of oxidation of solid char can be deduced. As the particles move through the early stage of the gaseous reaction zone, the oxidation rate per unit surface area is considerably increased by the super-equilibrium concentration of O, OH and H. The effects of those species are much greater than those of O_2 . These concentrations soon fall to near equilibrium values, with a commensurate decrease in the char burning rate. However, particles of less than $1\mu\text{m}$ in diameter can be entirely oxidized in the gaseous reaction zone by these active species. In that case the two zones merge and the solid carbon burns almost like a gas. If the chemical heat release rate from the carbon is added to that of the gas, then an associated increase in laminar burning velocity might be anticipated. With large particles, $15\mu\text{m}$ mean diameter used in the present study, it can be expected that the carbon heat release rate occurs over a more prolonged period and is unlikely to have much effect on the burning velocity. From the point of view of the ability of a flame to propagate, the burning of the solid phase is probably unimportant. It is probable that flame propagation and flame quenching are entirely controlled by processes occurring in the flame front during the gas phase of combustion. The characteristic flame front thickness, which is controlled by the gas phase of combustion, can be named "effective flame thickness".

A comparison in Fig.44 between the relation $\delta_l = D_q/2$ and the results of [38] shows that the effective thickness of a cornstarch dust-air flame can be considered as a constant ($\delta_l \approx 3\text{mm}$) over a wide range of variation of dust concentration. According to the thermal theory of a laminar flame the burning velocity u_l is expressed by $u_l \sim \alpha/\delta_l$, where α is the thermal diffusivity. It is evident from this relation that the laminar burning velocity should also be constant in the above dust concentration range. This conclusion is in agreement with the observation that the dust concentration does not influence the flame propagation velocity (see Figs. 22(a), 22(b), 40 and 41).

A simplified structure of laminar cornstarch dust flame is proposed in Fig. 45. The flame consists of three sub-regions:

- i) the preheat zone,
- ii) the gaseous phase reaction zone, and
- iii) the solid char burning zone.

The effective thickness of dust flame is determined by the preheat zone and the gaseous phase reaction zone. Heat conduction from the high temperature combustion region raises the particle temperature to start volatilization. The volatilization process is largely completed and gas phase reactions occur with high concentration and fast reaction rates of O, OH and H in the gaseous phase reaction zone. The temperature gradient in that zone is of the same order of magnitude as in a premixed laminar flame. The flame propagation is, in this case, controlled by heat conduction from the hot gas to the particles and by the rate of streamwise molecular diffusion of oxygen and volatiles. The solid char burning zone involves slow burning rate of the solid char with low concentration and slow reaction rates of O, OH and H. This solid char burning zone is much thicker than the gaseous phase reaction zone, and it resembles a hot tail in the dust flame.

The physical model of flame propagating in cornstarch dust-air mixture presented here is characterized by heat conduction and molecular diffusion, which control flame propagation in gaseous mixtures. The suggested mechanism of flame propagation coincides with the recent investigations of Smoot et al. [71]. Furthermore, this physical model can be applied to the combustion of dust-air only over a certain range of particle sizes. The flame in a dust-air mixture with particle diameters below $5\mu\text{m}$ behaves like that in a gas-air mixture. On the other hand, a mixture with particle diameters above a critical size of about $50\mu\text{m}$ for a given dust is nonflammable [141]. Thus, the burning velocity of a dust flame can be influenced by the particle size over certain range of diameters.

The strong similarity between the overall mechanisms of flame propagation in a dust cloud and those in liquid mists observed by Ballal and Lefebvre in their experimental work [73] makes it possible to apply a theoretical analysis of flame propagation in liquid mists to dust-air mixtures, and estimate the influence of the particle diameter on the burning velocity. According to Smoot et al. [71], the burning velocity is controlled, above all, by the rate of streamwise molecular diffusion of oxygen and volatiles. The time for molecular diffusion of the volatiles is proportional to the single particle decay time:

$$t_d = d_p^2 / C_2 \quad (6.1)$$

where d_p is the diameter of a drop or a dust particle and C_2 is the constant burning rate. The

burning velocity in a heterogeneous mixture is given by:

$$u_1 = \delta_1 / t_d \quad (6.2)$$

where δ_1 is the flame thickness. The flame thickness can be expressed as:

$$\delta_1 = \lambda / c_p \rho u_1 \quad (6.3)$$

where λ is the thermal conductivity, c_p is specific heat with constant pressure and ρ is density of unburned mixture. Making use of Eqs. (6.1), (6.2) and (6.3) we find:

$$u_1 = 1 / d_p (C_2 / c_p \rho)^{1/2} \quad (6.4)$$

For a liquid drop the constant C_2 can be found from [73]:

$$C_2 = 8\lambda \ln(1+B) / c_p \rho_l \quad (6.5)$$

where ρ_l is the density of the liquid and B is the mass transfer number. Finally :

$$u_1 = 2^{1/2} \lambda [\ln(1+B) / \rho \rho_l]^{1/2} / d_p c_p \quad (6.6)$$

taking the mean values of λ and c_p over the temperature range.

Eq.(6.6) gives the estimation of the influence of particle size on the characteristics of dust flames.

6.2 Turbulent Flame Propagation in Premixed Gas-Air Mixtures in Closed Tubes

6.2.1 Dispersion-induced turbulent flames

The influence of dispersion-induced turbulence on a gas flame is limited to very short ignition delay times. The highest values of the maximum rate of pressure rise correspond to ignition delay times within the range of choked jet flow from the dispersion pipe which occurs between 35ms and 100ms after the instant of activation of the solenoid valve. For ignition delay time between 100ms and 300ms, the combustion process corresponds to subsonic jet flow from the dispersion pipe, see Appendix C. For ignition delay times longer than 300ms the jet flow from the dispersion pipe practically does not exist and only some influence of residual decaying turbulence on combustion is observed. The influence of dispersion-induced turbulence on flame propagation is a transient process. As the rms turbulent velocity decreases with time its influence on flame propagation is always strongest

at the beginning of the combustion, and decreases with time. After 200ms this tendency is practically independent of the value of ignition delay times. The influence of dispersion-induced turbulence corresponding to different ignition delay times on the propagation velocity with their flame shapes in the 7.3% methane-air mixture is shown in Fig. 9. The flame shapes were taken from Schlieren pictures. These qualitative pictures seem to demonstrate that an acceptable regular turbulence field at ignition delay times ranging from 100 to 700ms is induced by the dispersion system. These figures also show that the dispersion-induced turbulence did not quench the flame in the direction of its axis and that the flame surface develops symmetrically.

The data of the maximum rate of pressure rise in the 0.93 meter test tube correspond to the first stage of combustion, under near adiabatic conditions. Thus, these can be used to estimate the role of dispersion-induced turbulence in activating the burning rate. It is found, on the basis of these data for methane-air mixtures in the range from lean (5.5% methane) to stoichiometric (9.5% methane) composition, that dispersion-induced turbulence can increase the maximum rate of pressure rise by a factor of three.

The maximum pressure rise is another important characteristics of the explosion in a closed vessel. Figures 31(b) and 32(b) illustrate the changes in the maximum pressure rise as a function of ignition delay time for a 0.93 meter and a 1.86 meter test tube. The maximum pressure rise during an explosion is influenced by the heat losses. Shorter time of the entire combustion process, leads to small heat losses and a higher maximum pressure rise. Thus, for a given mixture composition, the maximum pressure rise during an explosion reaches its highest value for the shortest time of combustion (see Figs. 31(c) and 32(c)). Of course, the maximum pressure rise during an explosion is higher for a shorter tube.

6.2.2 Obstacles-induced turbulent flames

The obstacles in the form of concentric rings were located in the middle part of a two-section tube (Fig.46). The length scale of the turbulence induced by obstacles is much greater than that induced by the dispersion system. The scale of turbulence depends on the tube diameter and the geometrical characteristics of the obstacles.

Figures 47-49 illustrate the influence of turbulence induced by the obstacles coupling with the dispersion-induced turbulence as compared with pure dispersion-induced turbulence on flame propagation in lean methane-air mixtures with 5.5% methane and 6.2% methane,

characterized by properties similar to those of cornstarch dust-air mixtures. Under the influence of turbulence due to obstacles coupled with dispersion-induced turbulence, the flame accelerates along 90% of the tube length, while under the influence of pure dispersion-induced turbulence it accelerates only along 30%. The high propagation velocity increases the maximum rate of pressure rise and cuts down the time of combustion. Analysis of pressure curves in Fig.47 indicate that the maximum combustion pressure decreased by the obstacles is 10% lower than that with no obstacles in spite the time of combustion being 3 times as short. The reduced maximum pressure rise indicates that obstacles with developed surfaces increase the heat losses. Similar conclusions can be drawn from Figs 48, 49. Although the time of combustion in the presence of obstacles is 6-7 times as short as that without obstacles, the maximum pressure rise is the same in both cases. A plateau on the pressure curve indicates that the heat release and the heat loss are in equilibrium. On the axis of the time, the plateau corresponds to about 100ms after the flame has passed the entire length of the tube and can be explained only by some volume combustion in the region of obstacles.

The role played by dispersion-induced turbulence in flame propagation under the influence of turbulence induced by obstacles in mixture composition with 5.5% methane and 6.2% methane is pointed out in Figs. 50 and 51. It is evident from these figures that

- i) the shorter the ignition delay time,
- ii) the higher the dispersion-induced turbulence intensity,
- iii) the larger the propagation velocity, and
- iv) the shorter the entire time of combustion,

in the initial part of flame propagation. However, for a given mixture, the propagation velocity in its final stage is near by the same, independent of the ignition delay time.

Figures 52-54 summarize the influence of obstacles-induced turbulence in methane-air mixtures on the following most important explosion characteristics:

- i) the maximum rate of pressure rise,
- ii) the maximum pressure rise of explosion, and
- iii) the propagation velocity of the flame front.

Experimental results of obstacles-induced turbulence coupled with dispersion-induced turbulence show that obstacles-induced turbulence plays a more important role in accelerating the flame front than dispersion-induced turbulence, in the range of parameters investigated.

6.3 Turbulent Flame Propagation in Premixed Dust-Air Mixture in Closed Tubes

6.3.1 Dispersion-induced turbulent flames

From the point of view of the maximum rate of pressure rise, the combustion of cornstarch dust-air mixtures, under the influence of dispersion-induced turbulence, is similar to the combustion of lean limit methane-air mixtures under the same conditions (see Figs. 31(a) and 32(a)). On the other hand, from the point of view of the maximum pressure rise, the combustion of cornstarch dust-air mixtures is similar to intermediate methane-air mixtures between the lean limit and the 7% methane, but only for very short ignition delay times, below 100 ms (see Figs. 31(b) and 32(b)). For ignition delay times longer than 100 ms the maximum pressure rise of explosion is also below that in lean methane-air mixtures with 6.2% methane. A combustion process influenced by the dispersion-induced turbulence is longer than that of the lean limit methane-air mixture under comparable conditions (see Figs. 31(c) and 32(c)). It is striking that the propagation velocity of dust flames is usually smaller than the propagation velocity of the lean limit methane-air flames (see Figs. 22(a,b), 40 and 41). Even for very short ignition delay times (high level of turbulence) the propagation velocities are also small.

Experimental results show that combustion of dust-air mixtures with a short ignition delay time (below 100ms) is very effective, since extremely high values of the maximum explosion pressure rise are obtained and the values of the maximum rate of pressure rise are also high (close to a 6.2% methane-air mixture). Three factors may influence the value of the maximum pressure rise at short delay times (<100 ms). The first is the level of dispersion-induced turbulence. The second factor is the continuous feeding of dust-air mixtures with streams of fresh air from the dispersion system, at the time when the reaction is in process. The third factor is an increased amount of dust in the mixture, since no time for deposit formation, is available. Figure 55(a) illustrates the influence of the intensity of turbulence and the amount of air participating in the combustion on the pressure history. The experiments were carried out under the same conditions as those for dust experiments. It is evident that the maximum pressure rise and the maximum rate of pressure rise are proportional to the amount of air participating in combustion, which is determined by the initial pressure in the test tube or in the air reservoir, and not to the level of turbulence. The experiments with dust dispersed by nitrogen with same ignition delay times seem to confirm this supposition (see Fig.55(b)). The maximum rate of pressure rise at a short ignition delay

time (<100ms) is influenced by the intensity of dispersion-induced turbulence and also by the maximum pressure rise of explosion which is a measure of the amount of dust participating in combustion. To eliminate the influence of the maximum pressure rise on the maximum rate of pressure rise, the parameter $(dp/dt)_{\max}/\Delta P_{\max}$ is introduced as a relative burning rate. The influence of dispersion-induced turbulence on this parameter is shown in Fig.14 for gas and dust flames. Figure 14 proves that the influence of dispersion-induced turbulence on a relative burning rate of cornstarch dust-air mixture is also similar to that of lean methane-air mixtures with a concentration of 5.5% methane.

The combustion of dust mixtures under influence of a high level of turbulence is characterized by a large scatter in the data. Figure 56 illustrates the history of pressure rise and the flame front location along the tube for flames propagating in cornstarch dust-air mixtures with a concentration of 550g/m^3 at highest possible level of turbulence corresponding to the ignition delay time of 50ms for four different experiments. It is worthwhile to analyse in detail each of these experiments from the point of view of the interrelation between the propagation velocity and the pressure, in order to understand, at least qualitatively, the reason for different flame behaviors.

Case A : An initial propagation velocity of flame front of 33.3m/s is extremely high. In the middle part of the tube it is 4.0 m/s and in the final part portion, 2.5m/s. The time of combustion as determined both by the flame propagation, $L(t)$ curve, and the maximum pressure rise, $P(t)$ curve, is the same and equal to 210ms. The maximum pressure rise during the explosion of about 0.43 MPa for these particular conditions is very low. The only logical explanation is that the flame failed to propagate in the initial part of the tube. With short ignition delay times such flame behavior was sometimes observed in visualization of experiments.

Case B : The propagation velocity of the flame front is equal to 8.5m/s, and is nearly the same over the entire length of the tube. The time of combustion is about 120ms from the point of view of flame propagation, and 200ms from the point of view of the maximum pressure rise. The maximum pressure rise of explosion, which is about 0.76MPa, is extremely high being close to that for a 8.5% methane-air mixture.

Case C : The flame starts to propagate slightly earlier than in the cases A and B. Its

propagation velocity is equal to 3.3m/s over the entire length of the tube, which is very low. The time of combustion is about 280ms from the point of view of flame propagation and 370ms from the point of view of the maximum pressure rise, which is equal to 0.66MPa, therefore is close to that of 7% methane-air mixture.

Case D : The flame starts to propagate at the same time as in the case C, but its propagation velocity is higher being 10m/s in the initial part of the tube, 4.5m/s in its intermediate region and 2.5m/s in the end part of the tube. Because the propagation velocity along the initial 40cm of tube length is high, the time of combustion is below the value characteristics for the case C and is 190ms from the point of view of flame propagation and 240ms from the point of view of the maximum pressure rise. The maximum pressure rise of 0.66MPa is equal to that in the case C or for a 7% methane-air mixture.

The burning rate as expressed by the mean rate of pressure rise $\Delta P_{\max}/\Delta t_{\max}$ has the same tendency to vary as the mean propagation velocity. In the case B, in which the mean propagation velocity is the highest of all the cases, $\Delta P_{\max}/\Delta t_{\max} = 0.38\text{MPa/s}$, while the mean propagation velocity of the case C, which is the minimum of all the cases, is characterized by $\Delta P_{\max}/\Delta t_{\max} = 0.178\text{MPa/s}$. As the case C, the mean propagation velocity of the case D has a burning rate corresponding to $\Delta P_{\max}/\Delta t_{\max} = 0.21\text{MPa/s}$ is not typical (the flame was probably partly extinguished). It is also worthwhile to notice that, usually, the flame front propagates the entire length of the tube before the pressure rise reaches its maximum value. It indicates the continuing process of heat release after the flame has run into the end of the tube.

Figures 57 and 58 illustrate the role played by the ignition delay time and the tube length in influencing the pressure rise and the flame location for cornstarch dust-air mixtures of the same concentration of 550g/m^3 as in Fig 56.

It follows from the preceding considerations that the large scatter of dust explosion characteristics especially for a flame under the influence of turbulence with small scale and high intensity, are caused by the irregular propagation velocity. The question that now arises

is what is the cause of large scatter of the propagation velocity. The likely reason of such a flame behavior is its propagation in near quenching conditions. For short ignition delay times (below 250ms) the rate of the mixing process is by one order of magnitude faster than the rate of chemical reaction. The characteristic mixing time can be estimated as $t_m = l/u'$, where l is the integral scale of turbulence and u' is the rms turbulent velocity. According to the turbulence measurements reported in Chapter 4, section 4.3, the characteristics mixing time can be of the order of $t = 6.7$ ms. The characteristics time of chemical reaction can be estimated from [93] as $t_{ch} = \delta_l/u_l$, where δ_l is the flame thickness and u_l is the laminar burning velocity. The flame thickness propagating in cornstarch dust-air mixtures can be determined after [38] as $\delta_l = 0.3$ cm. The laminar burning velocity can be estimated, on the basis of the present work and that of [102]. Since the behavior of flames in cornstarch dust-air mixtures is similar to flames in methane-air mixtures with 5.5% methane, the laminar burning velocity for cornstarch-dust flames can be considered as 7 cm/s, corresponding to a 5.5% methane-air mixture, or 5 cm/s, as the minimum propagation velocity in the methane-air mixtures. On the basis of these data the characteristic time of chemical reaction is $t_{ch} = 42.9$ ms or 60 ms. It was found in [93] that the relation between the chemical reaction time and the mixing time in gas flames, as expressed by the Karlovitz-Kovaszny criterion $K = t_{ch}/t_m$, can be used as a criterion of flame quenching by turbulence. The values of K were observed between 7 and 20 in a quenching process for methane-air mixtures with lean to rich methane concentrations. Applying this criterion to cornstarch-dust combustion in the presence of dispersion-induced turbulence, the value of this criterion is within the range of $K = (42.9/6.7)$ to $(60/6.7) = 6.4$ to 9.0 and indicates combustion at the quenching limit. It was observed that under near quenching conditions the reaction zone is disrupted into very diversified reacting regions of dimensions smaller than the integral scale of turbulence [93].

Similar results can be obtained, if Abdel-Gayed and Bradley criteria are used [111]. It was found in their paper that for turbulent Reynolds numbers based upon the integral length scale $Re_l = u'l/\nu = 171$, where ν is the kinematic viscosity, the critical ratio u'/u_l is, from the point of view of quenching by turbulence, about 9. The value of this ratio for combustion under the action of dispersion-induced turbulence is within the range $u'/u_l = 8.6$ to 12. It is seen again that the combustion conditions are close to the quenching limit.

On the basis of the experimental observations and the present analysis the following picture of combustion of dust-air mixtures under the influence of dispersion-induced turbulence is outlined. The flame propagates first in the volatile parts then, after burning occurs, in the remaining parts. This flame behavior can be observed in a qualitative manner on films made by a high speed camera and can be recorded additionally on oscilloscopes as a difference in time between the instant of flame arrival to the end of the tube and the instant of the maximum pressure rise attained. The quantity of the fuel in the volatile parts is limited and critical from the point of view of flame propagation [71]. In regions in which the quantity of the fuel in the volatile parts is small, the mixture in its gas phase is lean and the laminar burning velocity is low. Because the mixing process is very fast (by one order of magnitude faster than the process of the chemical reaction), there are regions in which the Karlovitz-Kovaszny criterion exceeds the critical values of $K=7$ to 20, and the flame cannot propagate locally in the gas phase. Thus, lean mixture (with large value of t_{ch}) and intense mixing (with small value of t_m) increase the Karlovitz-Kovaszny number (large value of K) and indicate that combustion near the quenching limit results in the scatter in the experimental data.

6.3.2 Obstacles-induced turbulent flames

Figure 59 compares the pressure history and the propagation velocity with and without obstacles for very short ignition delay time, equal to 100ms. An identical comparison is made in Fig. 60 for flames of the same mixture concentration but for an ignition delay time of 319ms.

Figure 61 compares the pressure history and location of the flame front along the tube in gas-air and dust-air mixtures, with comparable properties of laminar flames, in a 1.86 meter tube with obstacles. It shows that the propagation velocity of the flame front is slower for the dust flame. By contrast with the propagation velocity, the peak pressure rise during the explosion of dust-air mixtures is 50% higher than that of gas. Comparisons of the flame locations and pressure histories for the same gas-air and dust-air mixture for the 319ms ignition delay time is shown in Fig. 62.

The influence of the ignition delay time, which is related to the dispersion-induced turbulence, on the pressure history and the propagation velocity of the flame front along a

tube with obstacles is shown in Fig. 63. The propagation velocity of the flame front and the rate of pressure rise decreases with the increased ignition delay time. The amount of dust participating in the combustion increases with the decreasing ignition delay time. It can also be seen that the increased ignition delay time reduces the values of peak pressure rise for gas and dust flames, which can be explained by the increased role of the heat losses for a longer total time of combustion. In dust-air mixtures the total time of the combustion processes is longer and the rate of the pressure rise is lower than in gas mixtures.

The influence of dust concentration on the pressure history and the propagation velocity of the flame front along the tube with obstacles for very short ignition delay time (equal to 100ms) is shown in Fig. 64 and for an ignition delay time of 319ms, in Fig. 65. The general tendency of this influence can be expressed as follows: an increase in dust concentration results in a rise of the peak pressure rise, the maximum rate of pressure rise and the propagation velocity of the flame front and in a reduction of the entire combustion time. This influence is very substantial within the range of dust concentrations from 300 to 450g/m³ and less significant within the range from 450 to 750g/m³.

Figures 66-68 summarize the influence of obstacles-induced turbulence on the most important explosion characteristics in cornstarch dust-air mixtures, i.e., the maximum rate of pressure rise, the maximum pressure rise during the explosion and the propagation velocity of the flame front.

The experimental results of cornstarch dust combustion show that the maximum rate of pressure rise in the presence of obstacles is 20 to 30 times as high as with no obstacles, compared to 40 times for methane-air mixtures with concentrations of 5.5% methane; propagation velocities increase under the influence of obstacles 5 to 10 times for cornstarch dust-air mixtures and 9 times for methane-air mixtures with 5.5% methane. It is evident from these comparisons that the influence of the obstacles-induced turbulence on flame propagating in cornstarch dust-air mixtures still can be considered similar to that in 5.5% methane-air mixtures under comparable experimental conditions. A much higher scatter of data is the most visible difference characterizing a dust flame as compared with a gas flame. The influence of the ignition delay time on the propagation velocity of the flame front and the peak pressure rise is higher for a dust flame than that for a gas flame.

6.4 A Physical Model of Dispersion-Induced Turbulent Dust Flames

The influence of turbulence on dust flames in a comparable study with gas flames is the starting point for the analysis of a turbulent flame.

The dispersion-induced turbulence flow structure can be described on the basis of dispersion-induced turbulence measurements. It was shown in Chapter 4, section 4.3 that the measured turbulence parameters correspond to those characteristics of an ignition delay time of about 50ms. For a measured integral length scale of turbulence $l = 0.4\text{cm}$, a rms turbulent velocity $u' = 60\text{cm/s}$ and a kinematic viscosity $\nu = 0.14\text{cm}^2/\text{s}$, the associated turbulent Reynolds number is $Re_l = l u' / \nu = 171.4$. The Reynolds number characterizes a ratio of the inertia forces to the viscosity forces. The value of the Reynolds number based on the integral length scale shows that the action of viscosity on the eddies of that scale is small.

It is known that viscous dissipation occurs in eddies of the smallest dissipative scale characterized by Reynolds number based on the Kolmogorov microscale, $Re_\eta = u_\eta \eta / \nu = 1$, where u_η is the velocity and η the diameter of a thin dissipative vortex tube (Kolmogorov dissipative microscale). With these numerical values the characteristic mean eddy-break-up time is $1/u' = 6.7 \cdot 10^{-3}\text{s}$ and the energy dissipation rate per unit mass is $e = (u')^3 / l = 540000\text{cm}^2/\text{s}^3$. On the basis of [14,128], it is easy to determine two other scale of turbulence : the Taylor microscale $\lambda = (40.4 \cdot l \nu / u')^{1/2} = 0.19\text{cm}$ and the Kolmogorov dissipative microscale $\eta = \nu^{3/4} / e^{1/4} = 0.0085\text{cm}$. A mean cornstarch particle has a $15\mu\text{m}$ diameter of d_p . For a dust concentration of 600g/m^3 , which is the most frequently used in experiments, the average spacing between particles is about 0.14mm . For an assumed relative velocity w of about 10cm/s between the particles and the air, the associated Reynolds number is $Re_{dp} = d_p \cdot w / \nu = 0.11$. It shows that a dominant role is played by viscosity and that the influence of the turbulence on the local transport of mass and heat around a dust particle may be ignored. A comparison of the length scale of dust particles, turbulence eddies and interparticles spacing is made in Fig. 69.

It was shown in Chapter 6, section 6.1 that the characteristics of laminar flames propagating in cornstarch dust-air mixtures are similar to that of laminar flames propagating

in lean methane-air mixtures with concentrations of methane in the range from 5.5% to 6.0%. Numerical values of the most important characteristics of both flames are the same because their flame propagation is controlled by the same processes occurring in a gas phase. There are the following numerical values of the most important characteristics of both flames:

- i) adiabatic burning velocity, about 15cm/s [102],
- ii) burning velocity at the quenching conditions, about 7cm/s [93],
- iii) measured flame temperature 1700°K,
- iv) measured quenching distance 6mm [38], and
- v) effective flame thickness of about 3mm.

On the basis of these data the characteristic time of chemical reaction can be expressed as t_{ch}
 $= \delta_l / u_l = 42.9 \cdot 10^{-3} \text{ s}.$

The data show that the integral length scale of $l = 0.4\text{cm}$ is comparable with the flame thickness $\delta_l = 0.3\text{cm}$. The Kolmogorov microscale estimated as $\eta = 0.0085\text{cm}$ is 35 times lower than the flame thickness, the rms turbulent velocity $u' = 60\text{cm/s}$ is 8.6 times higher than the laminar burning velocity $u_l = 6 \text{ to } 7\text{cm/s}$, and the characteristic time of chemical reaction $t_{ch} = 42.9\text{ms}$ is 6.4 times longer than the characteristic life-time of the mean eddy $t_m = 6.7\text{ms}.$

All these data suggests that the mixing process plays a predominant role in the turbulent flames. If the integral length scale is comparable with the flame thickness, the turbulence increases seriously the intensity of the transport processes (heat and mass transfer) within the flame front thus increasing the flame propagation velocity. It is also easy to show that if the rms turbulent velocity u' is much higher than the laminar burning velocity u_l , this leads to the intensification of the transport processes in the flame volume, due to very fast mixing. If $u' > u_l$, the flame folds, deformed by turbulence, do not have enough time to burn completely over their entire surface, because, in the meantime, they are divided into pieces by turbulent fluctuations and they enter the new-formed eddies. Inside of these new eddies they are under the action of turbulent diffusion. In a turbulent flow field, produced by the dispersion system, interacting with a 3mm thick flame, a wrinkled laminar flame structure cannot exist. A laminar flame can propagate in a mixture from an initial flame fold, if it is

thicker than the thickness of laminar flame. If the initial flame fold thickness is the same as the laminar flame thickness δ_l , the flame ceases to propagate, because of the cooling effect of the fresh mixture. Geometrical considerations show that the heat transfer by conduction from the fold to the fresh mixture cannot be compensated by heat release [142]. Thus, every flame fold formed by turbulence will be quenched, if the integral scale of turbulence is less than (or comparable to) the thickness of the laminar flame. This quenching effect grows larger as rms turbulent velocity u' increases to become higher than the laminar burning velocity u_l .

It is useful to have an image of the structure of the gas phase of a turbulent dust flame, which can be done on the basis of the investigation of Chomiak and Jarosinski [93]. It was demonstrated in [93] for a lean methane-air mixture (5.7% methane) and small integral scales of turbulence ($l = 2.14$ and 6 mm) that in spite of very fast mixing (more than an order of magnitude faster than chemical reaction), the flame was not converted into a distributed reaction zone, but was disrupted into very diversified, intensely reacting regions of dimensions smaller than the integral length scale. The model of the structure of a turbulent dust flame front based on the information from [93] is represented in Fig. 70.

6.5 The Mechanism of Flame Acceleration by Obstacles

The significant influence of repeated obstacles on the acceleration of both gas and dust flames in a 1.86 meter closed tube has been presented. The flame acceleration by obstacles in cornstarch dust-air mixtures is similar to that in lean methane-air mixtures with concentration of 5.5% methane. The mechanism of gas flame acceleration by obstacles is still an open question.

A simple feedback mechanism for gas flame acceleration was proposed by Moen et al. [56], based on the assumption that the increase in the rate of burning of the flame fold due to the turbulence produced by the obstacles controls the acceleration process. The model assumed by Moen et al. [59] was that a flame fold (which does not continue to grow) has already been established, and that rate of burning of this flame fold is determined by the turbulence field which the flame propagates into. In this model the details of the turbulent combustion or the nature of the combustion zone are not considered.

To understand the nature of the mechanism of flame acceleration by the presence of

obstacles it is important to study a similar mechanism, such as that of the acceleration of a flame in a smooth tube analysed by Zeldovich et al. [99] and, by Chomiak [98]. It has been found that a flame starting from a closed end of a long tube is, sometimes, accelerated. Zeldovich et al [99] expressed an opinion that flame acceleration depends on the character of the motion of the gas before the flame front. As the motion of the gas through a tube with fixed walls continues, gas layers adjacent to the wall are slowed down, the motion of the gas along the tube axis thus being accelerated. The velocity distribution over the cross section of the tube becomes non-uniform, the velocities at the walls being below those at the tube axis above the mean velocity. The flame front extends, its area increases, the quantity of the burning mixture increasing also, in direct proportion.

The velocity of flame propagation in a tube is determined by that of the leading point of the flame [98]:

$$U_f = U_{\max} + U_t \quad (6.7)$$

where $U_{\max}$ is the maximum velocity in the mean velocity profile and U_t is the turbulent flame burning velocity at the point of $U_{\max}$ at the tube axis. The turbulent flame burning velocity is a function of the rms turbulent velocity. The turbulent burning velocity may be approximated by:

$$U_t = C_3 u' \quad (6.8)$$

where C_3 is typically in the range of 1 to 2. Eq.(6.7) may be rewritten in the form:

$$U_f = U_{\max} + C_3 u' \quad (6.9)$$

After the introduction of $\bar{U}$, the mean average flow velocity in the tube $U_f = U_{\text{eff}} + \bar{U}$, then the effective flame propagation velocity relative to the gas becomes:

$$U_{\text{eff}} = U_{\max} + C_3 u' - \bar{U} \quad (6.10)$$

For a turbulent flow in the tube, both $U_{\max}$ and u' are proportional to U and Eq.(6.10) may be written as:

$$U_{\text{eff}} = C_4 \bar{U} \quad (6.11)$$

where C_4 is a constant.

On the other hand, from the expansion of gases in the flame, we have:

$$\bar{U} = (\beta - 1) u_{\text{eff}} \quad (6.12)$$

where β is the density ratio across the flame,

The two equations (6.11) and (6.12) for u and u_{eff} have a solution only if $(\beta - 1)C_4 = 1$ otherwise no solution of the system exists which means that a stationary flow in the tube is impossible. For $(\beta - 1)C_4 > 1$ a certain effective burning velocity generates a flow velocity which increases the burning velocity etc. and a continual acceleration of the flow results whereas for $(\beta - 1)C_4 < 1$ a deceleration takes place and a decay of the burning rate to a laminar value. So, $(\beta - 1)C_4 > 1$ is a criterion for flame acceleration due to the flame shape and turbulence effects.

In smooth tubes the proportionality factor:

$$C_4 = [(u_{\text{max}} - \bar{u})/\bar{u}] + C_3 u'/\bar{u} \quad (6.13)$$

is 1/5 to 1/4 [98]. For flames propagating in lean methane-air mixtures, the factor $(\beta - 1)$ is about 3.5. Thus, in the case of lean mixtures the product $(\beta - 1)C_4$ is somewhat below unity and the flame is not accelerated. It has been estimated by Chomiak [98] that rough surfaces increase the irregularity of the velocity distribution in the cross section of the tube, which makes the coefficient C_4 increase. For a sufficient degree of roughness the product $(\beta - 1)C_4$ becomes greater than unity and the conditions become favourable for flame acceleration. The introduction of obstacles into the tube increases the degree of non-uniformity of the velocity distribution in a cross-section of the tube should more than in the case of rough walls which causes further increases in the coefficient C_4 and, as a consequence, creates conditions would more favourable for accelerating the flame.

The propagation of a gas flame from the closed end of a tube with obstacles was filmed by means of a high speed camera with a Schlieren optical system. Although the quality of the pictures is not very high, the photographs having been through plexiglass walls, the acceleration mechanism of a flame propagating in lean methane-air mixtures is clearly visible (Fig.71(a)). The propagation of dust flame from the closed end of a open rectangular duct with obstacles was filmed by means of a high-speed camera, shown in Fig.71(b).

The mechanism of flame acceleration in a tube with obstacles is illustrated in Fig. 72. The motion of the gas ahead of the flame front makes the flow turbulent in the presence of obstacles and the velocity distribution over a cross section of the tube becomes uneven. The high velocity of the flame is a result of the mixture being burnt in the pockets between obstacles, as a consequence of which the flow, which conveys the flame along the tube axis, is accelerated. This flame ignites the mixture in further pockets between obstacles, the rms turbulent velocity thus increasing gradually. As a result the acceleration of the flow along the axis of the tube is still higher. The increased velocity of the mixture means further increase in the velocity of the flame which leads, in turn, to more rapid ignition of the mixture in the pockets between obstacles. As the acceleration of the flame increases a shock wave is formed before the flame, its amplitude increasing progressively. The analysis of Fig. 59 to 66 shows that the behavior of dust flames is, from the point of view of propagation through a tube with obstacles, similar to that of gas flames in lean methane-air mixtures with 5.5% methane content. The fact that the final burning pressures of dust mixtures are higher than those of their gas counter-parts proves, however, that more energy is furnished during combustion. Part of that energy is produced at the flame front, the remaining part being obtained by afterburning some time later, away from the flame front. The energy supplied by afterburning does not influence the propagation velocity of a turbulent flame induced by obstacles, which approaches, similarly to the case of laminar flames, the value of the propagation velocity of a flame in a methane-air mixture with 5.5% methane content. The value of the maximum pressure rise $\Delta P_{\max}$ increases with increasing dust content in the mixture and with decreasing ignition delay time. For high dust concentrations in the mixtures (some 700g/m^3) and low ignition delay times (some 100ms) the increase in pressure rise as a result of afterburning is considerable and is comparable with the case of burning of a stoichiometric methane-air mixture (see Fig. 53), which proves that almost all of the oxygen available is consumed, in the course of the afterburning process.

CHAPTER 7

CONCLUDING REMARKS

7.1 Synthesis of the Experimental Results

A dispersion system has been developed to produce uniform dust suspensions and low-level dispersion-induced turbulence at the instant of ignition. A method for "calibration" of dust flames by means of well defined methane-air flames has been devised and applied for estimating cornstarch dust flame characteristics in a closed tube. Investigation into the influence of turbulence on flame propagation confirmed the cornstarch dust flame characteristics estimated by the calibration method. It has been shown that the influence of consecutive obstacles on flame propagation is, at least, one of the most effective way to accelerate dust flames.

The present investigation has increased the confidence in some dust flame characteristics determined previously. It has also increased the conviction that the dust flame characteristics can be considered as fundamental quantities to characterize a dust-air mixture composition.

7.2 General Conclusions

- 1) For investigating premixed dust flame characteristics a dispersion system has been developed, which produces a good quality uniform dispersion of dust, a low level of dispersion-induced turbulence and an acceptable dust suspension at the ignition delay time of 300 ms.
- 2) The measurements showed that a laminar gas or dust flame propagating in a closed tube can be considered as adiabatic during its first stage of propagation.
- 3) A method for estimating laminar flame characteristics has also been developed. The method is based on the analysis of turbulent flame characteristics varying under the action of the decaying turbulence. It has been found that, for the turbulence parameters corresponding to an ignition delay time longer than 300 ms, explosion

characteristics such as the maximum rate of pressure rise or the propagation velocity of the flame front asymptotically approach the values, characteristic of a laminar flame. Characteristics of dust flames have been compared in this method with the characteristics of a well defined flame propagating in methane-air mixtures, under the same experimental conditions.

- 4) The characteristics of a laminar flame propagating in a cornstarch dust-air mixture of a given range of concentration are similar to those of a laminar flame propagating in a lean methane-air mixture within the methane concentration range from 5.5% to 6.0%. This able us to expect that flame propagation in these two mixtures is controlled by the same or similar processes. The numerical values of the most important characteristics in a cornstarch dust-air mixture are measured or are estimated on the basis of the 5.5% to 6.0% methane content in methane-air mixture to be as following :

--maximum rate of pressure rise : (measured in the present study)	0.1-0.2 MPa/s
--flame temperature : (measured in the present study for dust flame, which agrees with that of estimated value for 6% methane-air mixture [102])	1700 °K
--adiabatic burning velocity : (estimated in comparison with a lean methane-air flame [102])	15 cm/s
--burning velocity at the quenching condition : (estimated in the comparison with a lean limit methane-air flame [102])	7 cm/s
--mean rate of pressure rise : (measured in the present study)	0.4-1.1 MPa/s
--quenching distance : (measured in the same appartus [38])	6 mm
--effective flame thickness : (estimated on the basis of [38])	3 mm

- 5) It has been found, that a flame cannot propagate freely downwards in a cornstarch dust-air mixture tested over a range of cornstarch concentration from 0.24kg/m³ to

4.0 kg/m³. Similarly, a flame cannot propagate freely downwards in a methane-air mixture leaner than 6% methane. The most probable reason is that of low propagation velocity [137].

- 6) A laminar flame propagating in a cornstarch-dust-air mixture consists of three sub-regions: the preheat zone, the gaseous phase reaction zone and the solid char burning zone. Flame propagation and flame quenching are controlled by processes in the gas phase.
- 7) The dispersion system investigated in the present work is similar to other pneumatic dispersion systems for standard vessels used for dust explosion experiments. Most likely, all these systems create turbulence parameters with no analogue to the natural conditions, which are characterized by a large integral scale of turbulence. The developed dispersion system creates isotropic turbulence fields with a mixing rate more than 6 times the value characteristic for the chemical reaction rate of the dust flame.
- 8) The high ratio of the mixing rate to the chemical reaction rate results in flame propagation under conditions approaching those of quenching. This results in considerable scatter of the propagation velocities followed by scatter in all the other parameters.
- 9) Since the integral scale length is comparable with the flame thickness and the rms turbulent velocity is much higher than the laminar burning velocity, the dispersion-induced turbulence increases the intensity of transport processes within the flame front.
- 10) Explosions with short ignition delay time, below 100 ms, are very effective, since the maximum pressure corresponds to about 8% methane instead of 6% methane in methane-air mixtures. Three factors influence the value of the maximum overpressure at short delay times. The first is the high level of dispersion-induced turbulence. The second factor is the continuous feeding of dust-air mixture with streams of fresh air from the dispersion system, at the time when reaction is in progress. The third factor is an increased amount of dust in the mixture as no time for deposit formation is available.
- 11) The significant influence of repeated obstacles on the acceleration of both gas and dust flame in a 1.86 meter closed tube is observed in experiments. By passing through 12

ring-obstacles with the total length of 1 meter located at 0.5 meter from the point of ignition the maximum rate of pressure rise in the presence of obstacles is 40 times in 5.5% methane-air mixtures, and 20-30 times in cornstarch dust-air mixtures. The propagation velocity of flame fronts increases under the influence of obstacles is 5 to 10 times in cornstarch dust-air mixtures and 9 times in 5.5% methane-air mixtures. The flame acceleration by repeated obstacles is caused mainly by the effects of nonuniformity of the mean velocity and the mixture being burnt in pockets between the obstacles.

7.3 Recommendations for Future Work

Some conclusions can be drawn from the results of the present investigation into problems of combustion of cornstarch dust with $15\mu\text{m}$ particle size in a closed tube of $L/D = 5, 10, D = 0.19$ meters in diameter. They are limited to dust with a large amount of volatile gases such as vegetable grains or powdered foodstuffs. It is advisable to investigate, in future work, the influence of dusts, of different kinds, different particle size and different amounts of oxygen on the dust flame characteristics determined in conjunction with the explosion characteristics. It is suggested that the estimation of the dust flame characteristics from different shapes and sizes of test apparatuses in future experiments can employ the comparative method developed in the present study, in which dust flame is "calibrated" by a well defined gas flame. If necessary some direct measurements of flame characteristics can be selected to make complement for the comparative method.

Statement of Originality and Contribution to Knowledge

- I. - The author of the present thesis has developed a systematic comparative method, drawing upon earlier experiments of others, of estimating dust flame characteristics. This provides an effective tool for gathering dust flame data and represents a distinct contribution to the knowledge of dust explosions. In particular, the comparative method can be employed to verify scattered experimental data obtained from various open tubes and burners in order to increase confidence in some of their values.
- II. A further contribution consists in a systematic study of the decay features of dispersion-induced turbulence in a closed explosion apparatus and its qualitative and quantitative influence on dust explosion characteristics and flame characteristics.
- III. In addition, it has been established, for the first time, that the most effective method to achieve dust flame acceleration is by placing obstacles in the path of the flame.
- IV. Finally, it has been demonstrated in the present thesis, for the first time, that the dispersion system used, similar to other pneumatic dispersion systems employed in standard vessels, creates turbulent explosion conditions not similar to those found in the industrial accidents. Therefore, standard laboratory explosion testing apparatus are probably able to play only a limited role in dust research studies. These procedures can, however, still provide us with some understanding of the fundamental characteristics of dust flames.

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APPENDIX A

The Validity of the Cubic Law

($K_{st} = \text{constant}$)

The maximum pressure rise and the maximum rate of pressure rise constitute explosion characteristics which are most frequently used for comparison and can also serve as a rough estimate of the dust explosion hazard. From the maximum rate of pressure rise a parameter termed the K_{st} factor can be obtained, in accordance with so-called the "cubic law". It is defined as the product of the maximum rate of pressure rise and the cube root of the vessel volume. According to Bartknecht [7], who carried out some experiments with a large number of combustible dusts, K_{st} is constant for a given dust-air mixture. He considers the K_{st} factor as a synonym for the violence of an explosion. Bartknecht proposed to use the K_{st} factor as an explosion characteristic of a given dust-air mixture enabling comparisons to be made among different apparatus, thus allowing the predication of the course of an explosion of this mixture in a large vessel, based on the results of laboratory tests [7]. According to Bartknecht [7] the K_{st} value can also serve as a measure of the explosion hazard in a relative classification system.

Let us examine the validity of the cubic law for a dust-air mixture on the basis of the classical theory of constant volume explosion. The theory of constant volume explosion has been considered by numerous investigations in the past [9, 106]. For the purpose of the present work, it is not necessary to be accurate and concerned with the details. It is sufficient to outline the essential features to get the important parametric dependence.

It is assumed that the flame is thin compared to the characteristic length scale of the vessel and that the explosion phenomenon is similar to the case of homogeneous gas flames. It is tempting to derive a burning velocity for dust-air mixtures from the pressure-time curve using the standard theory. Given a pressure-time curve, one can always assume a propagating flame front progressively releasing energy and thereby pressurizing the vessel as it measured by the transducer. However, the pressure-time trace only represents progressive

release of energy not necessary entirely located in a propagating front, volumetric burning of the contents behind the flame front being the second component of the pressure rise. Thus the "burning velocity" derived from the $P(t)$ curve for dust explosions in a closed vessel may not necessarily correspond to the real flame front velocity of the dust mixture. A real burning velocity is probably slightly less than that measured value or derived from the pressure-time curve.

It is assumed that the mixture is a perfect gas and that the specific heat ratio γ has an average constant value for the burnt and unburnt gases. The internal energy (U) of a volume (V), filled with an explosive mixture the chemical energy of which, per unit mass (Q), is given by:

$$U = MC_v T = MRT / (\gamma - 1) = PV / (\gamma - 1), \quad (A-1)$$

where T is an averaged temperature of the entire mass inside the volume V . Thus the rate of increase of internal energy of the volume is:

$$dU/dt = (V/(\gamma - 1)) dP/dt, \quad (A-2)$$

and assuming the energy release to be effected by some fictitious (or real) propagating combustion front at a velocity u_f relative to the gas ahead of it, one can write:

$$dU/dt = (V/(\gamma - 1)) dP/dt = A u_f \rho Q, \quad (A-3)$$

where ρ is the gas ahead of the front. Assuming isentropic compression of the gas in the vessel, one can write $\rho = \rho_0 (P/P_0)^{1/\gamma}$ and note that $\rho_0 Q = MQ/V$ and:

$$MQ = V \Delta P_{\max} / (\gamma - 1), \quad (A-4)$$

Combining Eqs. (A-3) and (A-4) we find:

$$(V/A) dP/dt = u_f \Delta P_{\max} (P/P_0)^{1/\gamma}. \quad (A-5)$$

The area of the flame front is proportional to the volume $V^{2/3}$, thus the left hand side may be written as $(V^{1/3}/C_A) dP/dt$ where C_A is some constant of proportionality. The rate of pressure rise depends on the local pressure P , for the maximum pressure rise $P = P_{\max}$ and:

$$K_{st} = V^{1/3} (dP/dt)_{\max} = C_A u_f \Delta P_{\max} (P_{\max}/P_0)^{1/\gamma}. \quad (A-6)$$

According to (A-4) the maximum pressure rise is a function of the amount of chemical energy

contained in the mixture and, for a given mixture, the left hand side is proportional to the burning velocity u_l . If the burning velocity is a property of the mixture, then the right hand side is constant giving the so-called cubic law, $K_{st} = V^{1/3}(dP/dt)_{max} = \text{constant}$.

The validity of the cubic law is clear. It requires that the burning velocity u_l and the maximum pressure rise ΔP_{max} be dependent only on the properties of the mixture. However, for the heterogeneous dust mixtures introduced into the vessel by means of a pressurized dispersion system, the burning velocity u_l depends not only on the properties of the mixture, but on the turbulence of the dispersion system as well. Also, the maximum pressure rise would be sensitive to the burning rate due to gravity setting of the dust. Thus it is fortuitous to expect that the cubic law is valid for dust mixtures, independent of the size and the shape of the vessel, but dependent of the technique of the dispersion system or the procedure used.

APPENDIX B

Dynamic Picture of Flame Propagation in Quiescent Methane-Air Mixtures

The combustion process in a closed cylindrical tube was investigated by [127] and analyzed in detail by Guenouche [128] and Dunn-Rankin et al. [129]. Their analyses were limited to stoichiometric gas mixtures and to a small diameter apparatus (within the range of 25-53 mm). The present investigation, with a rather large scale apparatus, with downward and upward propagating flames, and with a different mixture composition shows physical pictures of flame propagation similar to their findings. Figure B-1 presents the pressure history and the flame front location along the tube for three methane-air mixture compositions. After ignition at the end of the tube the flame propagates in the direction of its axis in two different stages. In the first stage the flame speed is augmented by the expansion of the hot gases. The flame accelerates while its surface develops from hemispherical to an increasingly elongated semi-ellipsoidal shape (Fig.B-2). The axial velocity of the flame increases gradually until the flame surface area reaches a maximum value. During the first stage of its development the flame front is not in contact with the walls therefore the combustion process can be considered as adiabatic. Wall temperature measurements show that heat transfer to the wall starts only at the beginning of the second stage of the flame propagation, indicated by the change in the slope of the flame location curve in Fig.B-3.

Figure B-3 shows typical trace of the locations of the flame front and the surface temperature rise of the tube wall as functions of time in methane-air mixture with two methane content of 6.2% and 9.5%. The second stage of the flame propagation starts while the flame reaches the side walls of the tube. Then the area of the flame surface decreases very rapidly, because the roughly cylindrical part of its surface vanishes. The cooling by conduction to the wall causes the density of the product gases to increase. Both of these effects cause deceleration of the flame velocity. The shape of the flame in this stage of propagation is "tulip" like [129]. Flow deceleration in the second stage causes the flame to be unstable in the sense of the Taylor-Markstein instability [147,148]. The Markstein instability can be discussed in term of two processes of a different nature. The first is related to the cellular structure of the flame observed during its laminar propagation, the second to the interaction of the compression or rarefaction wave with the flame, which can follow combustion in a very strong mixture, much stronger than that under investigation. The stability of laminar flames

was analyzed by Matkstein [148] and Istratov and Librovich [149] on the basis of the history of the theory of Landau [150]. Their analysis shows that the onset of instability occurs at a critical Reynolds number (based on the tube diameter) $Re \approx 1000-2000$, which is a function of the expansion ratio. Reynolds number is defined as $Re = ru_f/v$, where r is the flame front radius and v is the kinematic viscosity, u_f is the laminar burning velocity.

An analysis of Fig. B-1 shows that in the 0.93 meter tube the value of pressure increase in the first stage of the flame propagation in methane-air mixtures of 9.5%, 7.3% and 6.2% methane content is equal to 12%, 17% and 20% of the maximum pressure rise, respectively. The leaner the mixture, the slower the combustion process, the higher the heat losses in the second stage of the flame propagation and the further the maximum pressure rise from adiabatic. The measured "channelled" axial propagation velocity of semi-ellipsoidal flames in the first stage of its propagation appears to be about 5 times as fast as the calculated velocity for spherical propagation. The measurements carried out in at different points of the tube shown in Fig. 27(a) that for the methane-air mixture in the range of 6% to 9% methane content propagation velocity is a linear function of mixture composition, which is the case of the measurements in spherical vessel reported by Andrew and Bradley [102]. This indicates that although the flame accelerates, it still retains its laminar property. Measurements also show that the first stage occupies 50% and 36% of the whole length when L/D is 5 and 10, respectively.

The reproducibility of a combustion process is satisfactory in the first stage of flame propagation and relatively poor in the second stage in which it is sometimes influenced in various degrees by instability phenomena. Uncontrolled vibrations usually appear at the end of the flame propagation. They influence, to various degrees, the maximum pressure and the rate of pressure rise. Earlier investigations in [127,128] were concerned with flame propagation in the direction of gravity acceleration. To reveal the role of gravity in flame propagation, downward and upward propagating flames were tested in the present study. Although some differences in the amplitudes of pressure and propagation velocity were observed, (higher values for downward propagating flames) the two-stage character of flame propagation was the same.

APPENDIX C

Dynamic Characteristics of Dispersion System Employed Jet Turbulence

In the present study, the dispersion system consists of an air reservoir ($V = 230\text{cm}^3$), a solenoid valve, a small dust vessel ($V = 10\text{cm}^3$), and a dispersion pipe ($d = 1.4\text{ cm}$, $l = 93\text{ cm}$, $V = 126\text{cm}^3$) equipped with evenly distributed orifices ($\phi = 1.0\text{-}2.0\text{ mm}$) located in one line. Either the velocities of the jet flow or the intensities of jet turbulence are related to the pressure in the air reservoir. Since pressure in the reservoir is not steady, the outflow from the dispersion pipe is transient. It is difficult to investigate these processes by a theoretical analysis. Nevertheless, it is necessary to have some fundamental understanding of the dispersion system action even in some qualitative way.

The pressure discharge process through orifices of the dispersion pipe is one of the important dynamic characteristics of the dispersion system. A dominant factor determining the characteristics of jets flow and jets turbulence is the ratio P_o/P_a , where P_o is the pressure of the upstream flow near the orifices and P_a is the initial pressure in the test tube. If the pressure ratio $P_o/P_a > [(\gamma+1)/2]^{\gamma/(\gamma+1)}$, where γ is the gas specific heat ratio, the jet is choked at the vena contracta and its pressure is greater than P_a . On the other hand, if $P_o/P_a < [(\gamma+1)/2]^{\gamma/(\gamma+1)}$, the outflow is subsonic.

The pressure discharge process in the air reservoir, at both the entrance and the end of the dispersion pipe is measured by means of three pressure transducers respectively, shown in Fig. C-1. Figure C-2 shows typical curves of pressure discharge as a function of time at these three positions. In order to examine the influence of the two-phase medium on the pressure discharge process, two cases were tested. While one is the dispersion of pure air, the other is the dispersion of air with cornstarch-dust particles.

The measured curves in Fig. C-2 suggest that the dynamic characteristics in the

dispersion system can be divided into three stages:

- i) After activation of the solenoid valve in the first sequence of time from 20ms to 40ms, the pressure in the air reservoir steeply decreases from 1MPa to 0.5MPa; simultaneously, in the dispersion pipe, pressure increases from 0.1MPa to 0.5MPa. In the case of the dispersion of pure air, the pressure at both ends of the dispersion pipe reaches the peak value almost at the same moment, and their two peak values are very close to each other, e.g., that in the entrance position is only 1.07 times higher than at the end of the tube. Hence, in this case, the pressure discharge process as well as the pressure along the length of the dispersion pipe can be considered uniform. In the case of dispersion of air with cornstarch-dust particles, the pressure at the entrance of the dispersion pipe reaches the peak value several milliseconds earlier and is 1.3 times higher than that at the end of the pipe. Although measured results show that in the case of two-phase medium, the values of peak pressure between two ends has a 30% difference, the shape and tendency of the pressure discharge curves do not change from the case of the dispersion of pure air. Therefore, in the case of the two-phase medium, it can be approximately considered that the process through the whole length of the dispersion pipe is still uniform.
- ii) In the next sequence of time from 40 ms to 100ms, $P_o/P_a > 2$, and choked flows occur from the dispersion pipe through a series of orifices into the test tube, and supersonic jets are generated. At that time, the pressure in the air reservoir continues to decrease. The shapes of the pressure discharge curves in the dispersion pipe for air and air with cornstarch dust have some differences, but the tendency of the curves is similar. The duration of this choking stage is a little longer for the dispersion of air with cornstarch dust (120ms) than that for air only (100ms).
- iii) In the final sequence of time from 100ms to 200ms, $P_o/P_a < 2$, and subsonic jets are generated.

The pressure ratio P_o/P_a in the dispersion system is not only controlled by the initial pressure, but also by the size of the dispersion orificies. Two dispersion pipes with different total cross-section area of all the orificies were tested. The area of the orificies of the first pipe is taken as the largest value possible, which is equivalent to the area of the cross-section of

the dispersion pipe ($d = 1.4\text{cm}$). The area of the orifices in the second pipe compared to the first one is reduced by a factor of 2. Experiments showed that there are higher values of peak pressure and a larger duration of pressure discharge in the dispersion pipe with small orifices than those with large orifices. All experimental results of these two systems are summed up and shown in Tables C-1 and C-2.

The above measurements demonstrate that the effect of the two-phase medium on the characteristics in the pressure discharge process can be considered as a second-order important. Hence, the behavior of a choked jet and a subsonic jet in a two-phase medium is replaced by those in the gas phase, which are well known from gasdynamic. They are described as follows, in terms similar to those presented in [143].

Figure C-2(a) shows that the choked jets occupy a substantial part of the pressure discharge process. Further expansion of these choked jets to P_0 occurs by means of two-dimensional expansion waves centered at the vena contracta boundary which cause the jet area to increase and accelerate the flow to supersonic velocities. Since any area increase in the supersonic flow is accompanied by further expansion, compression waves originate from the jet boundary in order to maintain the pressure on this boundary at the ambient pressure level P_a , thereby reducing the area increase. These compression waves coalesce and form oblique shock waves which cannot reflect regularly from the jet centerline. A Mach disc is formed and the jet becomes subsonic behind the normal shock associated with the Mach reflection. The diameter in the jet maximum area $\phi_{\max}$, which can be estimated following [144,145], is 1.6 times the diameter of the orifice, under conditions with $P_0/P_a = 5$. Therefore, for an isentropic expansive flow, the maximum Mach number in the present supersonic jet is around 2.

Subsonic jets, which occupy the final stage of the pressure discharge process (shown in Fig.C-2(a)) are considered three-dimensional across the orifice area. The streamlines continue to contract until nearly uniform conditions are achieved at the vena contracta. At this minimum cross-sectional area the jet pressure is equal to the ambient pressure P_a and the jet diameter is less than the orifice diameter.

Figure C-3 shows variations of the centerline velocities of both supersonic and

subsonic jets along their axis. The data of supersonic jets are obtained from Eggers [144] and Johannsen [145] study of free axially-symmetrical jets of Mach number 2.22 and 1.4. The data of subsonic jets are obtained from Wygnanski and Fiedler [146] experimental investigation of the self-preserving turbulent axisymmetric jet in incompressible flow.

The experimental data in Fig. C-3 shows, in both supersonic and subsonic jets, that decreasing of the centerline velocities of jets along their axis have almost the same tendency, except at distances near the orifices. Where $x/d = 10$ to 20, the supersonic jet velocities do not decrease with distance as opposed to the subsonic jet case.

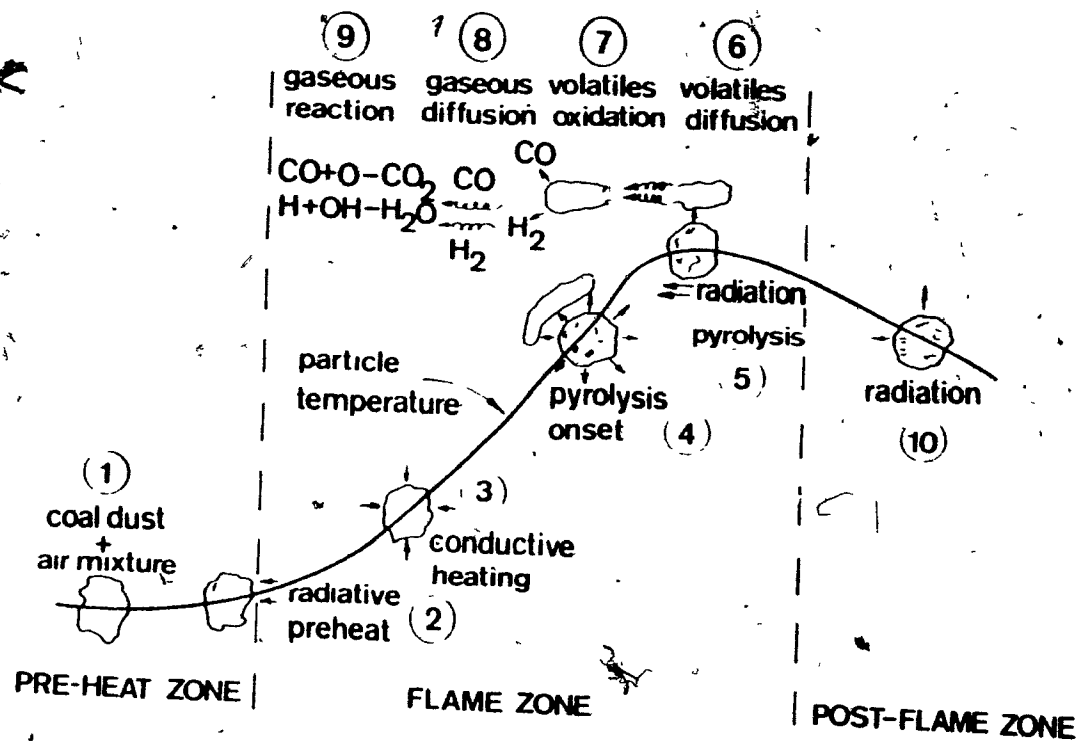


Fig.1. Propagation mechanism of a laminar thin coal dust-air flame [71].

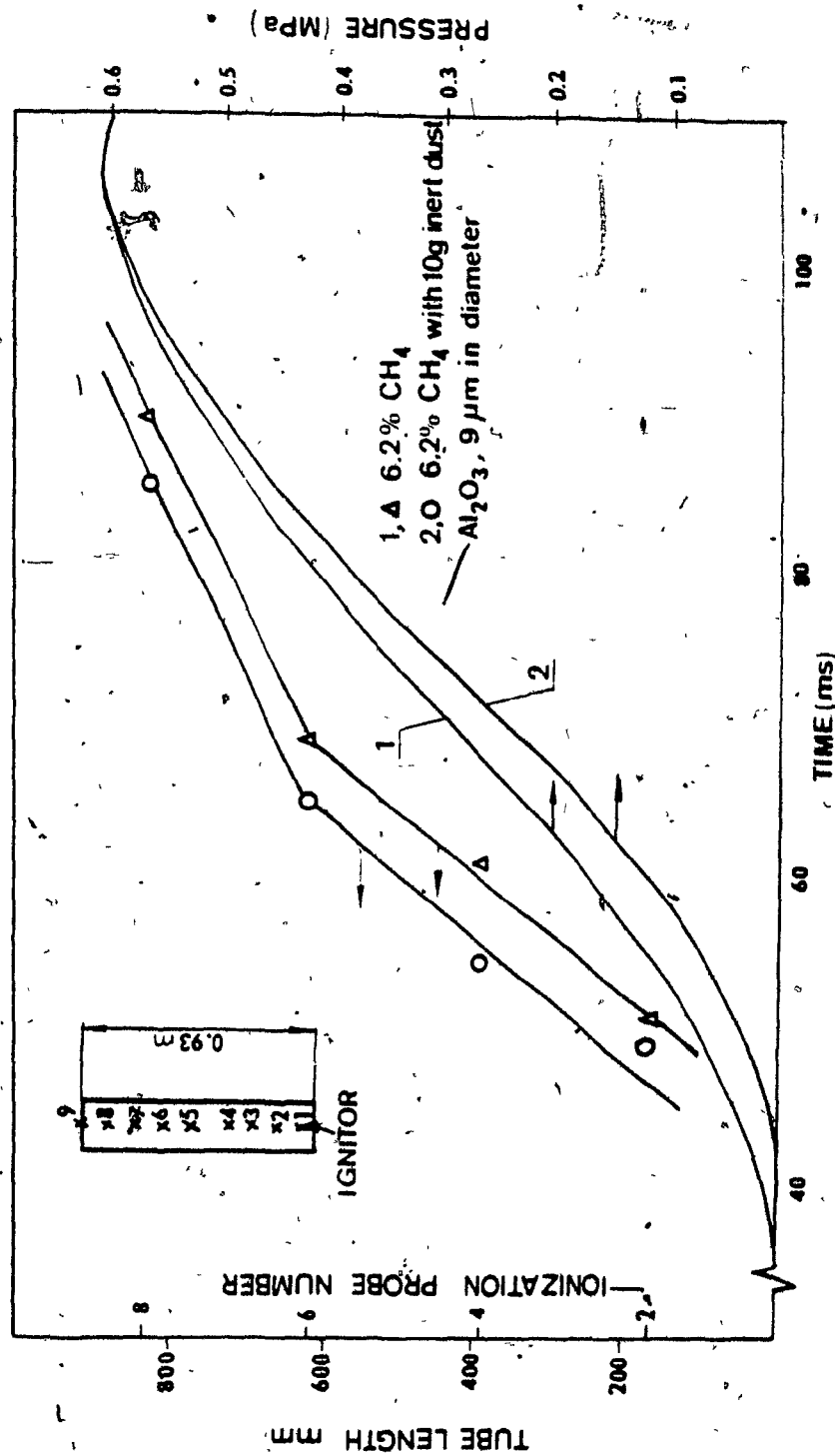


Fig.2. The influence of inert dust on the pressure history and the location of the flame front along a 0.93 meter closed tube in 6.2% methane-air mixture for a ignition delay time of 50 ms.

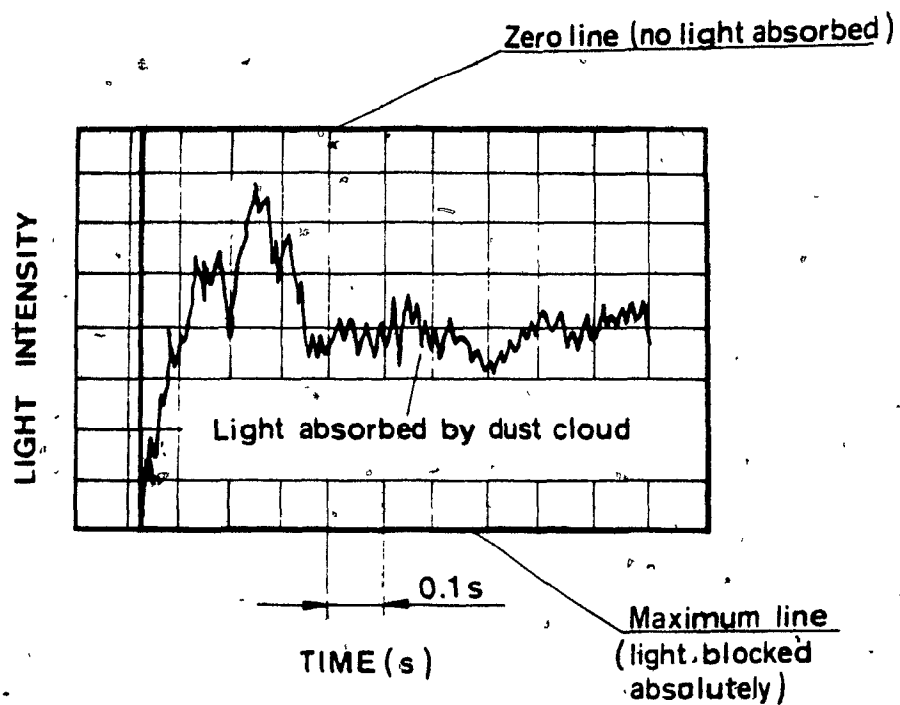


Fig.23. The light trasmission versus the time in bottom-section of the dust dispersion box (see Fig. 21(b)) for a dispersion pipe without bar.

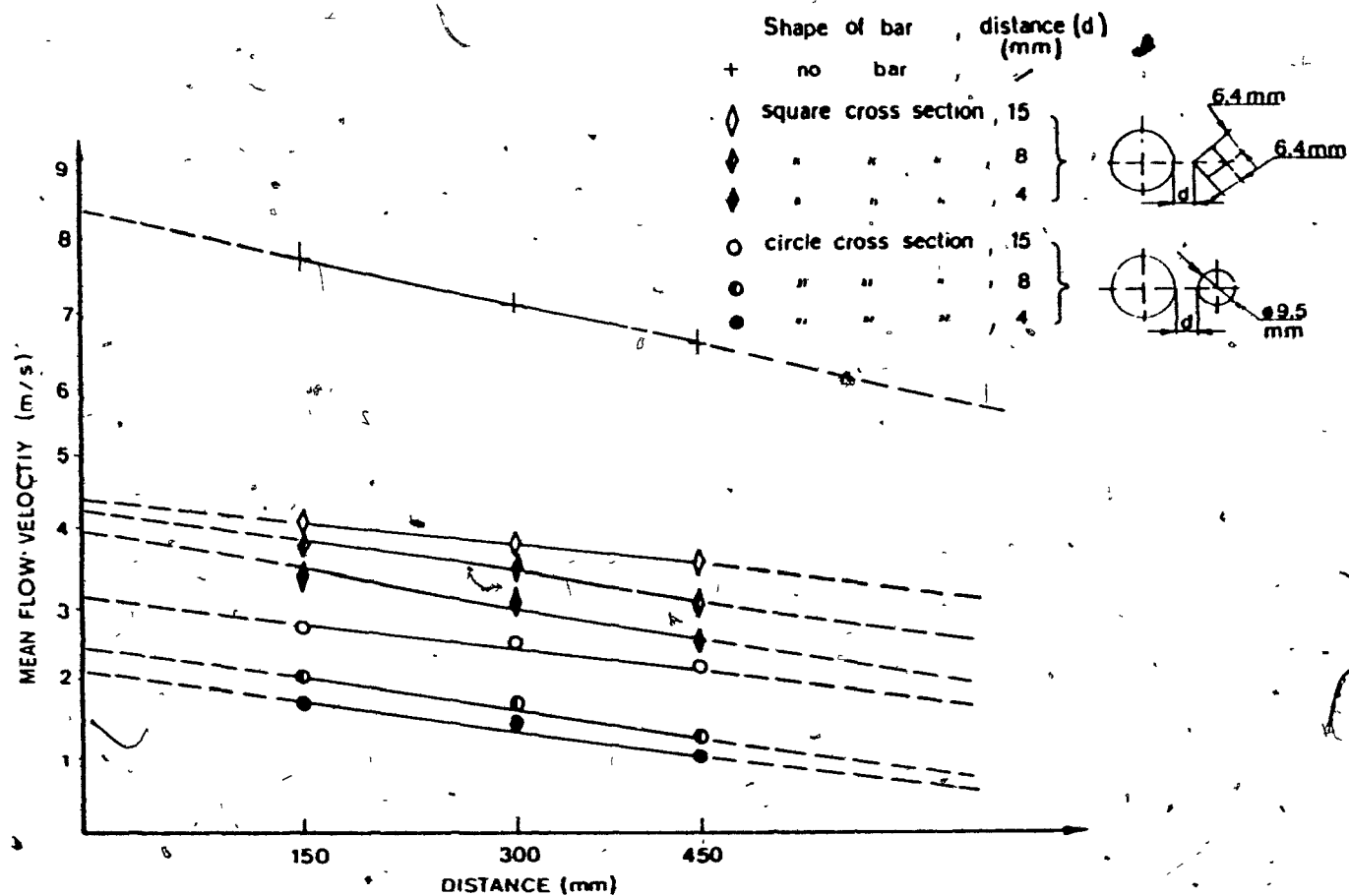


Fig.4. The mean flow velocities produced by the dispersion jets versus the distance from the dispersion pipe along the jet axis in the bottom cross-section of the dust dispersion box (see Fig.21(b)) in dispersion system I.

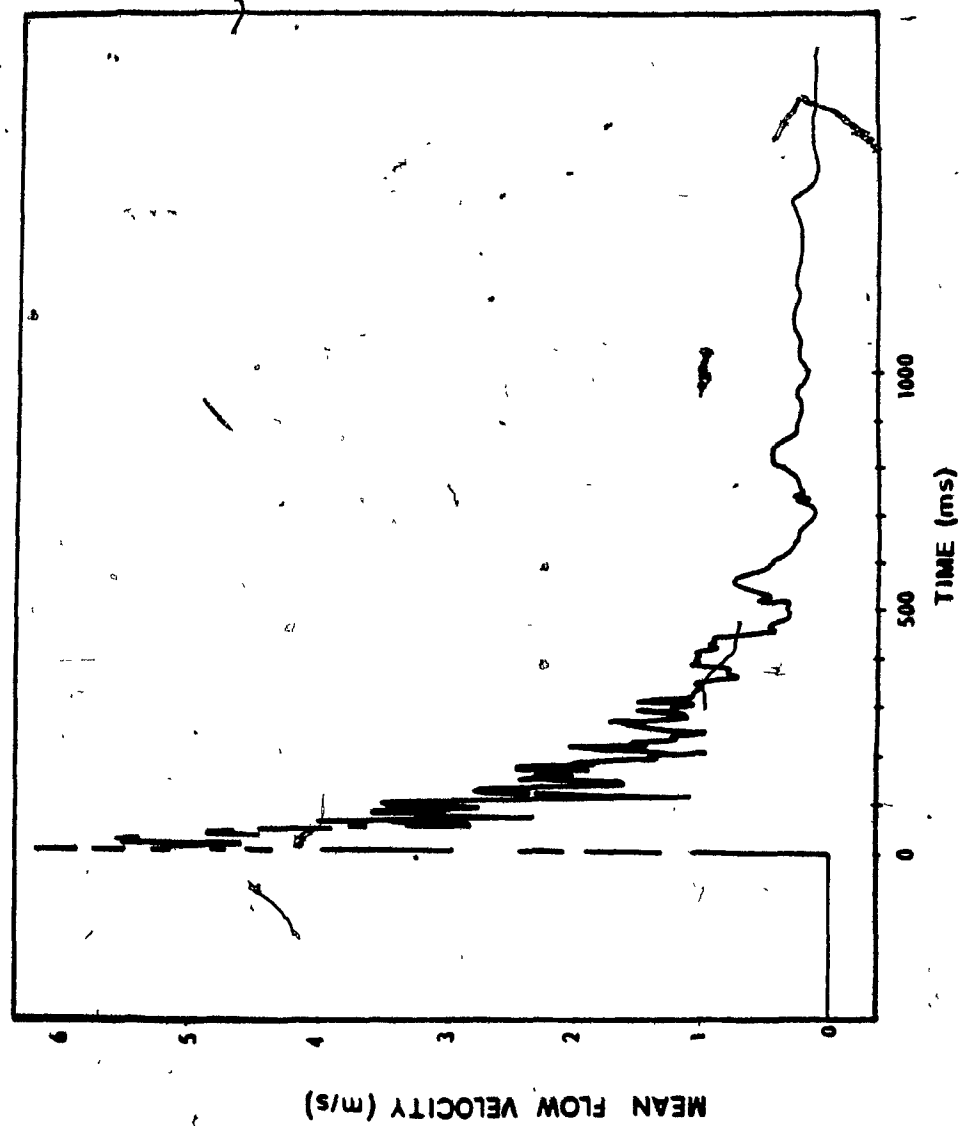


Fig.6. The mean velocity with rms turbulence velocity superimposed as a function of time.

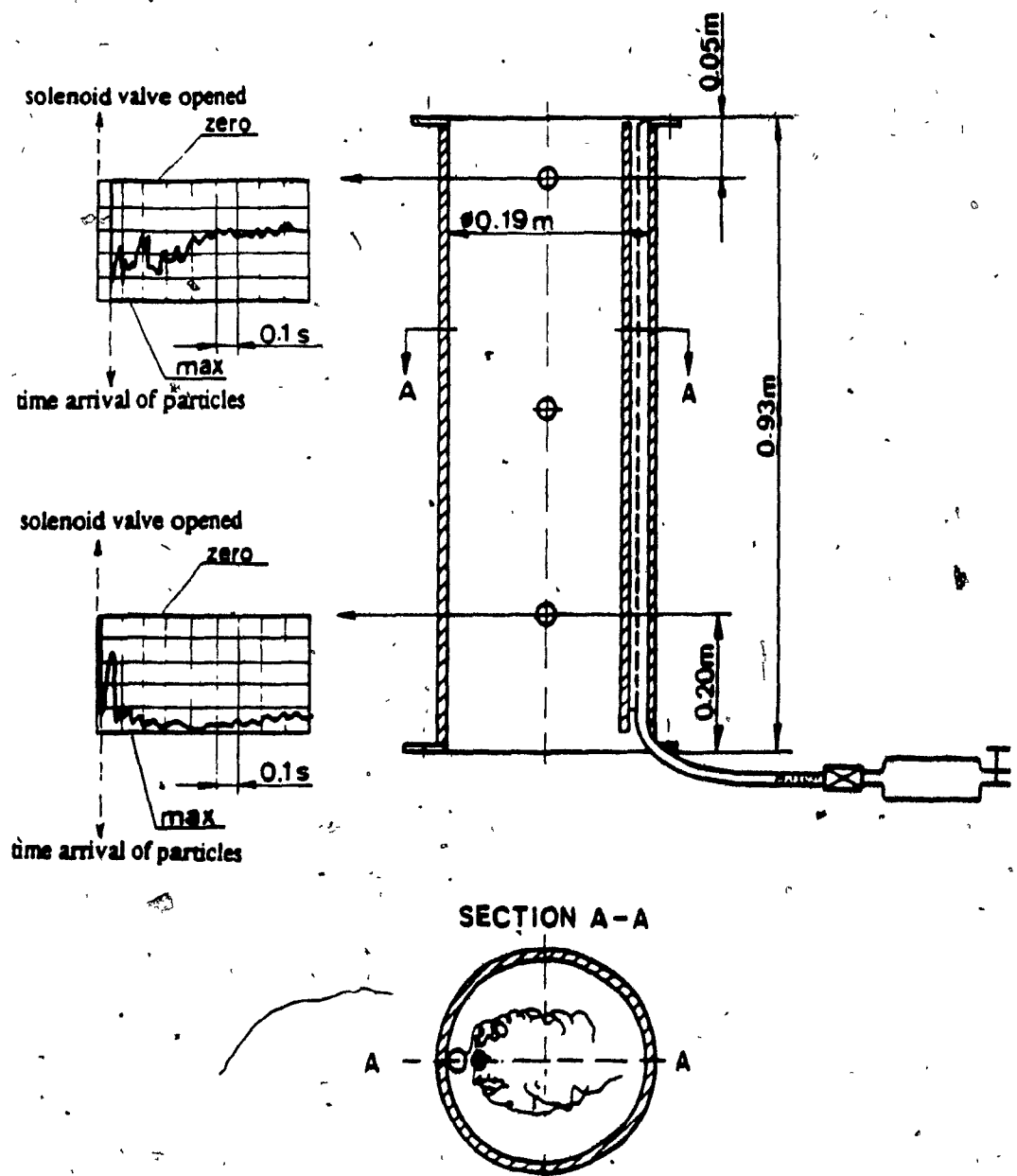


Fig.5. The relative dust concentration (according to the light transmission measurements) versus time at top and bottom section of the test tube, respectively.

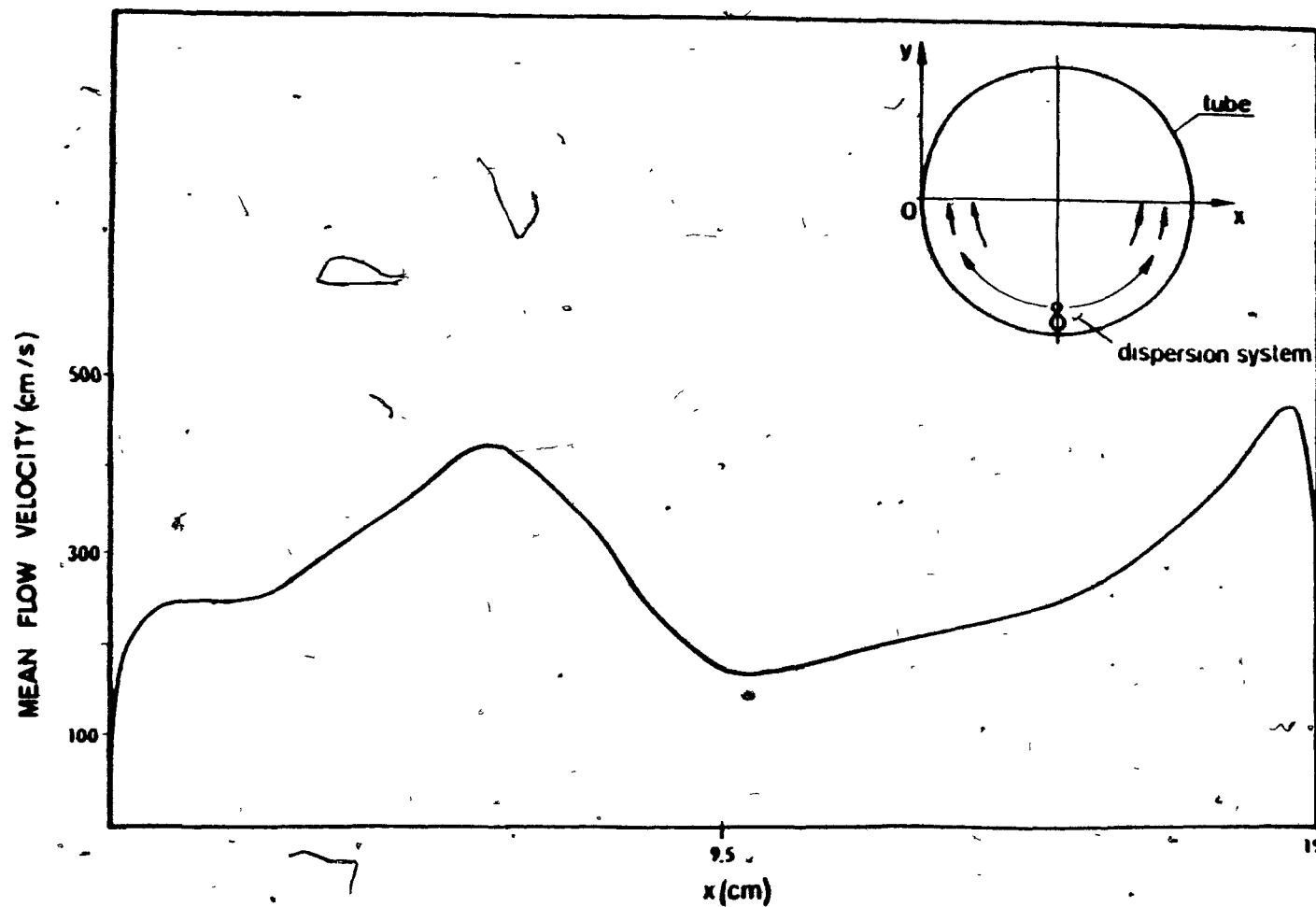


Fig.7. The mean velocity in the direction of y axis produced by dispersion system measured in one-section of test tube along the x axis.

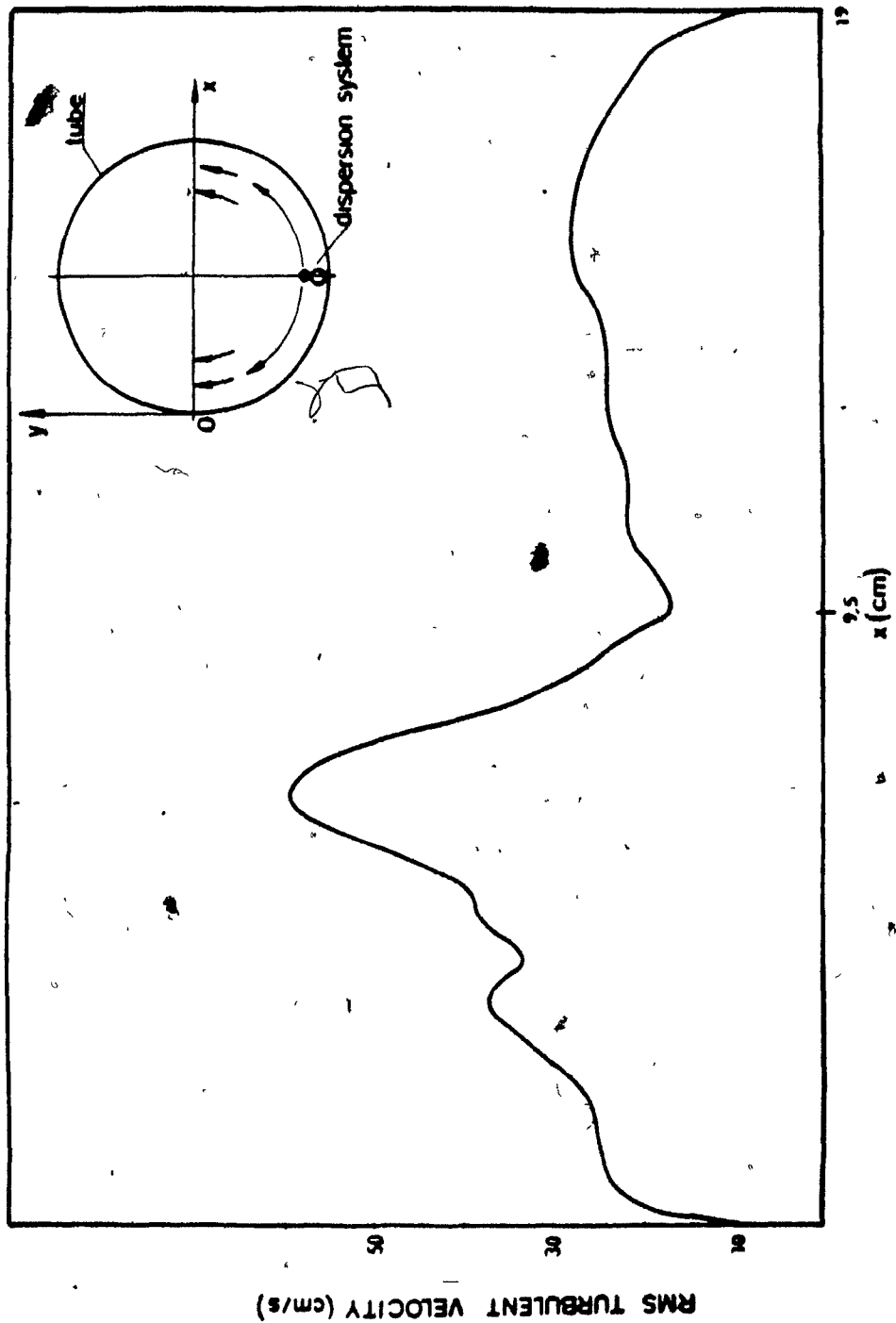


Fig. 8. The rms turbulent velocity in the direction of y axis produced by dispersion system measured in one-section of the test tube along the x axis.

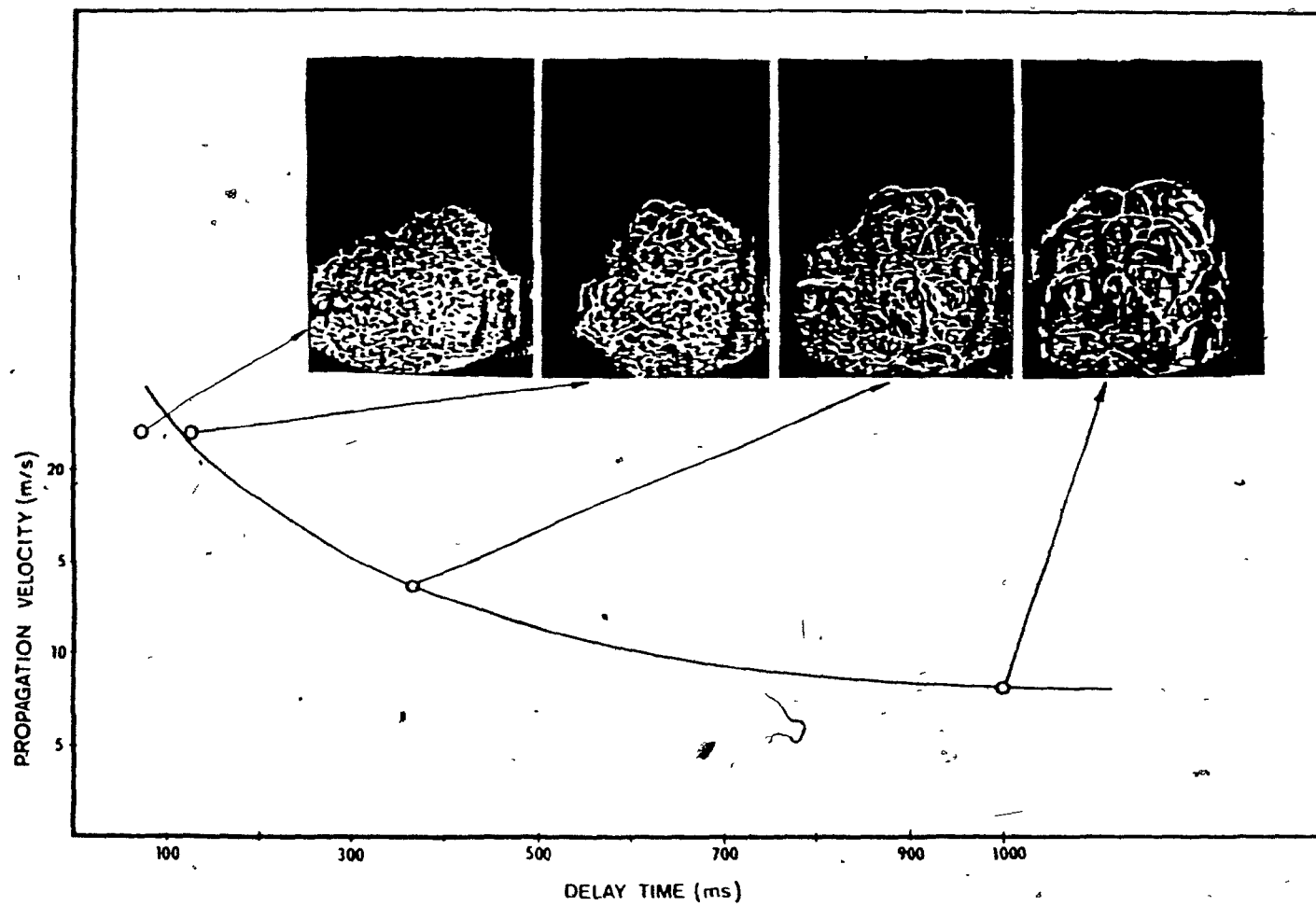


Fig.9. The influence of dispersion-induced turbulence on the propagation velocity and the flame shape.

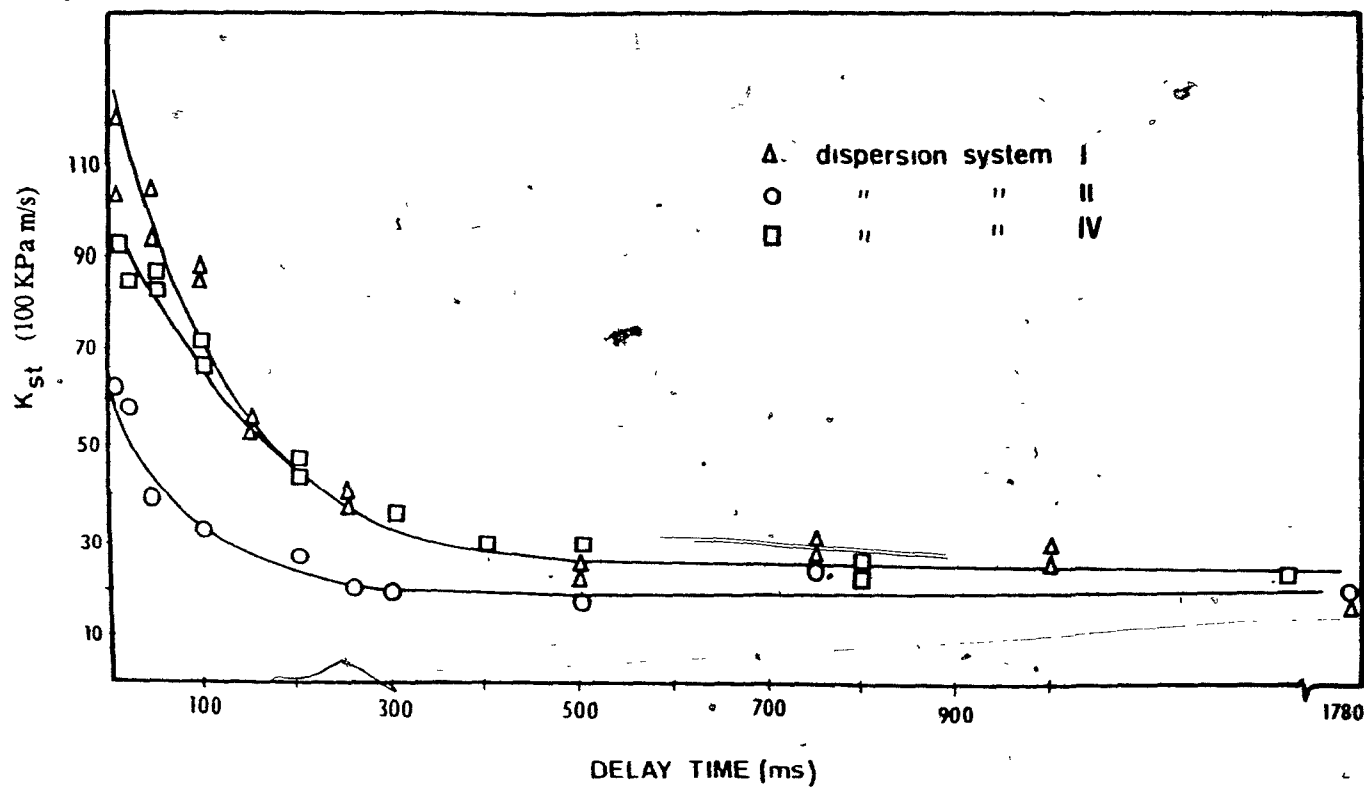
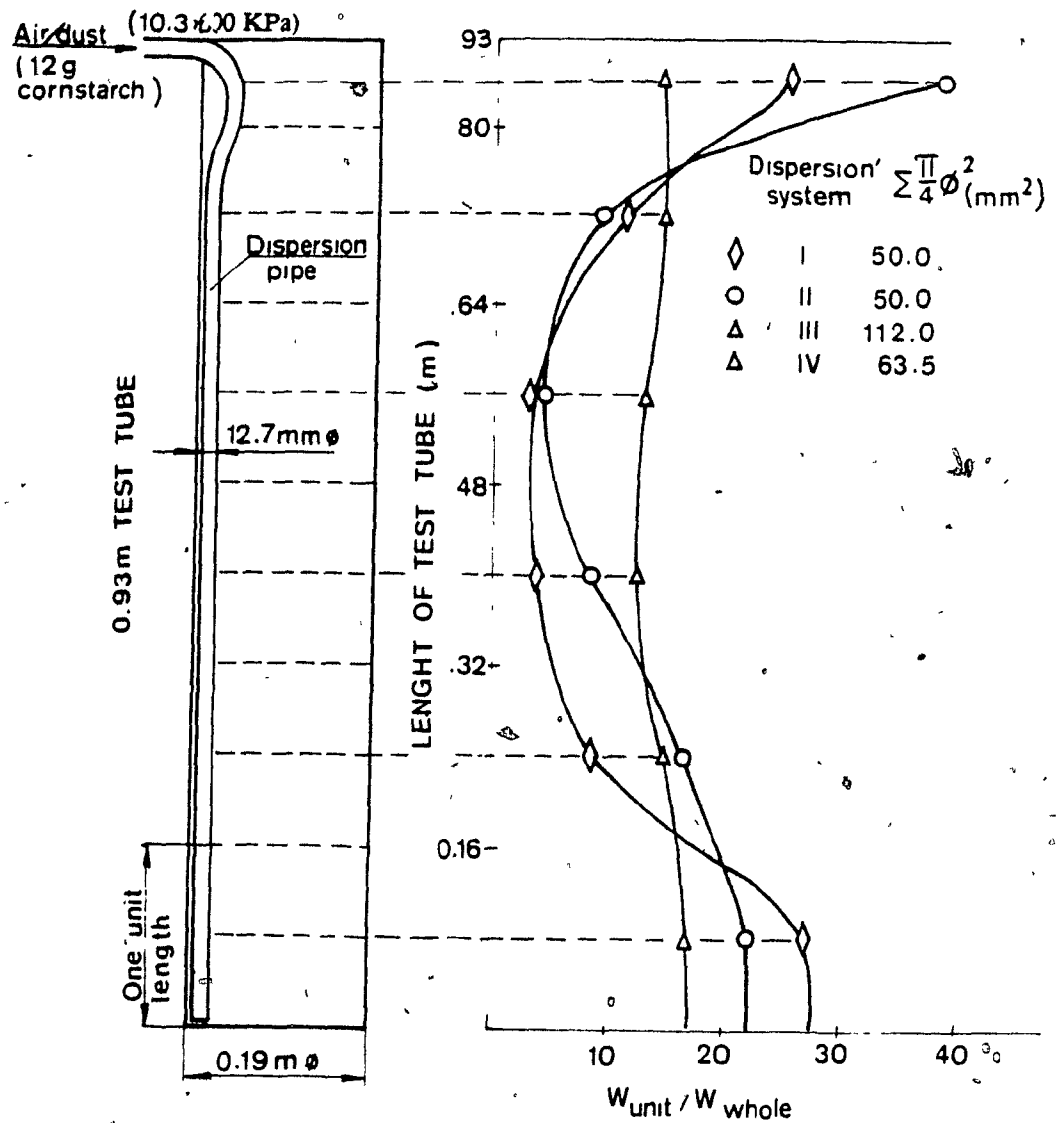


Fig.10 (a). The factor K_{st} as a function of the ignition delay time in a 0.93 meter tube, for three dispersion system, determined for a stoichiometric methane -air mixture (9.5% CH_4).



$\pi d^2/4$ (=126.7 mm²) is the cross-section area of dispersion pipe,

$\sum \pi \phi^2/4$ is the total cross-section area of orifices,

W_{unit} is the amount of dust dispersed into per unit length of the tube,

W_{whole} is the amount of dust dispersed over the entire tube length.

Fig.10 (b). The initial distribution of dust concentration along the axis of the test tube in four various dispersion systems.

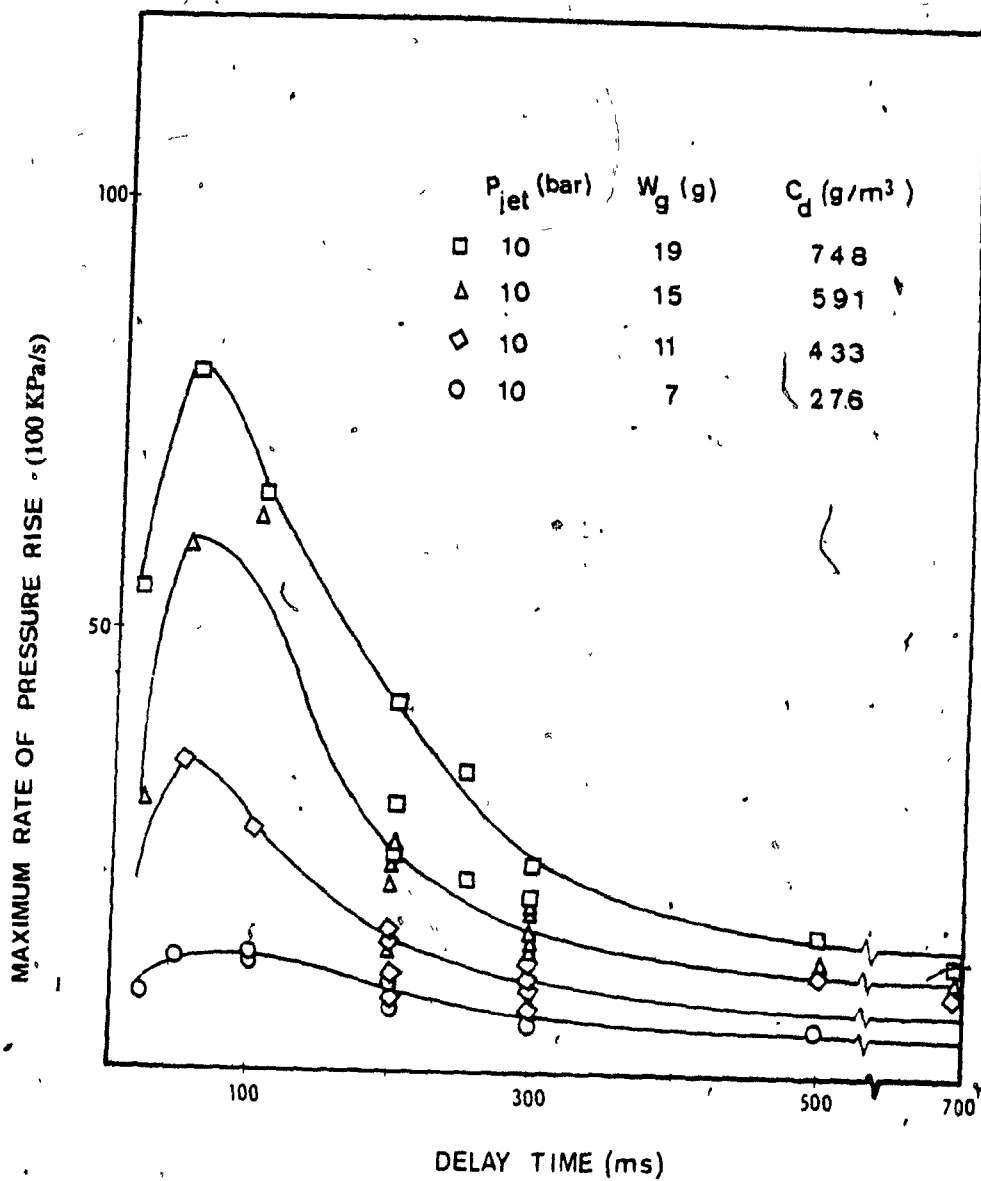


Fig.11. The maximum rate of pressure rise as a function of the ignition delay time for different dust concentrations.

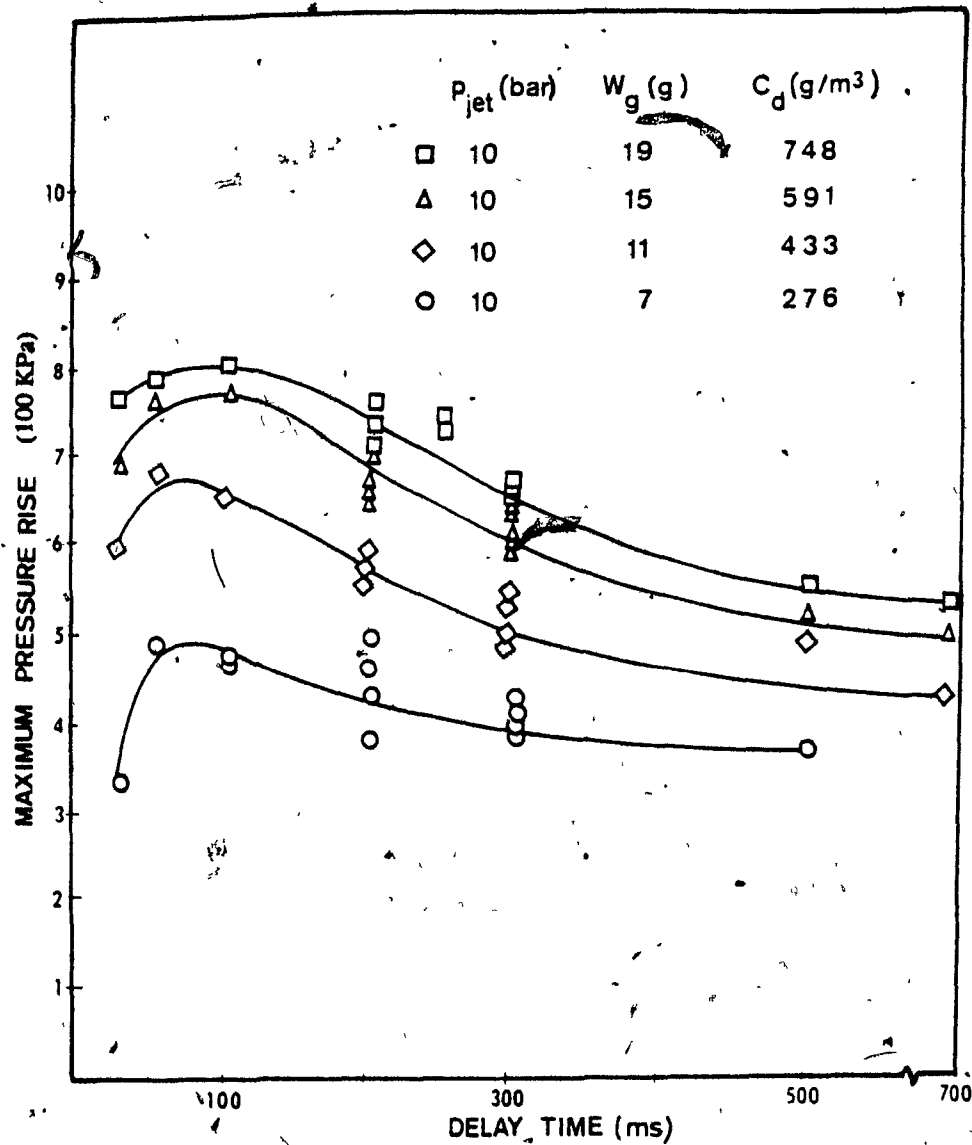


Fig.12. The maximum pressure rise as a function of the ignition delay time for different dust concentrations.

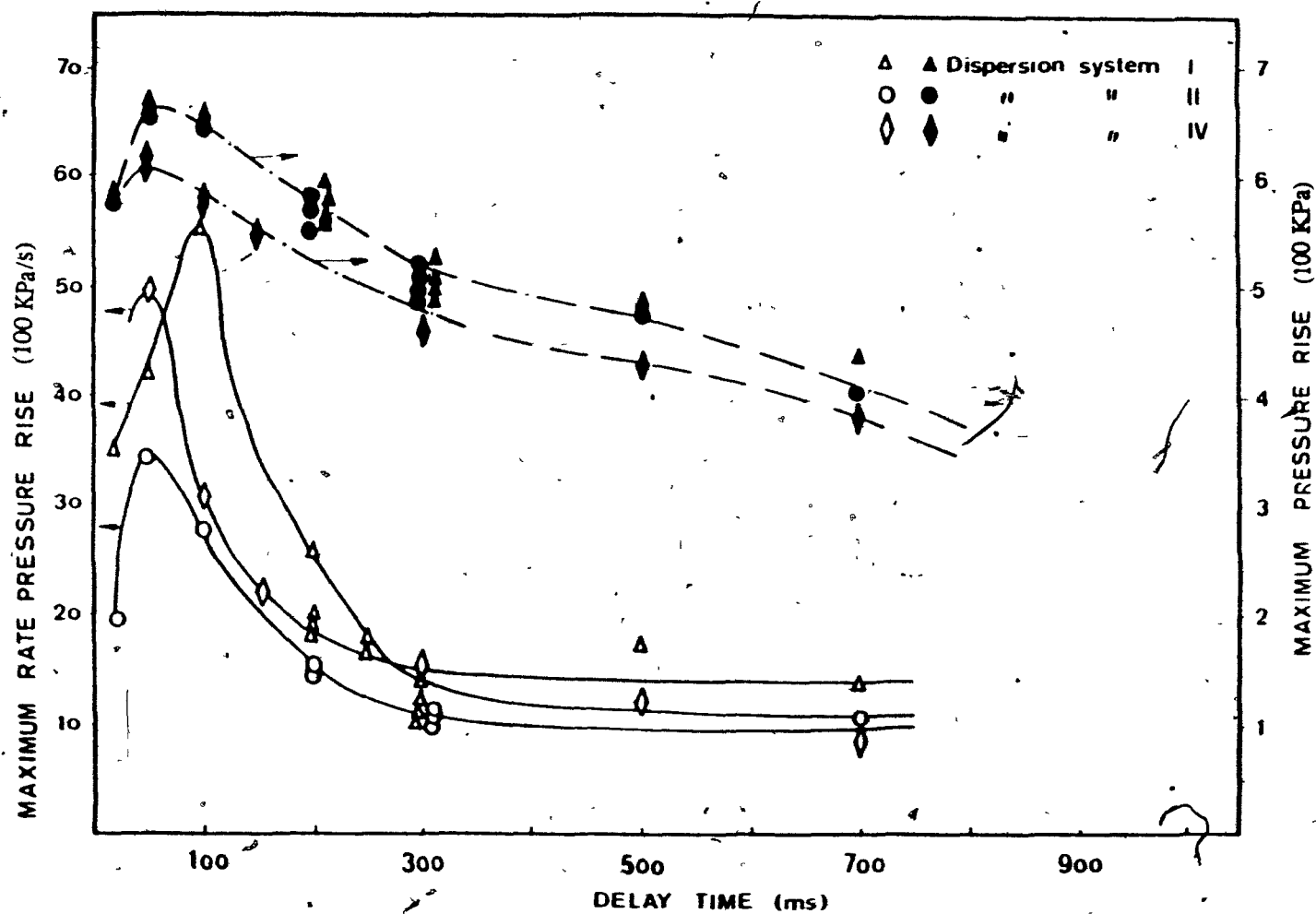


Fig 13. The maximum rate of pressure rise and the maximum pressure rise as a function of the ignition delay time in a 0.93 meter tube for three selected dispersion systems with $P_{jet} = 8.6$ bar and $C_d = 395$ g/m³.

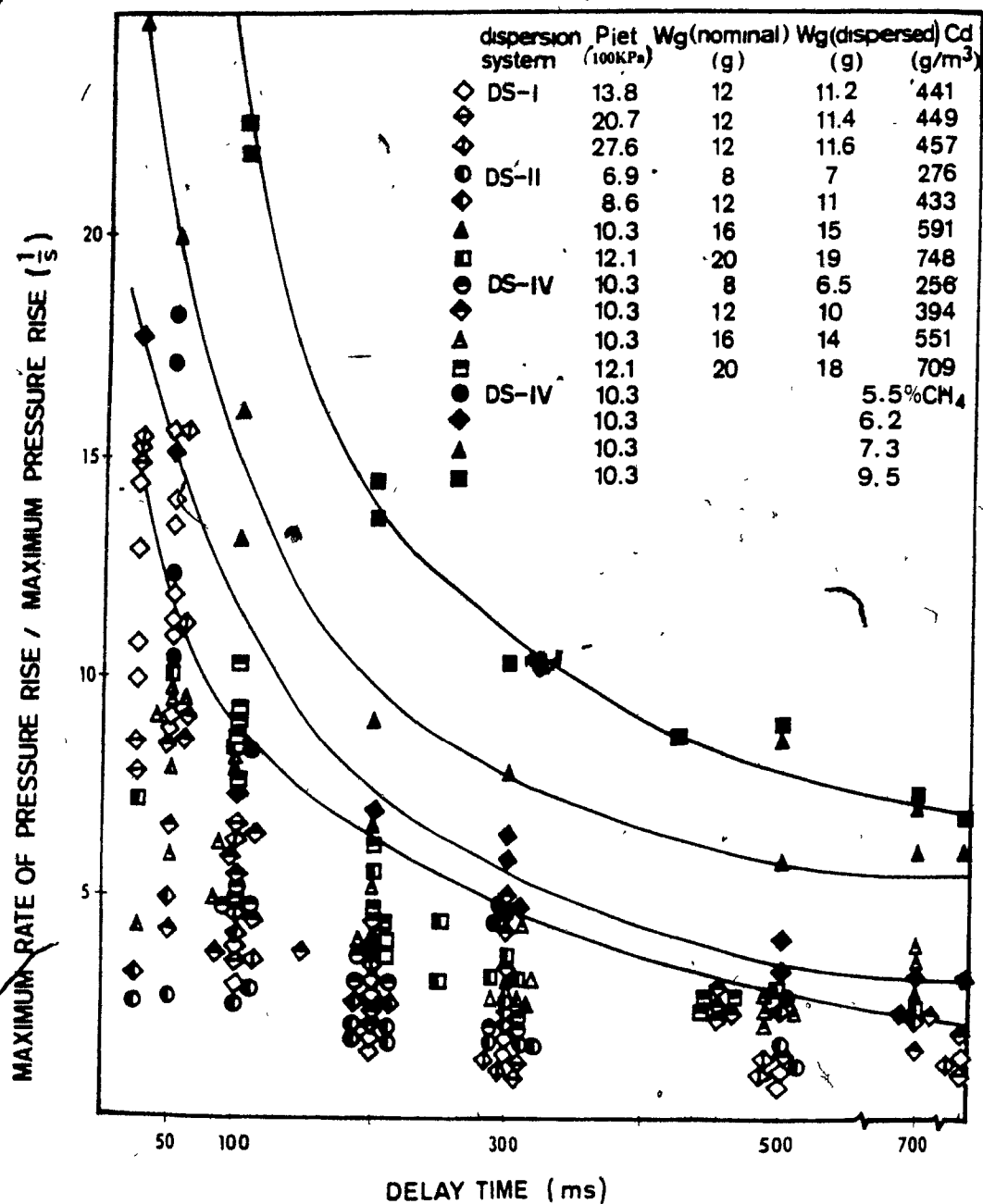
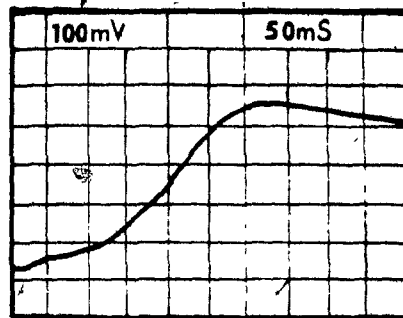
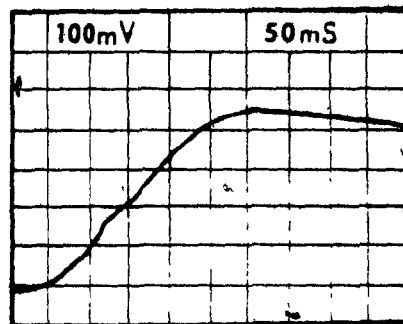


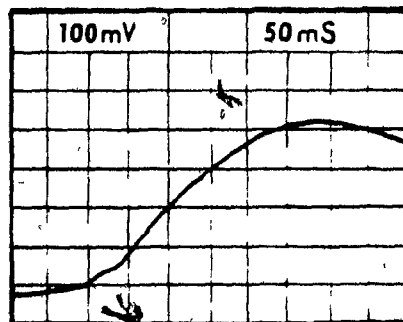
Fig.14. The ratio of maximum rate of pressure rise to the maximum pressure rise as a function of the ignition delay time in a 0.93 meter tube for three selected dispersion systems. (The characteristics of DS -I, II, IV see Fig 10 (b)).



Dispersion system I



Dispersion system II



Dispersion system IV

Fig.15. The pressure history of combustion in a 0.93 meter tube at the ignition delay time of 100 ms for three selected dispersion systems with a nominal concentration of cornstarch dust $C_d = 395 \text{ g/m}^3$.
(The characteristics of DS -I, II, IV see Fig.10(b)).

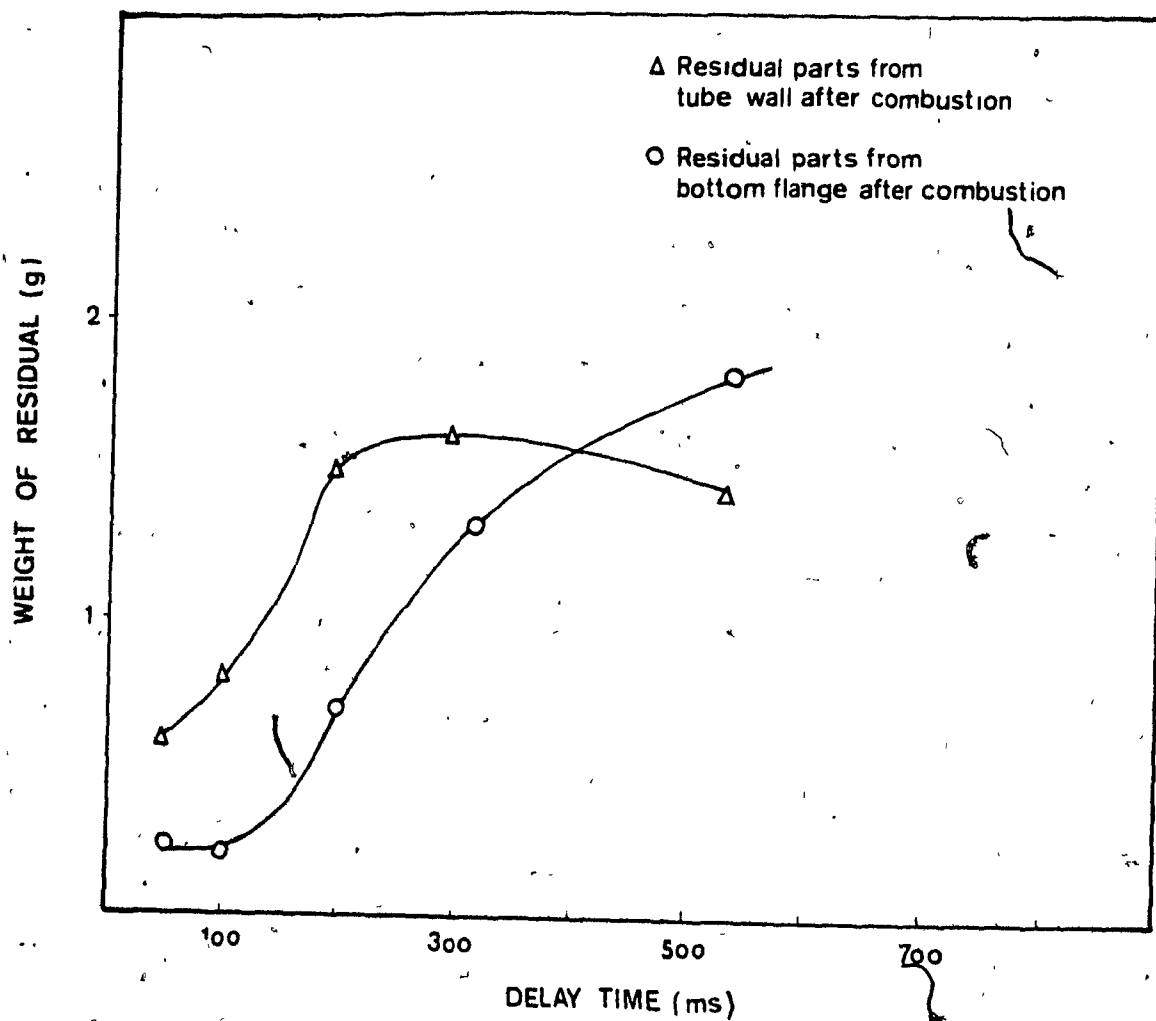


Fig.16. The residual part of dust collected after combustion from the tube wall and the bottom flange as a function of the ignition delay time.

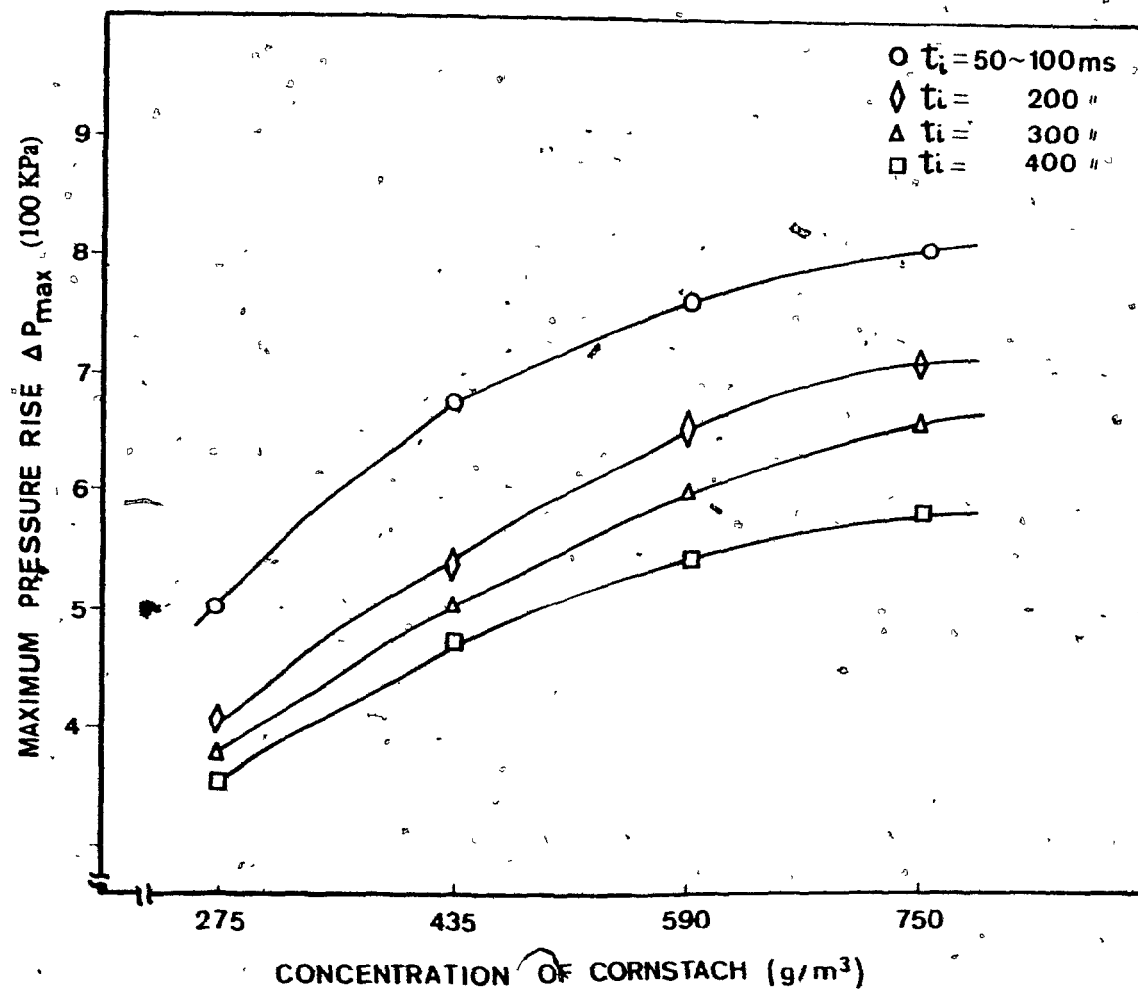
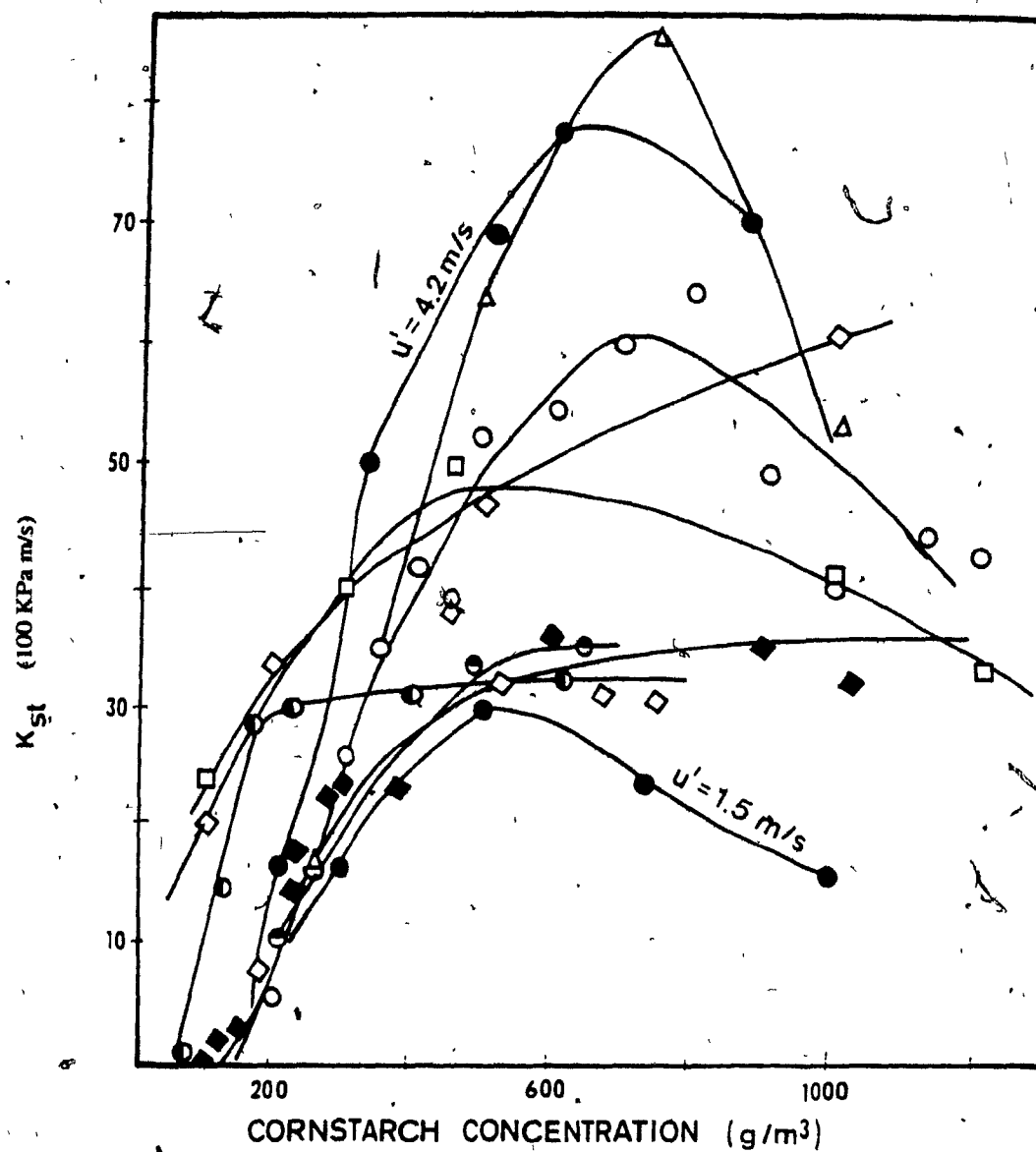
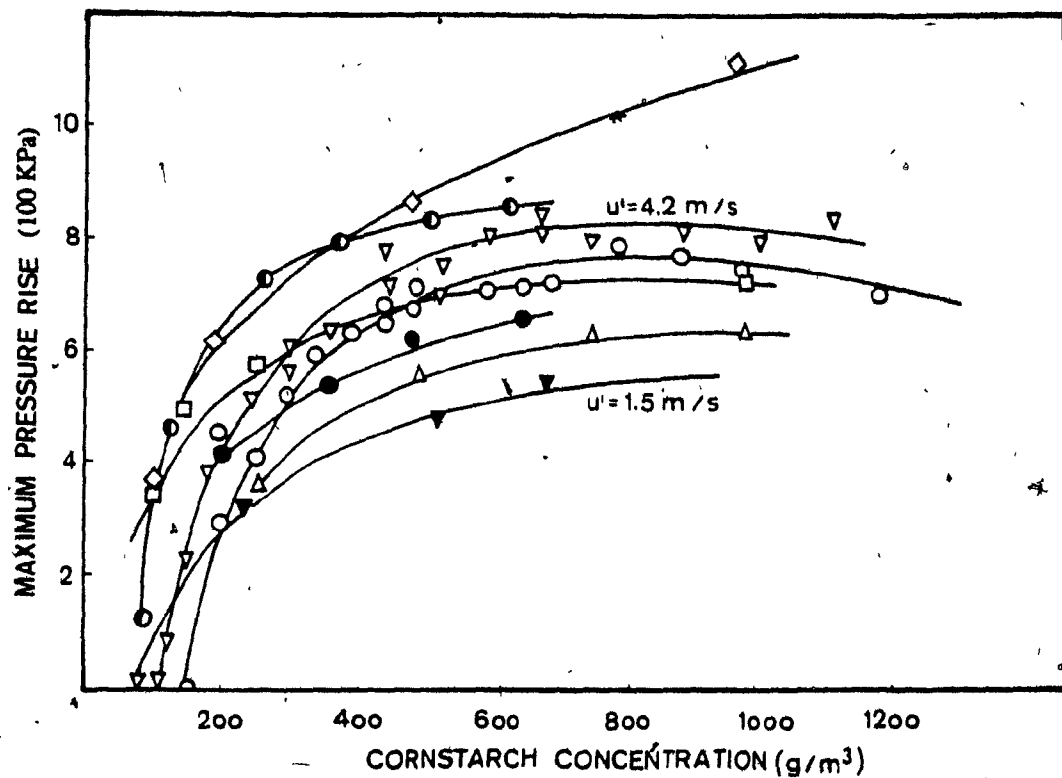


Fig.17. The amount of dust participating in combustion (which is indicated by the maximum pressure rise) as a function of the cornstarch dust concentration for various ignition delay time in a 0.93 meter tube with dispersion system II.



- Present study, $V = 0.025 \text{ m}^3$ (C),
 - ◆ Bond et al. [20], $V = 0.333 \text{ m}^3$ (S),
 - Bond et al. [20], $V = 0.180 \text{ m}^3$ (C),
 - Nagy et al. [9], $V = 0.00123 \text{ m}^3$ (C),
 - Bond et al. [20], $V = 0.18 \text{ m}^3$ (C),
 - △ Cocks et al. [67], $V = 0.02 \text{ m}^3$ (S),
 - ◇ Hartmann et al. [4], $V = 0.00123 \text{ m}^3$ (C),
 - Kauffman et al. [21], $V = 0.95 \text{ m}^3$ (S),
- (C: indicates the cylinder, S: the sphere.)

Fig.18 (a). A comparison of the results obtained for the K_{st} factor in a cornstarch dust -air mixture as a function of the cornstarch concentration.



- Present study $V = 0.025 \text{ m}^3$ (C),
 - ▽ Bond et al. [20], $V = 0.333 \text{ m}^3$ (S),
 - Bond et al. [20], $V = 0.180 \text{ m}^3$ (C),
 - Bond et al. [20], $V = 0.180 \text{ m}^3$ (C),
 - △ Cocks et al. [67], $V = 0.02 \text{ m}^3$ (S),
 - ◇ Hartmann et al. [4], $V = 0.00123 \text{ m}^3$ (C),
 - Nagy et al. [9], $V = 0.00123 \text{ m}^3$ (C),
 - ▼ Kauffman et al. [21], $V = 0.95 \text{ m}^3$ (S),
- (C : indicates the cylinder, S : the sphere.)

Fig.18 (b). A comparison of the results for the maximum pressure rise in a cornstarch dust-air mixture as a function of the cornstarch concentration.

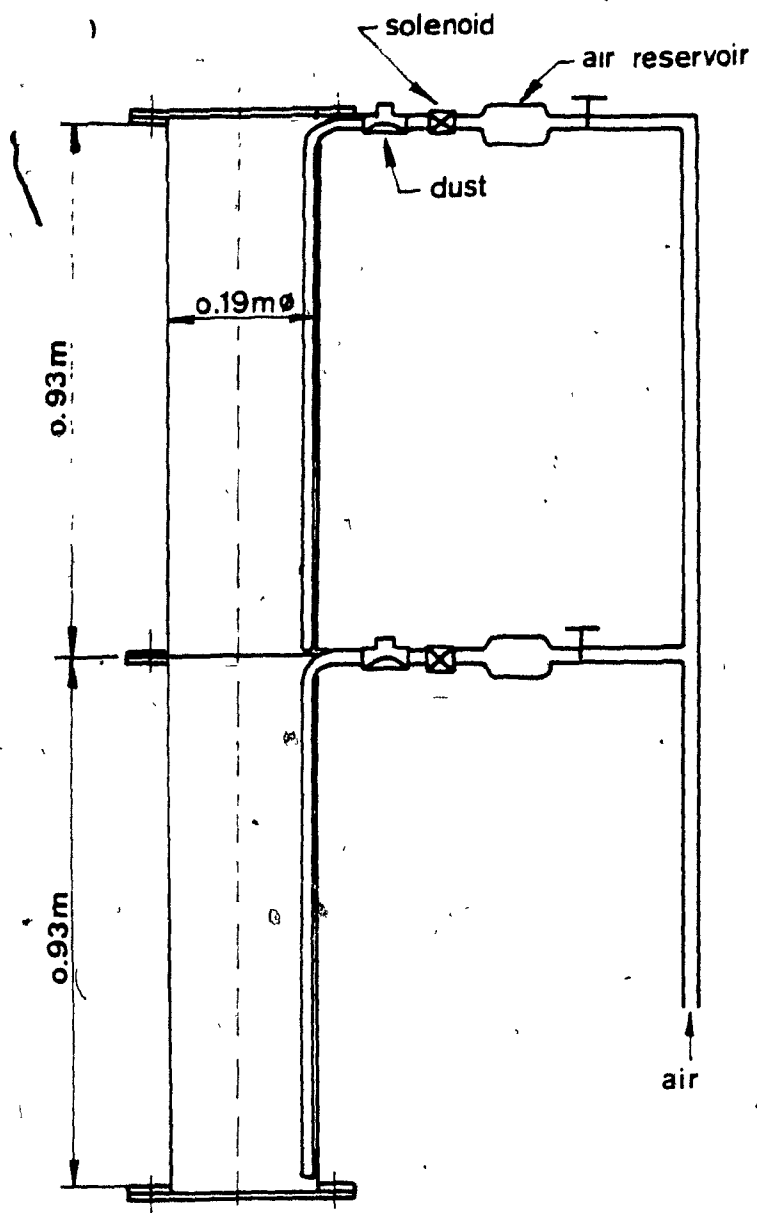


Fig. 19. Present test tube for studying dust flame propagation.

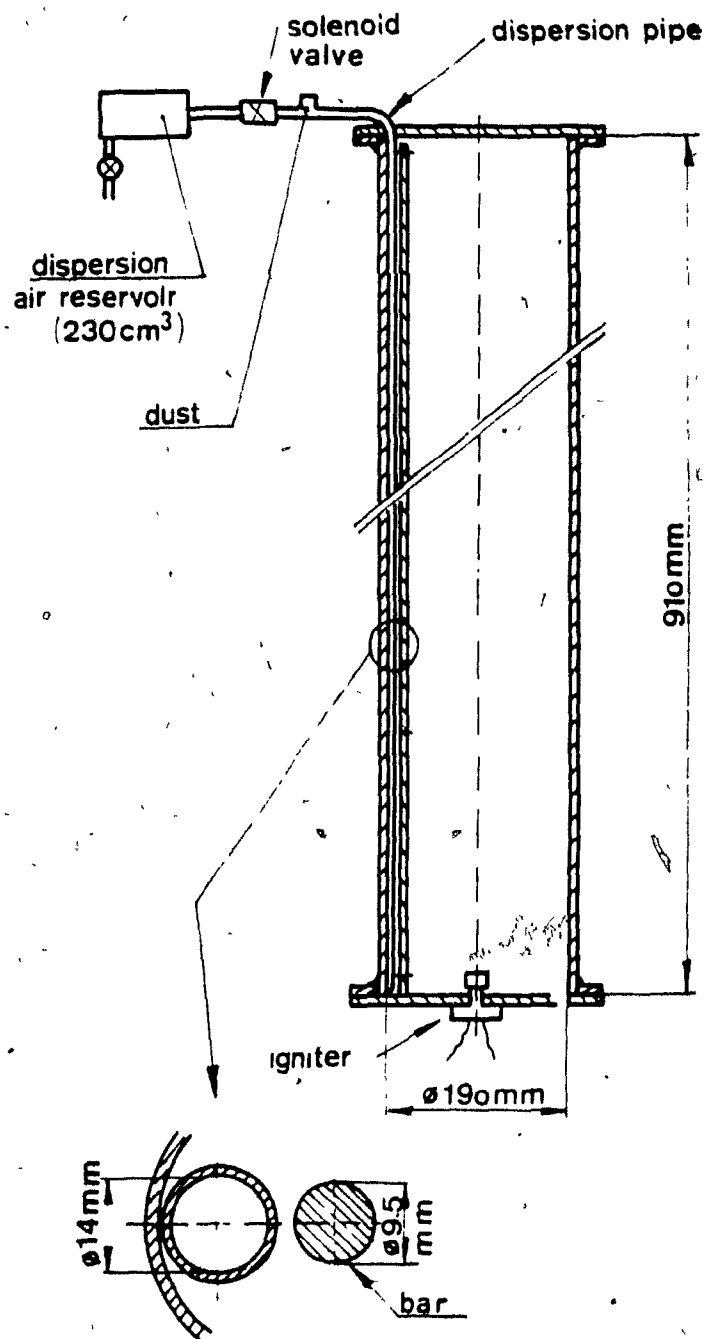


Fig.20. Schematic diagram of present experimental apparatus.

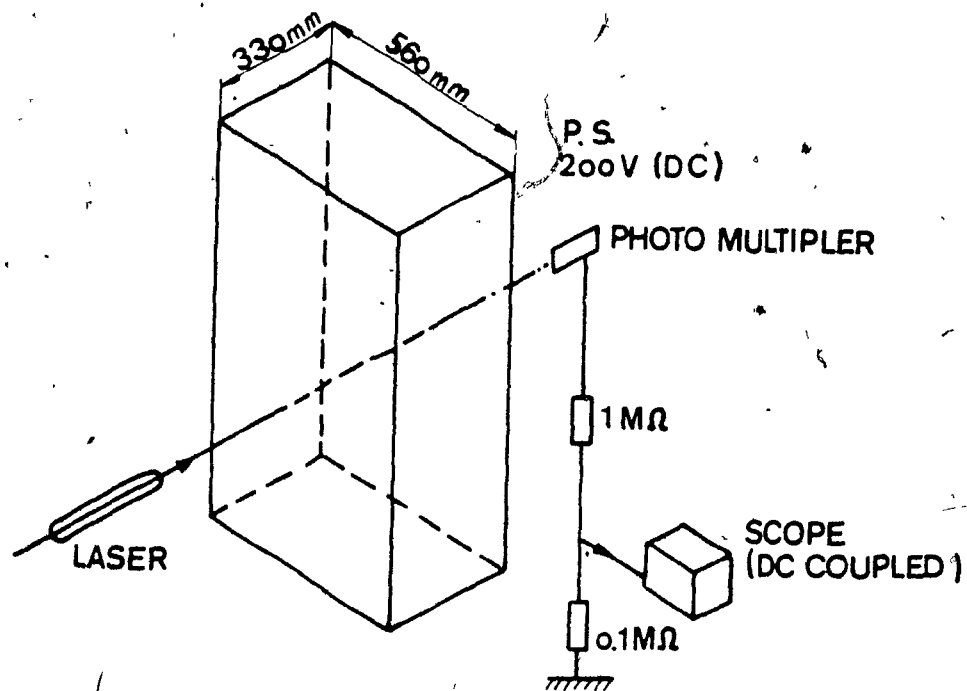


Fig.21(a). Optical arrangement of light transmission measurement for testing dust dispersion

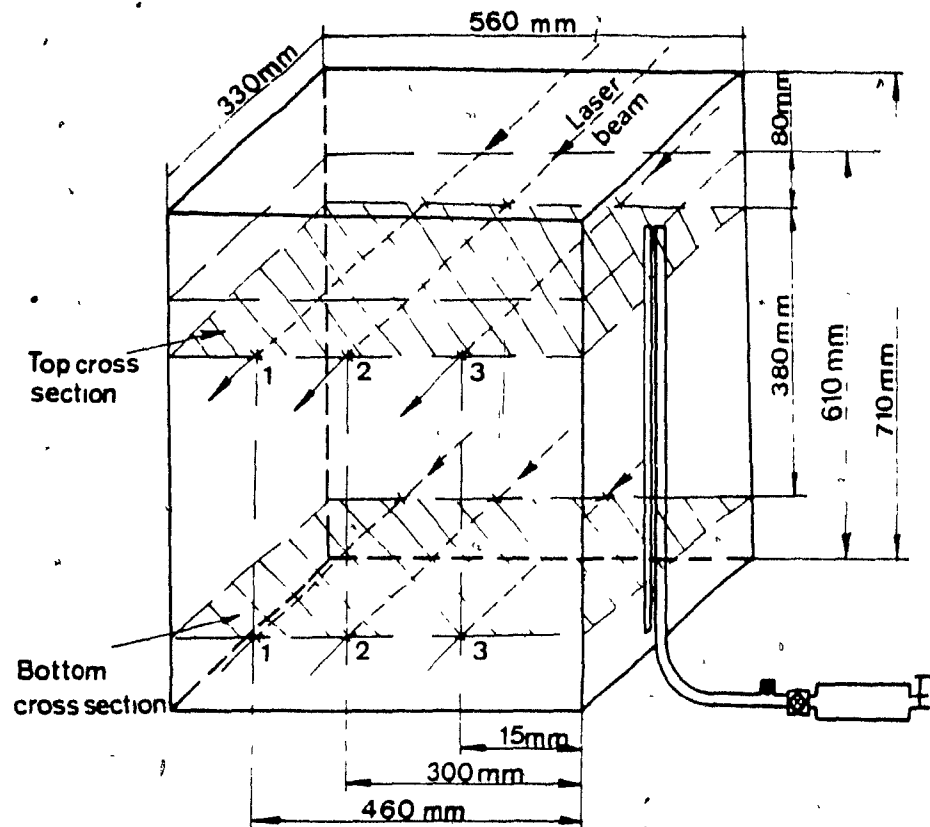


Fig.21(b). Dust dispersion box.

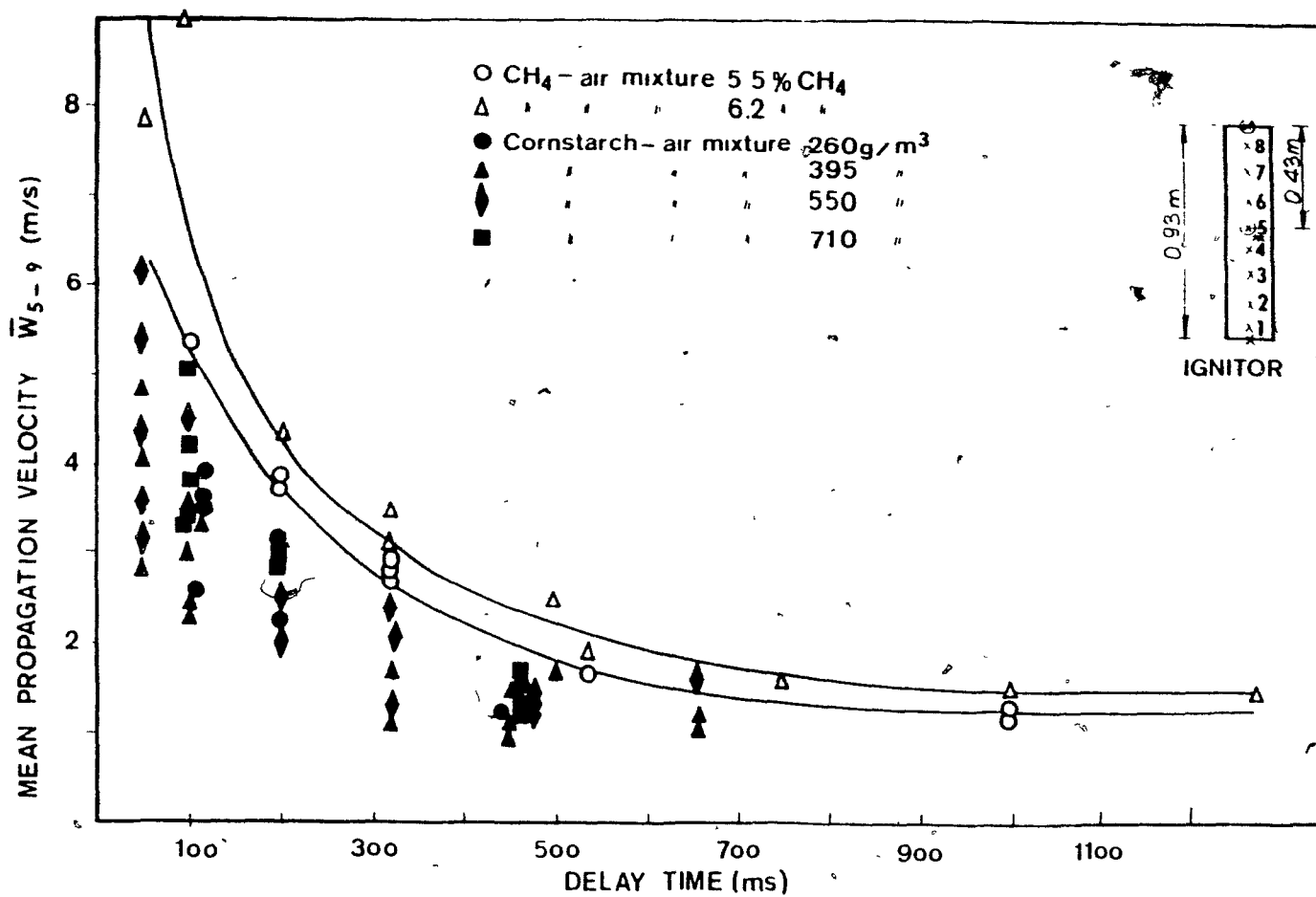


Fig.22 (a). The mean propagation velocity of the flame front in the second stage of propagation through a 0.93 meter closed tube as a function of the ignition delay time for gas and dust flames.

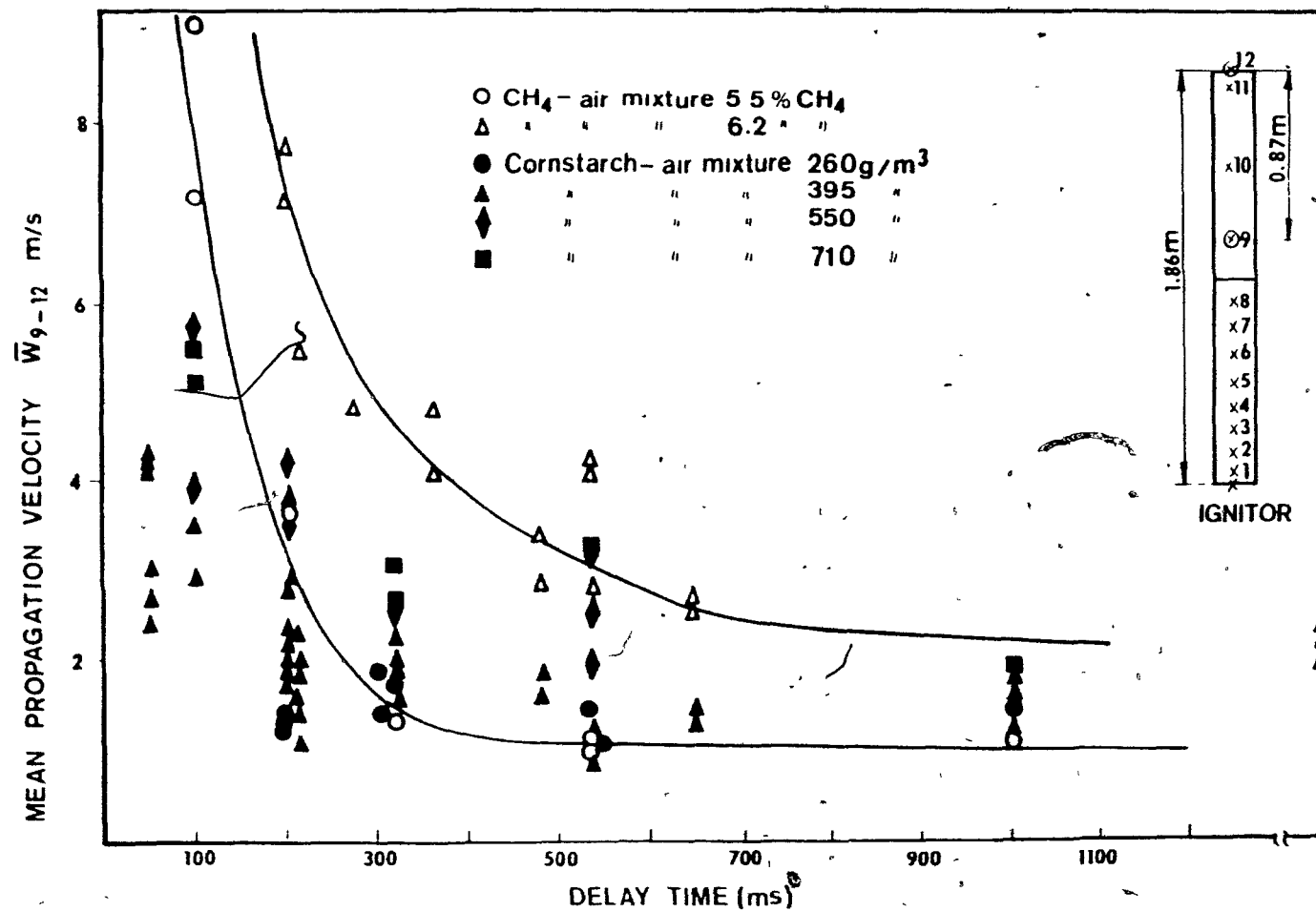


Fig.22(b). The mean propagation velocity of the flame front in the second stage of propagation through a 1.86 meter closed tube as a function of the ignition delay time for gas and dust flames.

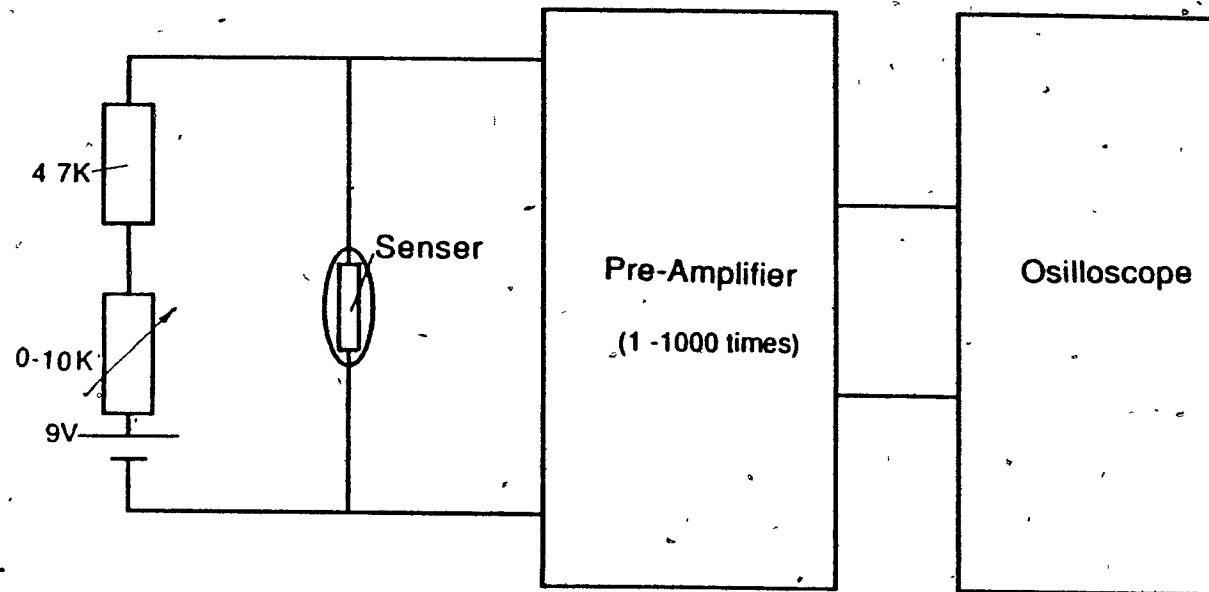


Fig.23 (a). The foil resistance thermometer set for measuring the surface temperature rise of the wall of the test tube during the combustion process.

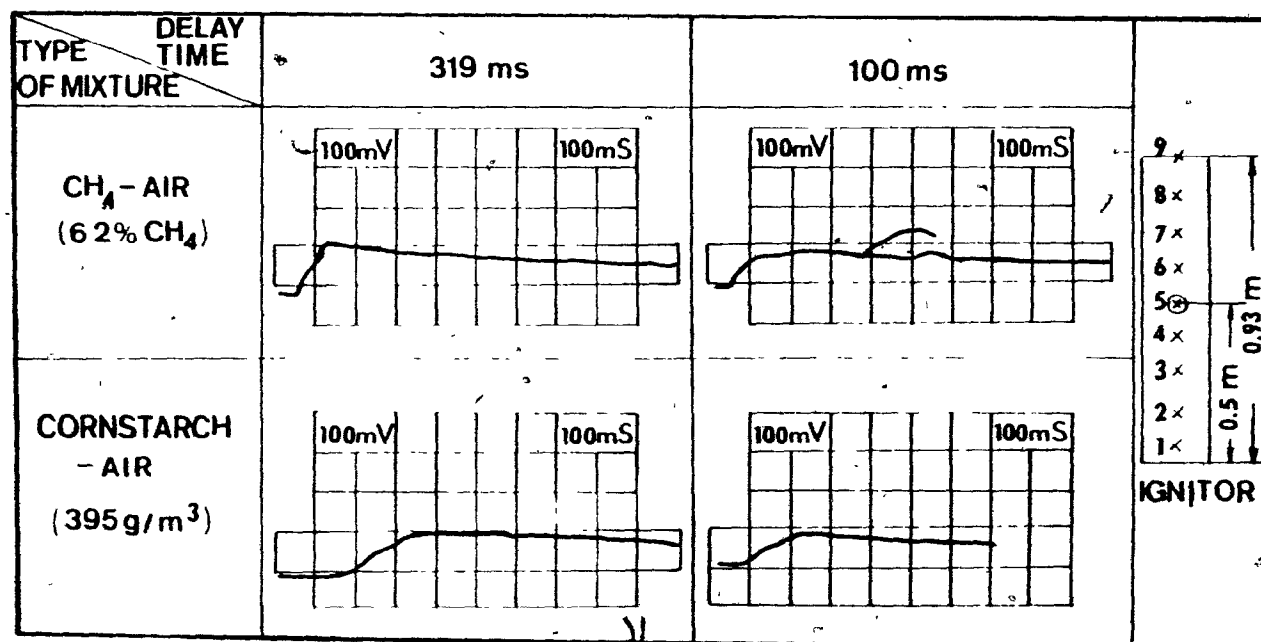


Fig.23(b). The surface temperature rise of the wall of the test tube measured at 0.5 meter from the ignition as a function of time in a 0.93 meter tube.

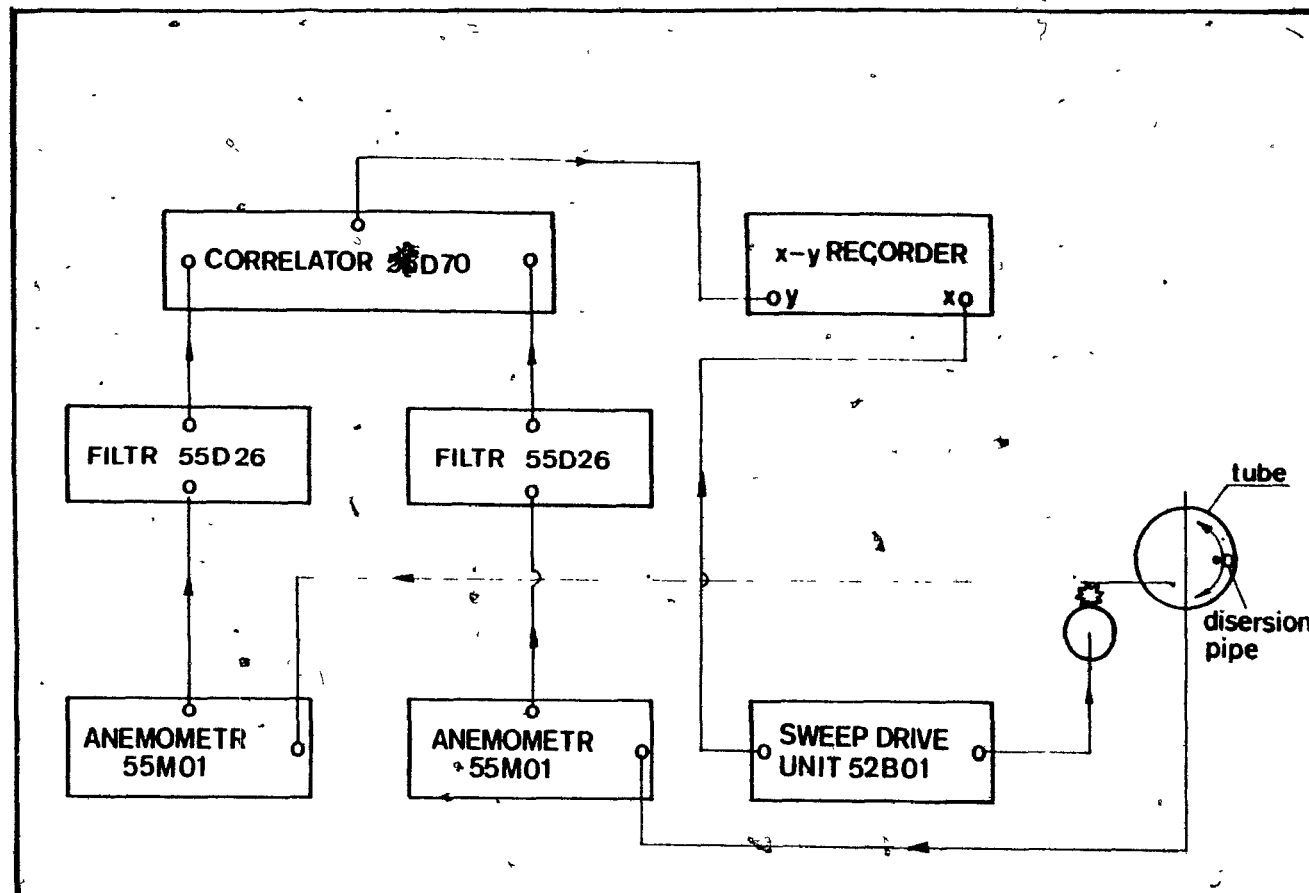


Fig.24. The DISA thermoanemometer set for measuring the mean velocity and rms turbulent velocity produced by the dispersion system.

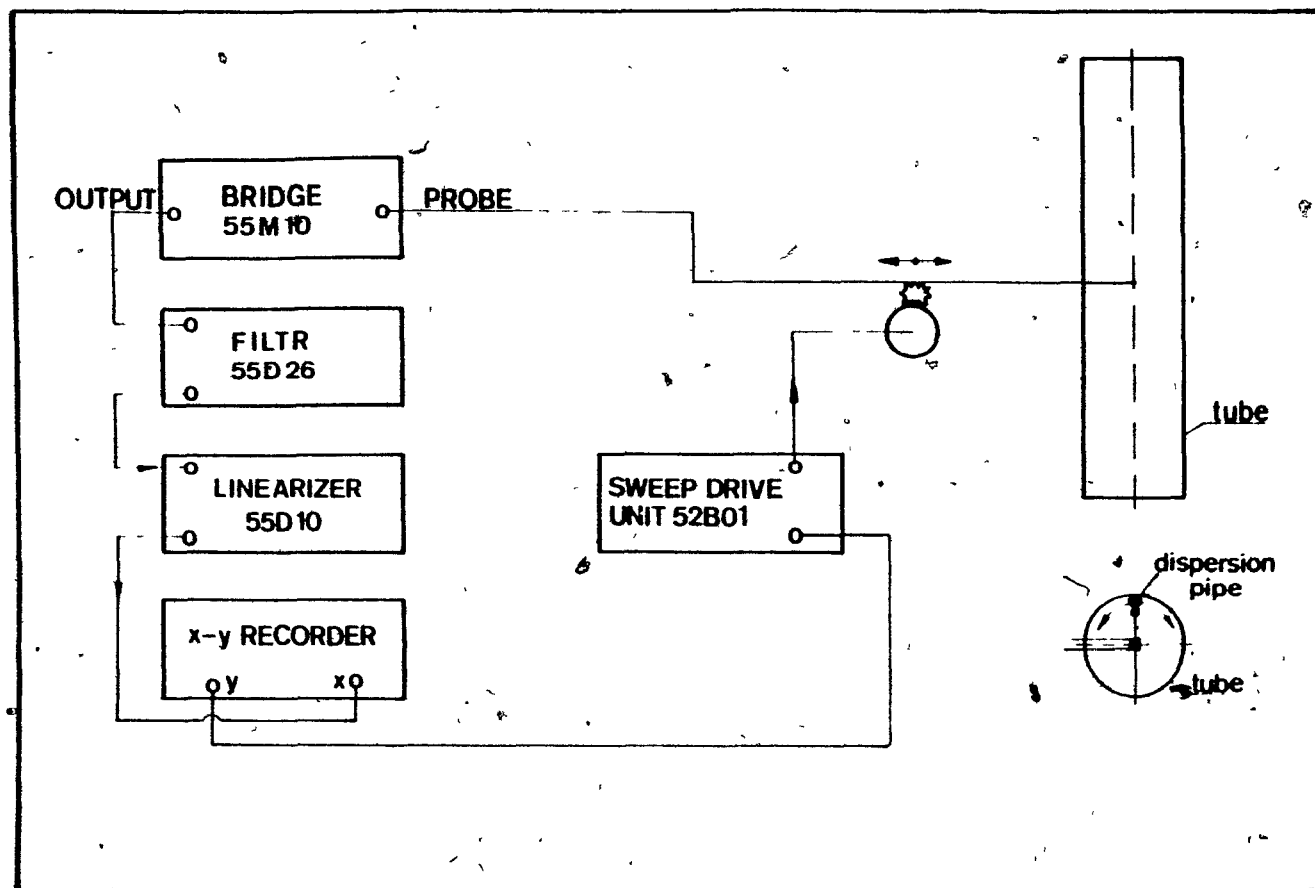


Fig.25(a). The DISA thermoanemometer set for measuring the integral scale of turbulence.

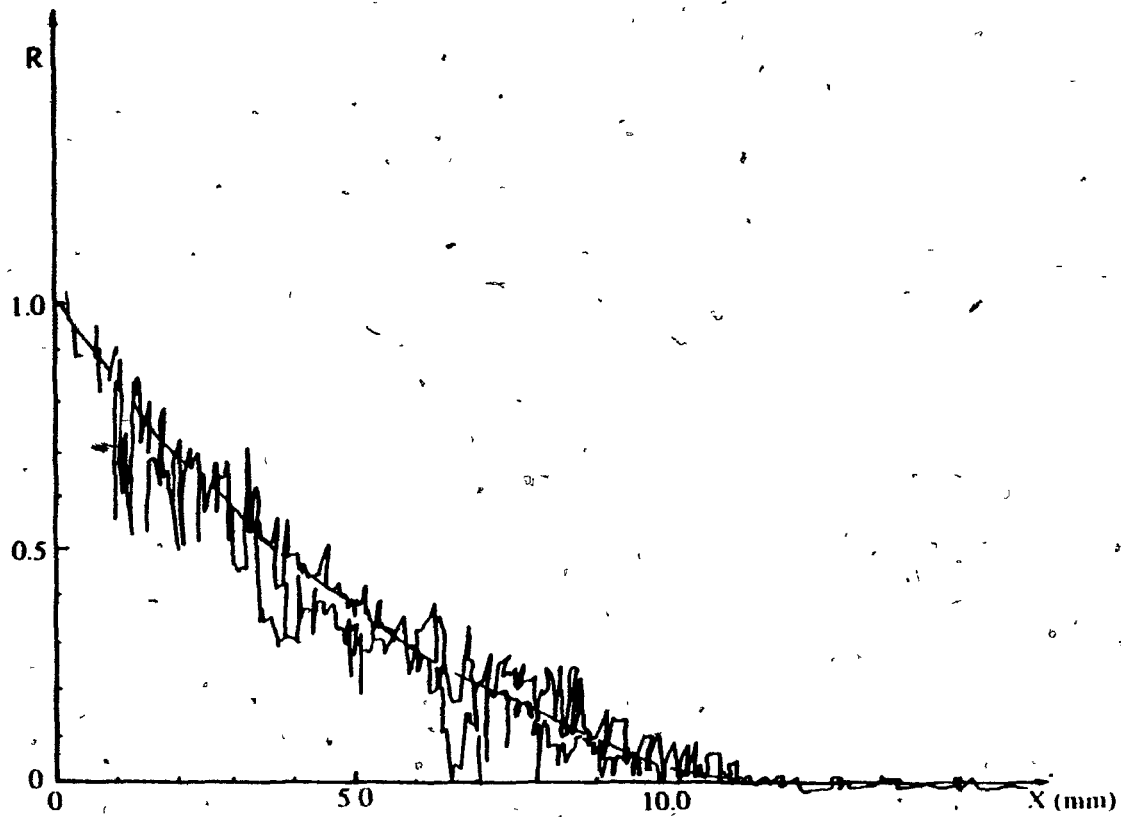


Fig.25(b). The correlation function versus time for calculation of integral scale of turbulence measured at the point A in one selected cross-section of the test tube.

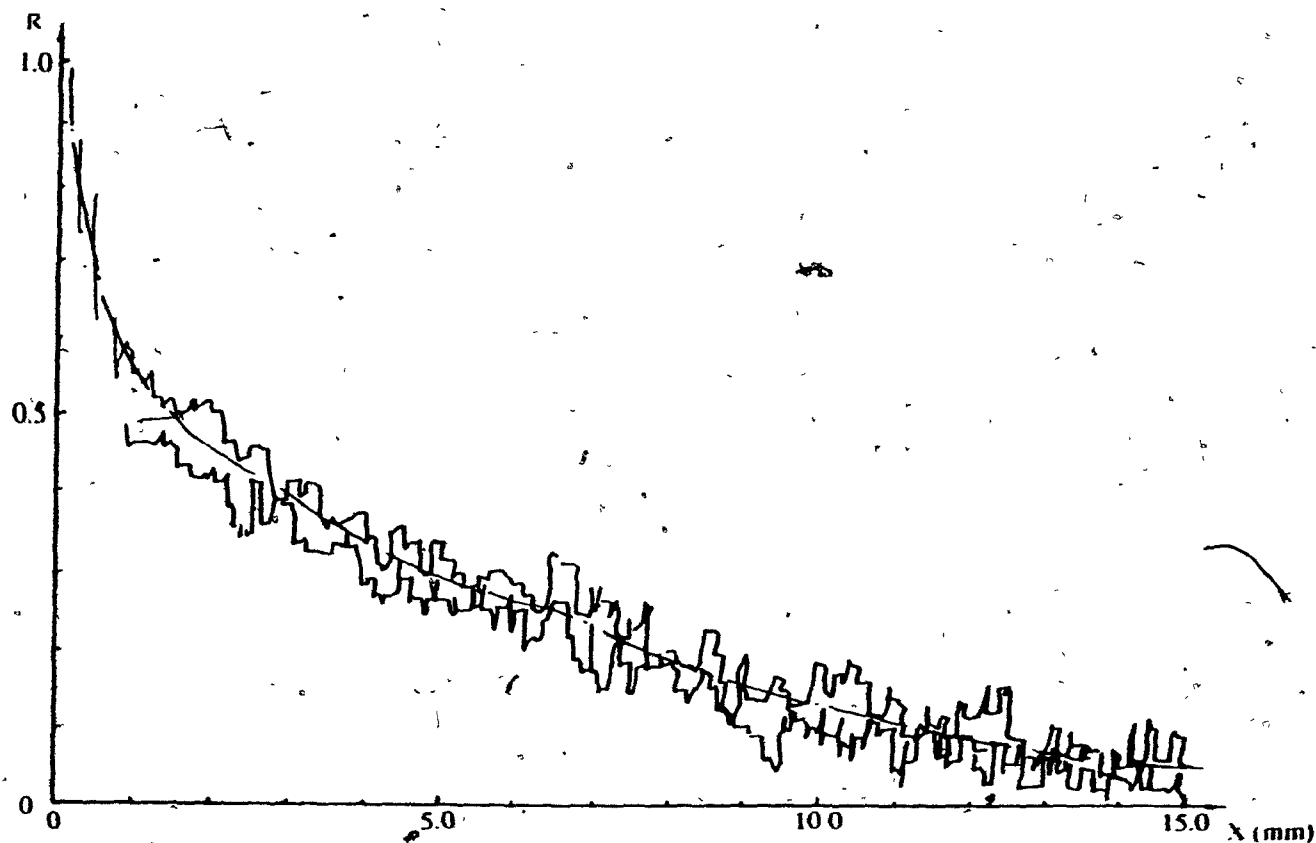


Fig.25(c). The correlation function versus time for calculation of integral scale of turbulence measured at the point B in one selected cross-section of the test tube.

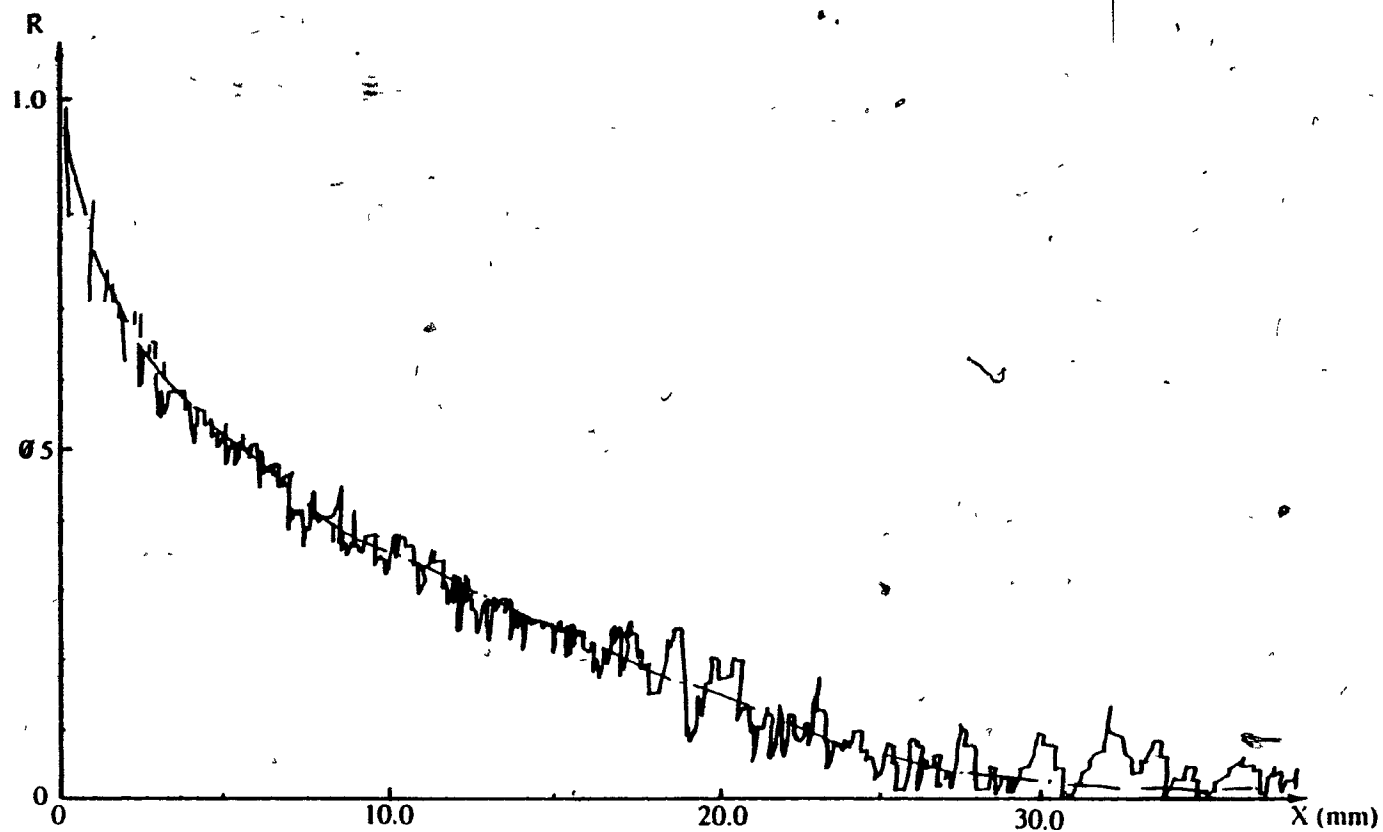


Fig.25(d). The correlation function versus time for calculation of integral scale of turbulence measured at the point C in one selected cross-section of the test tube.

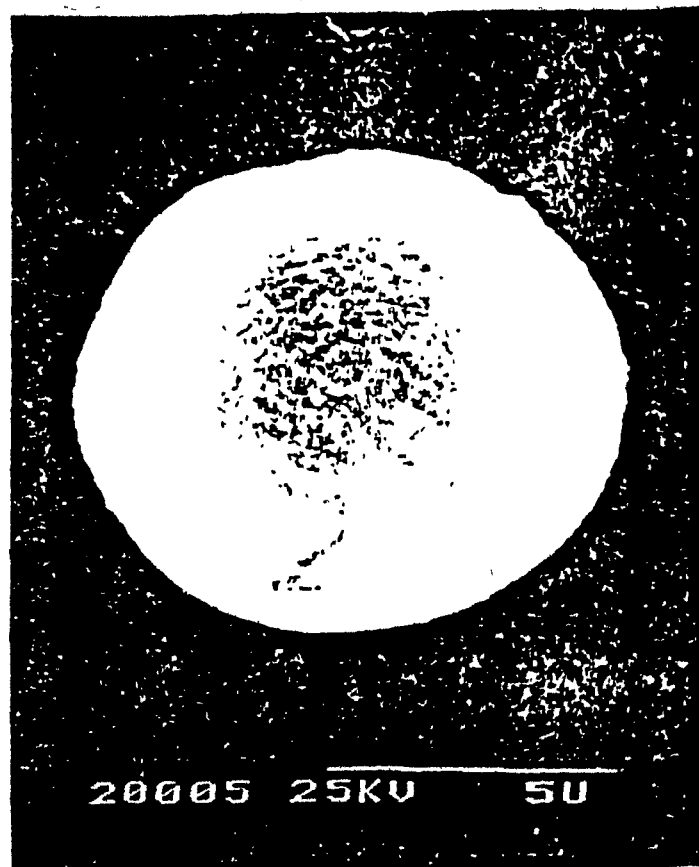


Fig.26. S.E.M. photograph of cornstarch particle.

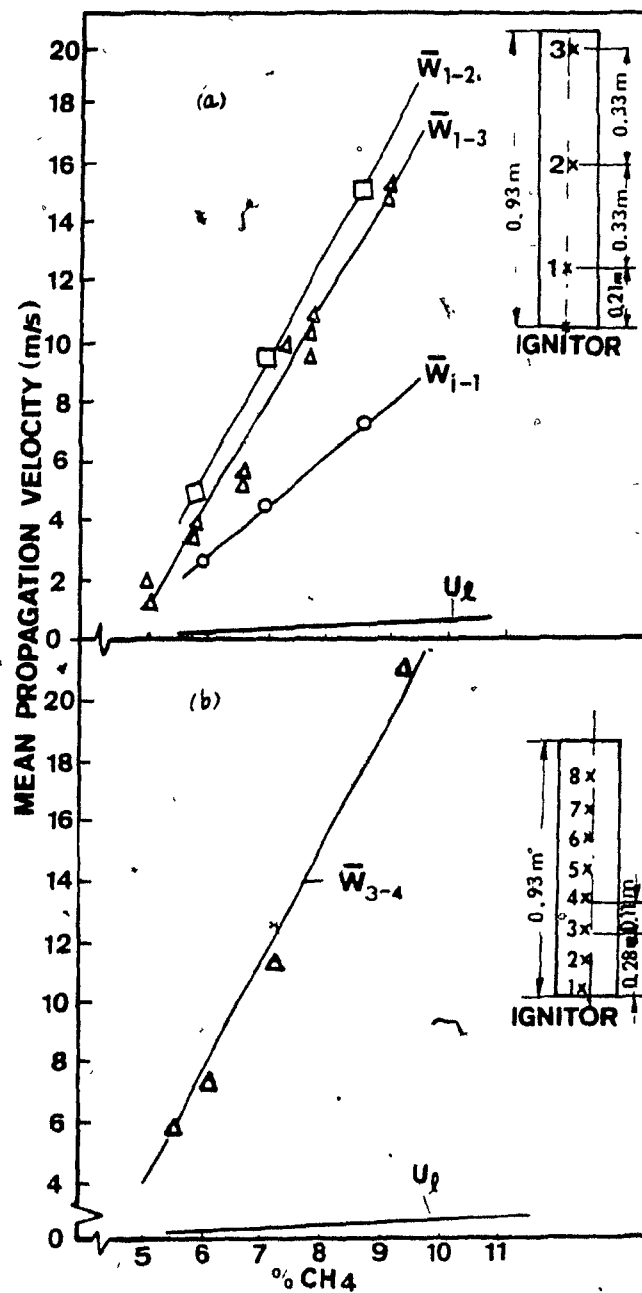


Fig.27. The mean propagation velocity of the flame front in a 0.93 meter closed tube as a function of the mixture composition.

(a). quiescent premixed mixture,

(b). under dispersion-induced turbulence influence at the ignition delay time of 500 ms

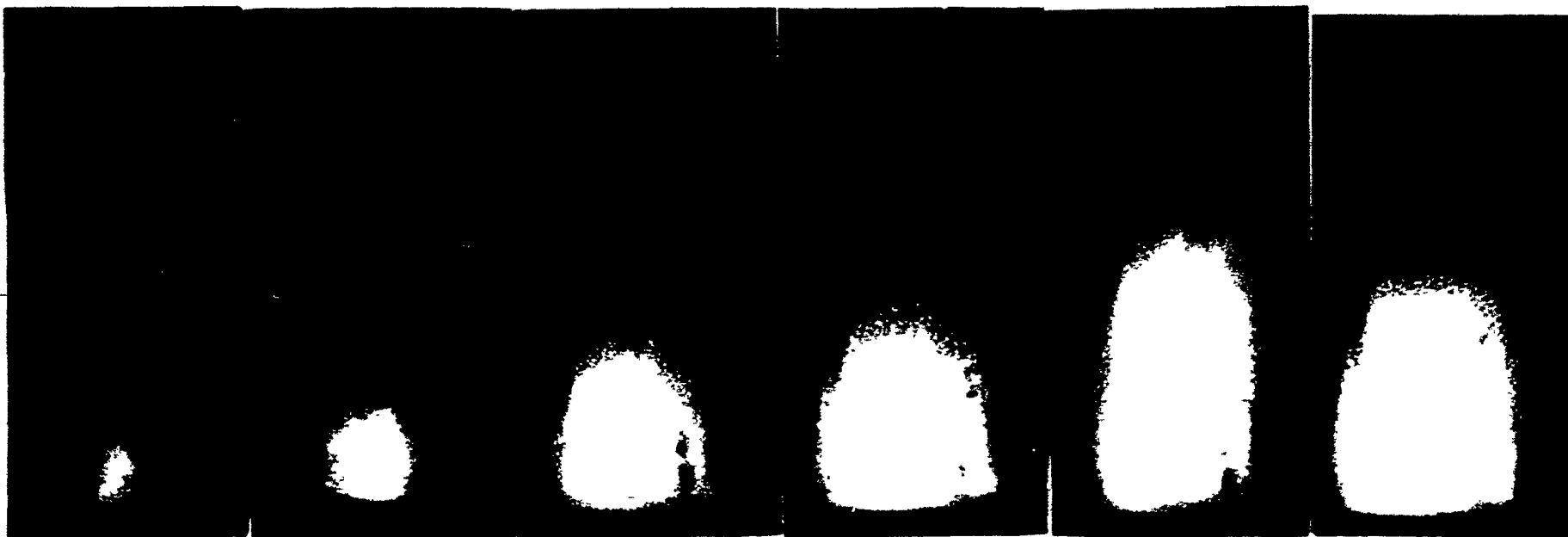


Fig.28. A sequence of flames extracted from a high-speed movie of cornstarch dust-air flame propagating from a closed end of an open rectangular duct (178mm x 178mm x 1000mm). Ignitor with 0.6 grams black powder, 30 ms time interval between frames with initial frame 20 ms after ignition. Ignition delay time = 430 ms, Cornstarch dust concentration = 560 g/m³.

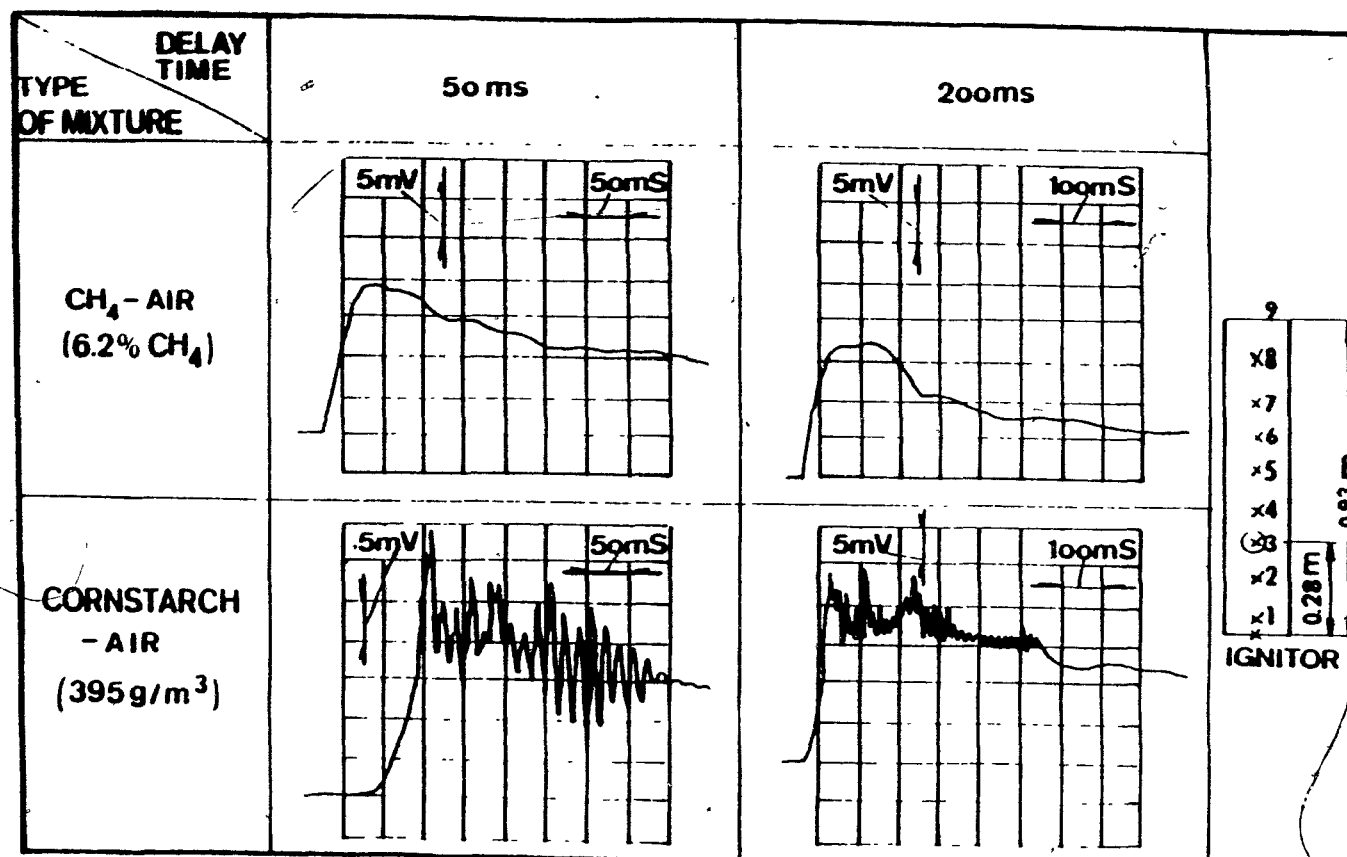


Fig.29. Typical temperature profiles of flames measured at 0.28 meter from the ignitor in a 0.93 meter closed tube.

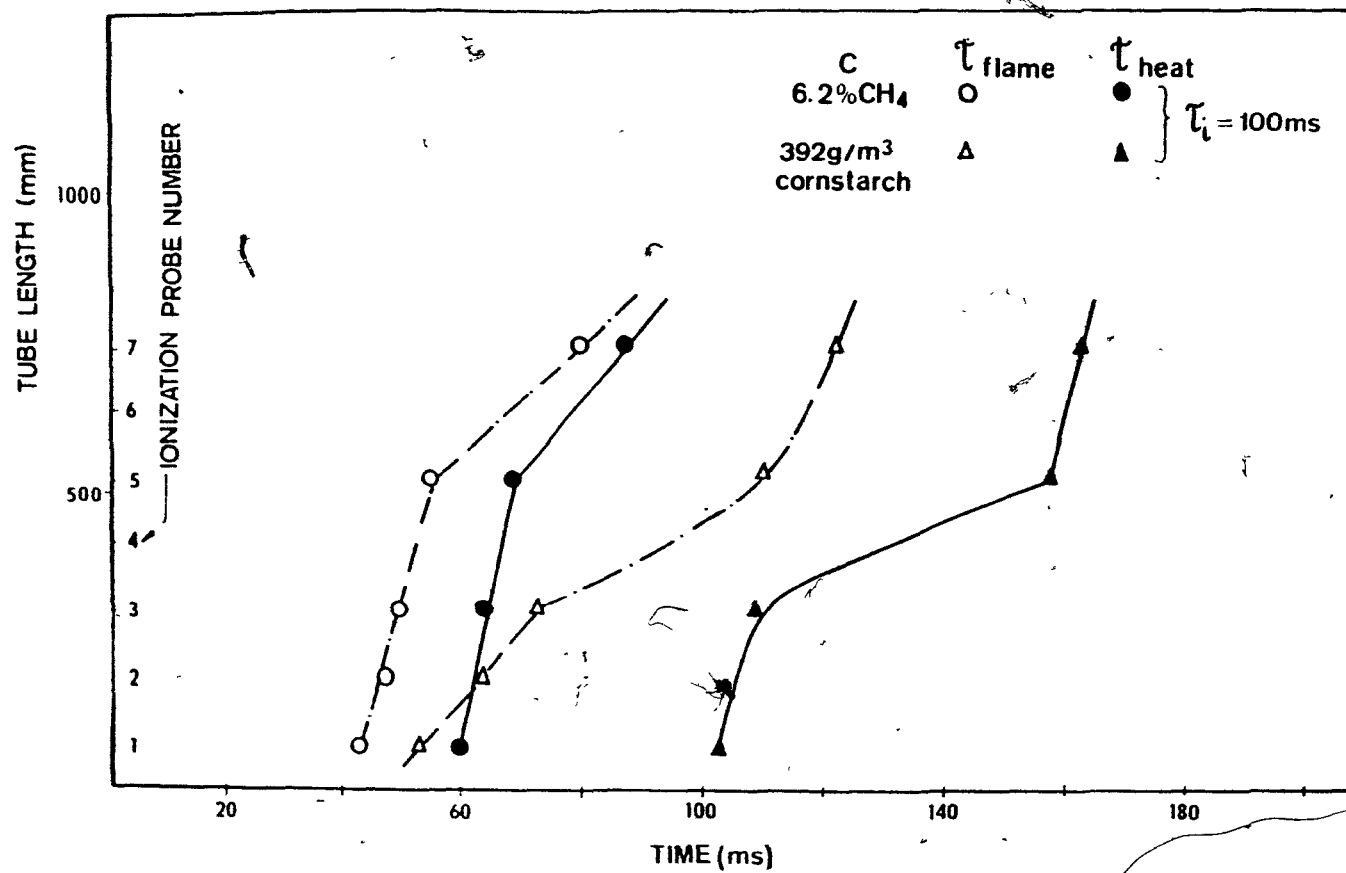


Fig.30(a). The locations of the flame front and the surface temperature rise of the wall of the test tube in a 0.93 meter closed tube as functions of time at the ignition delay time of 100 ms.

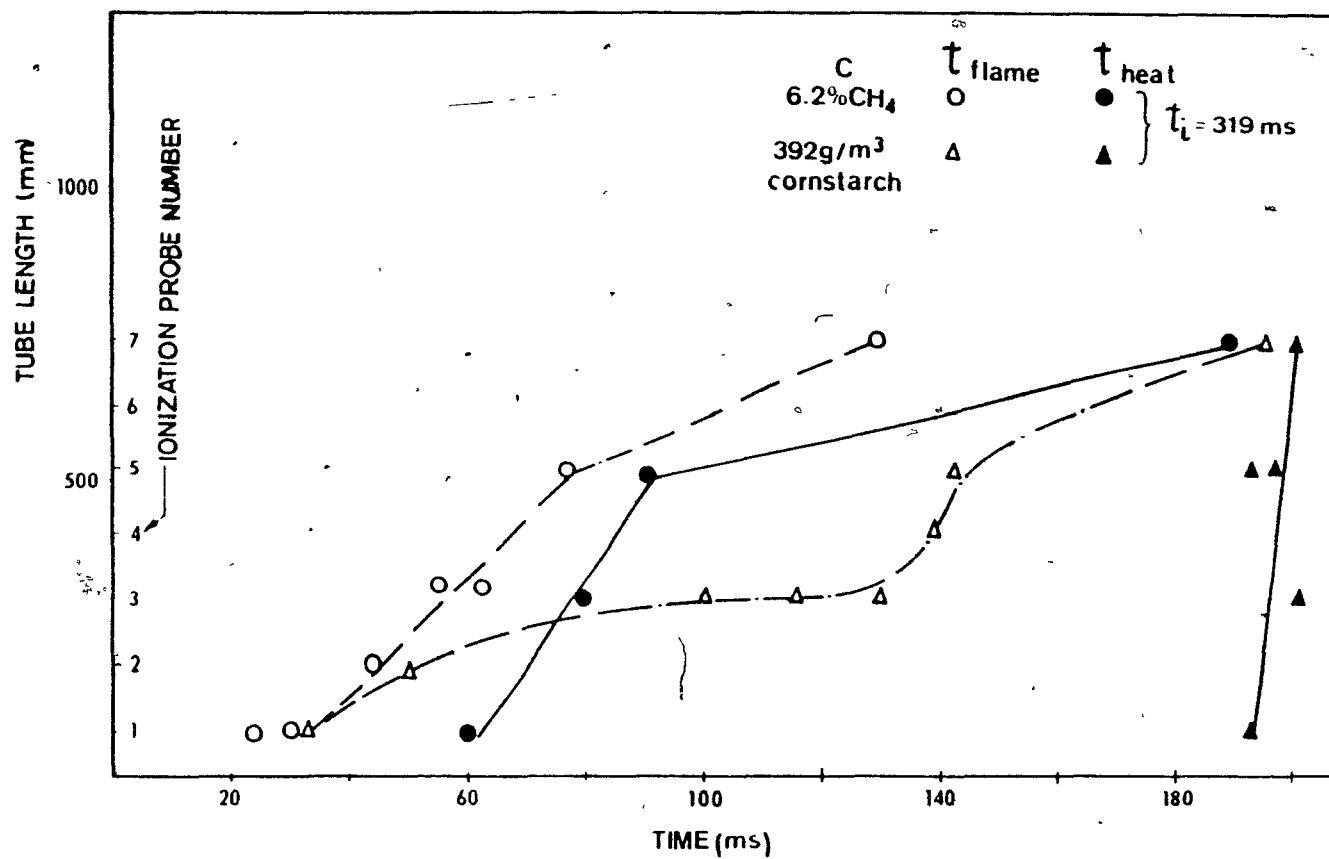


Fig.30(b). The locations of the flame front and the surface temperature rise of the wall of the test tube in a 0.93 meter closed tube as functions of time at the ignition delay time of 319 ms.

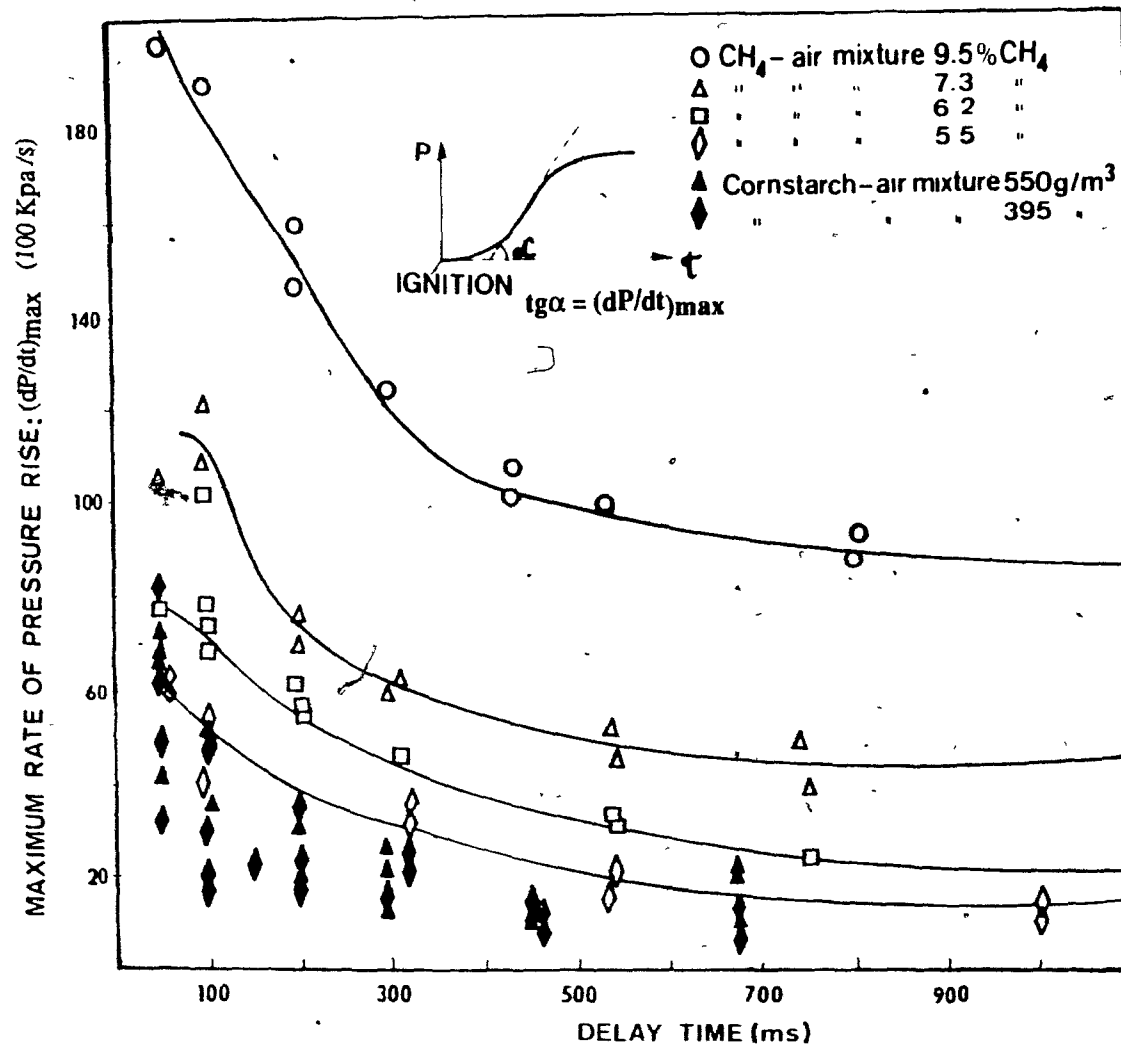


Fig.31(a). The maximum rate of pressure rise for gas and dust combustion as a function of the ignition delay time in a 0.93 meter closed tube.

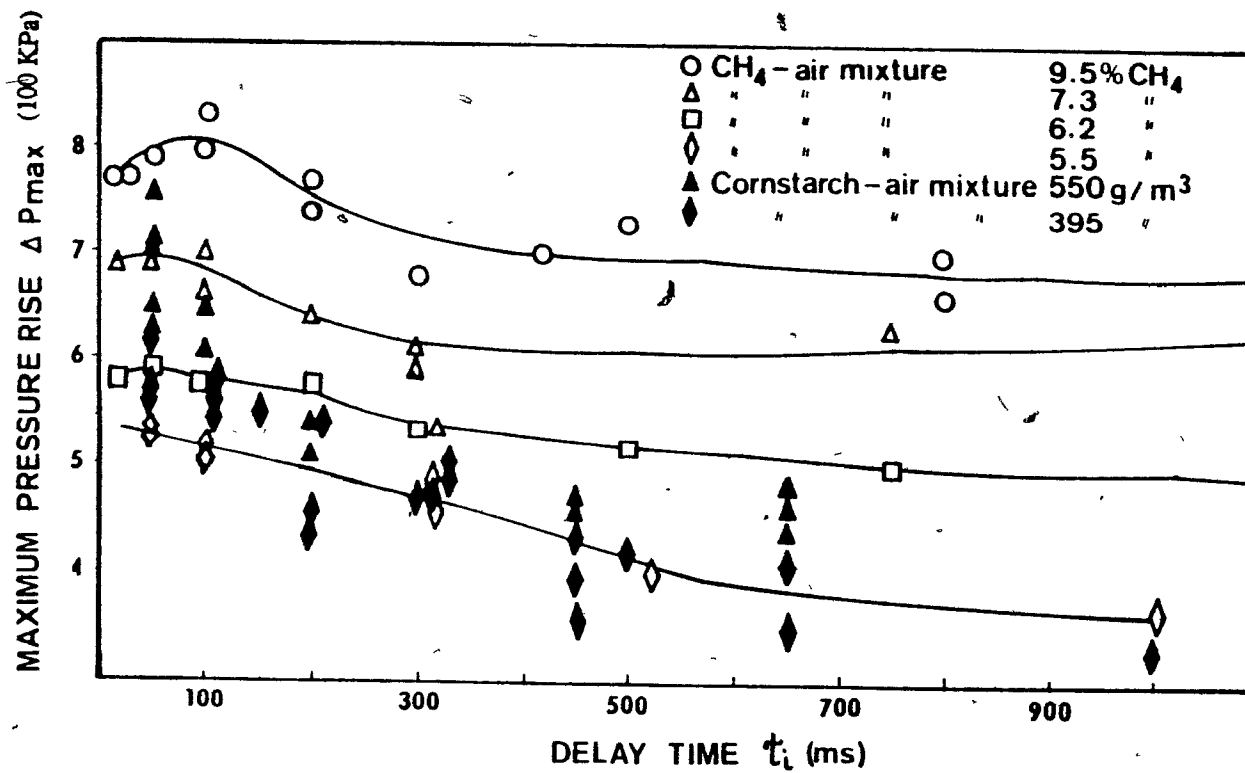


Fig.31(b). The maximum pressure rise of gas and dust combustion as a function of the ignition delay time in a 0.93 meter closed tube.

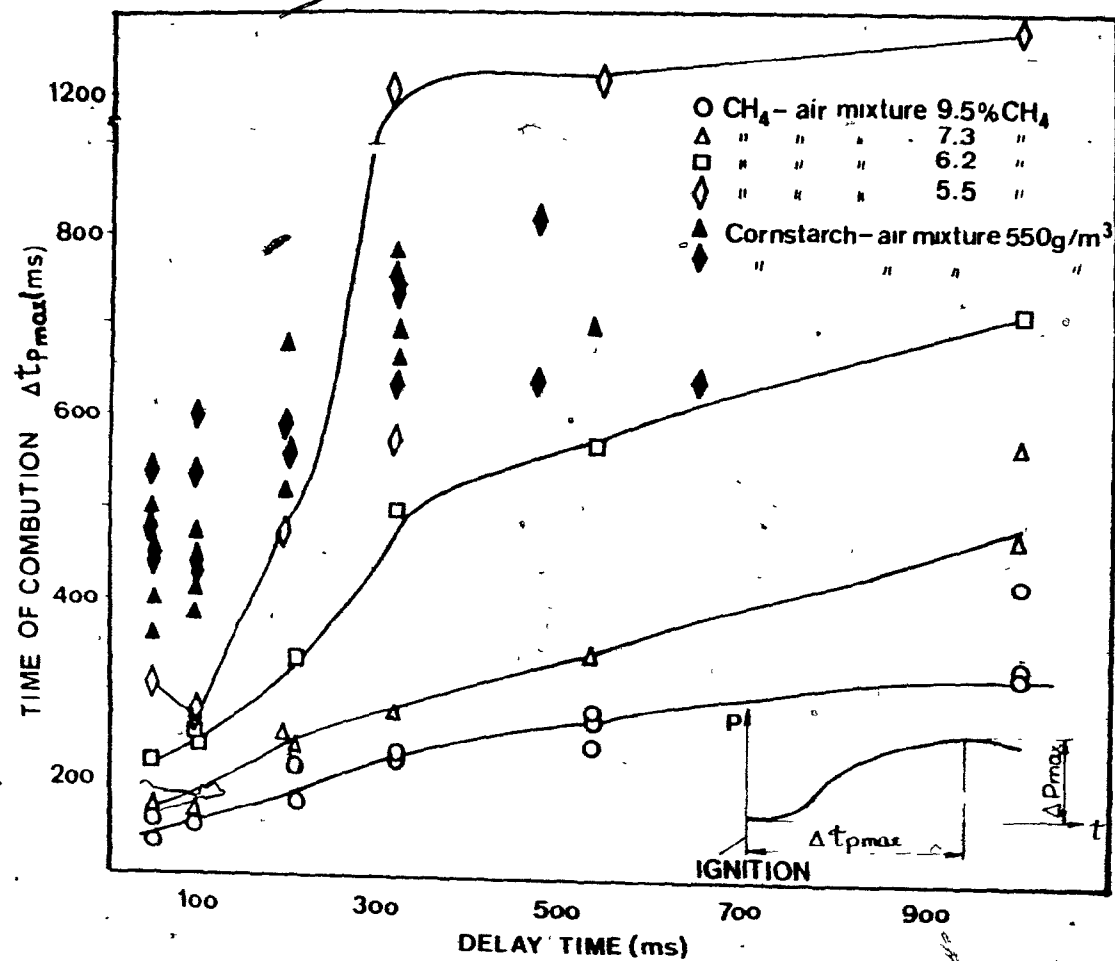


Fig.31(c). The time of combustion of gas and dust mixtures as a function of the ignition delay time in a 0.93 meter closed tube.

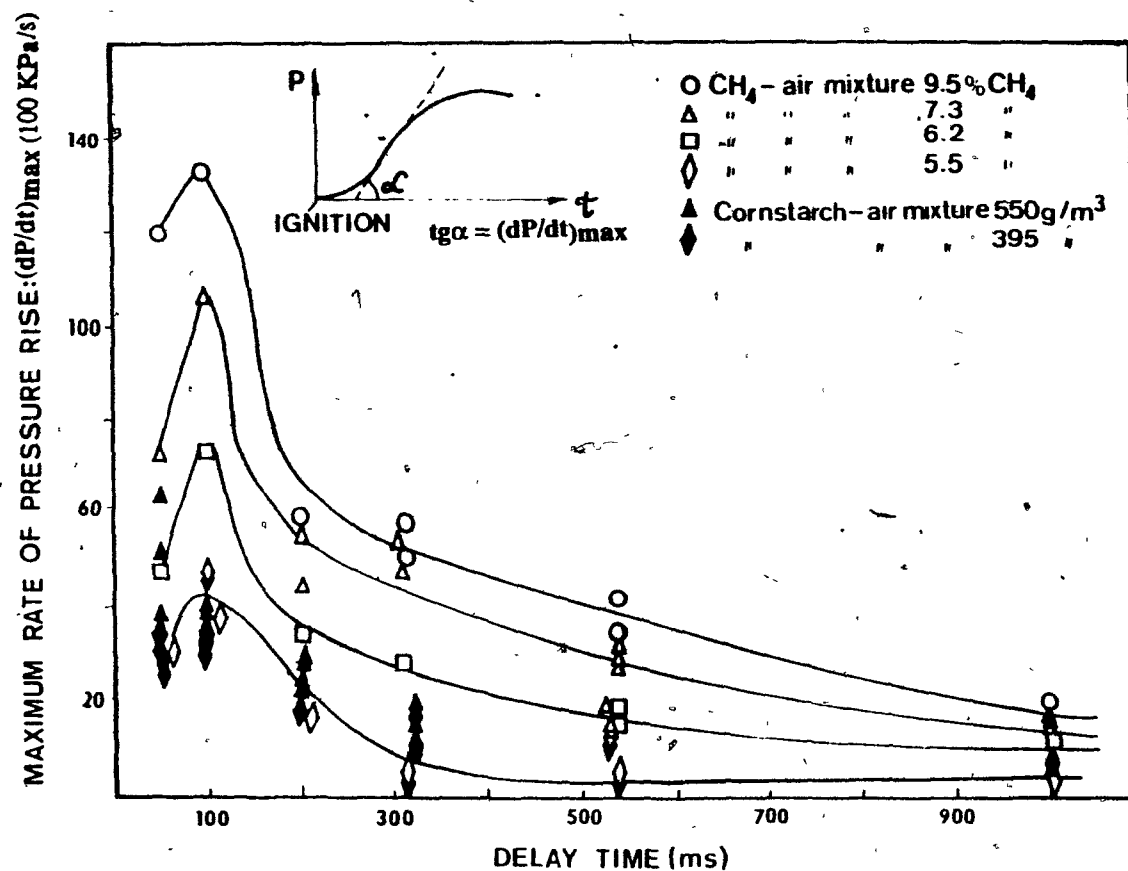


Fig.32 (a). The maximum rate of pressure rise for gas and dust combustion as a function of the ignition delay time in a 1.86 meter tube.

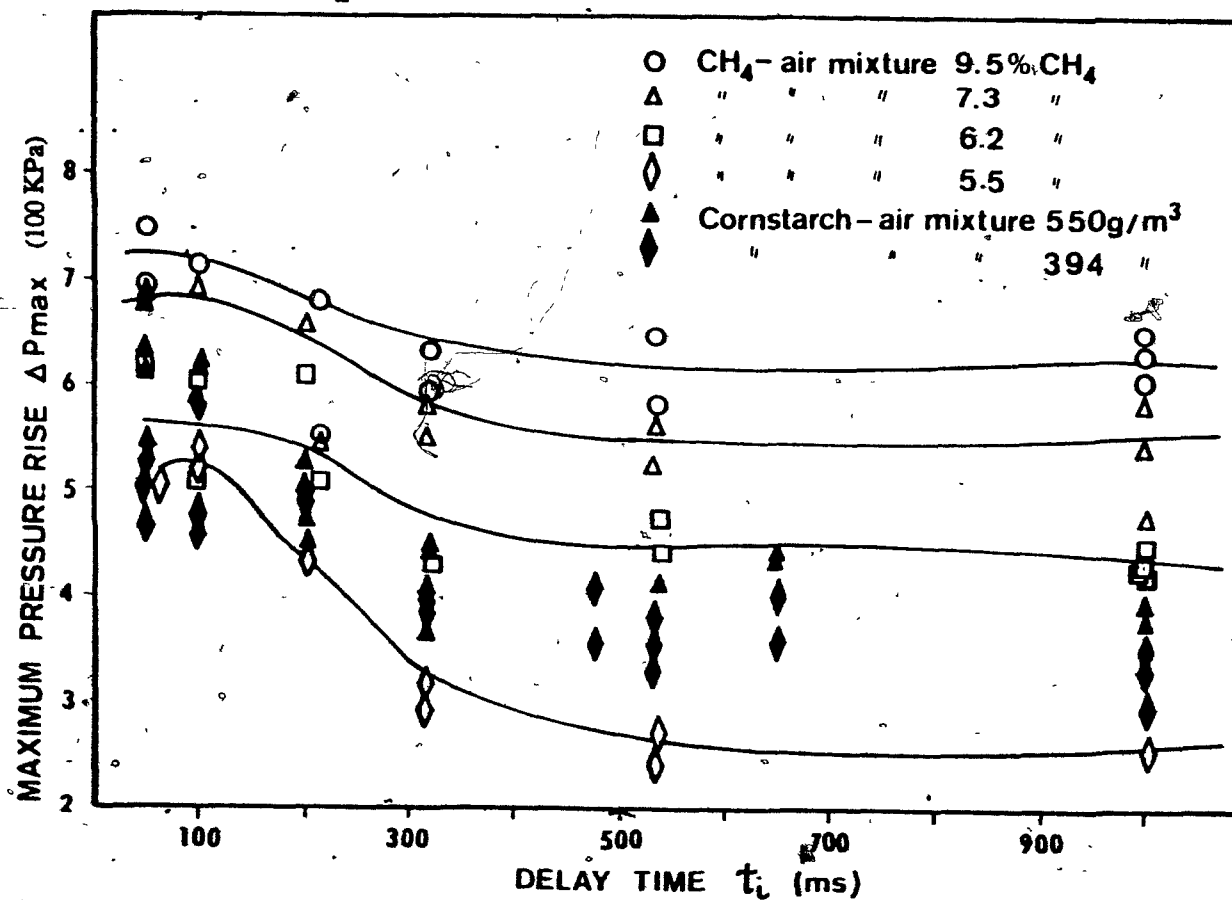


Fig.32(b). The maximum pressure rise of gas and dust combustion as a function of the ignition delay time in a 1.86 meter tube.

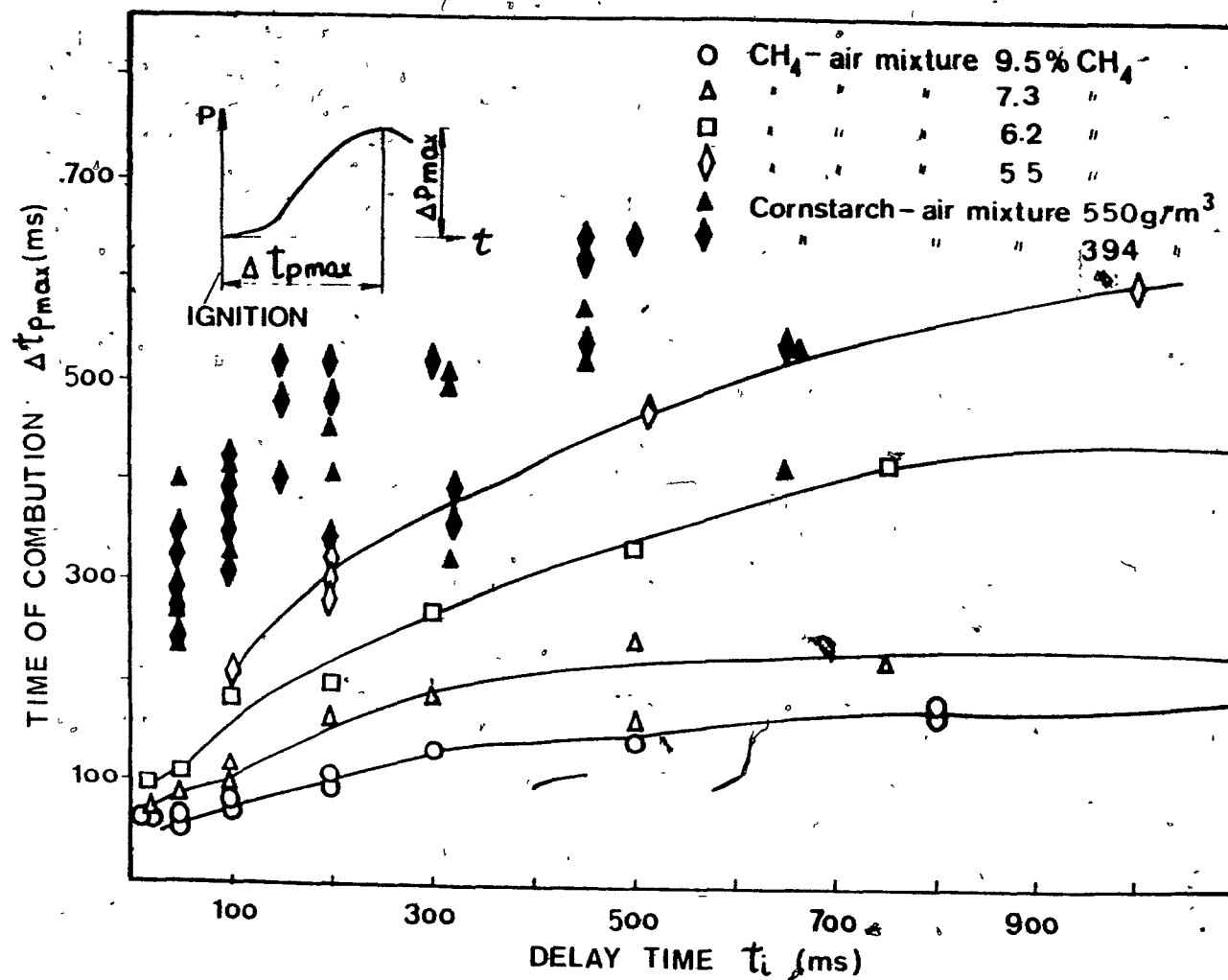


Fig. 32(c). The time of combustion of gas and dust mixtures as a function of the ignition delay time in a 1.86 meter tube.

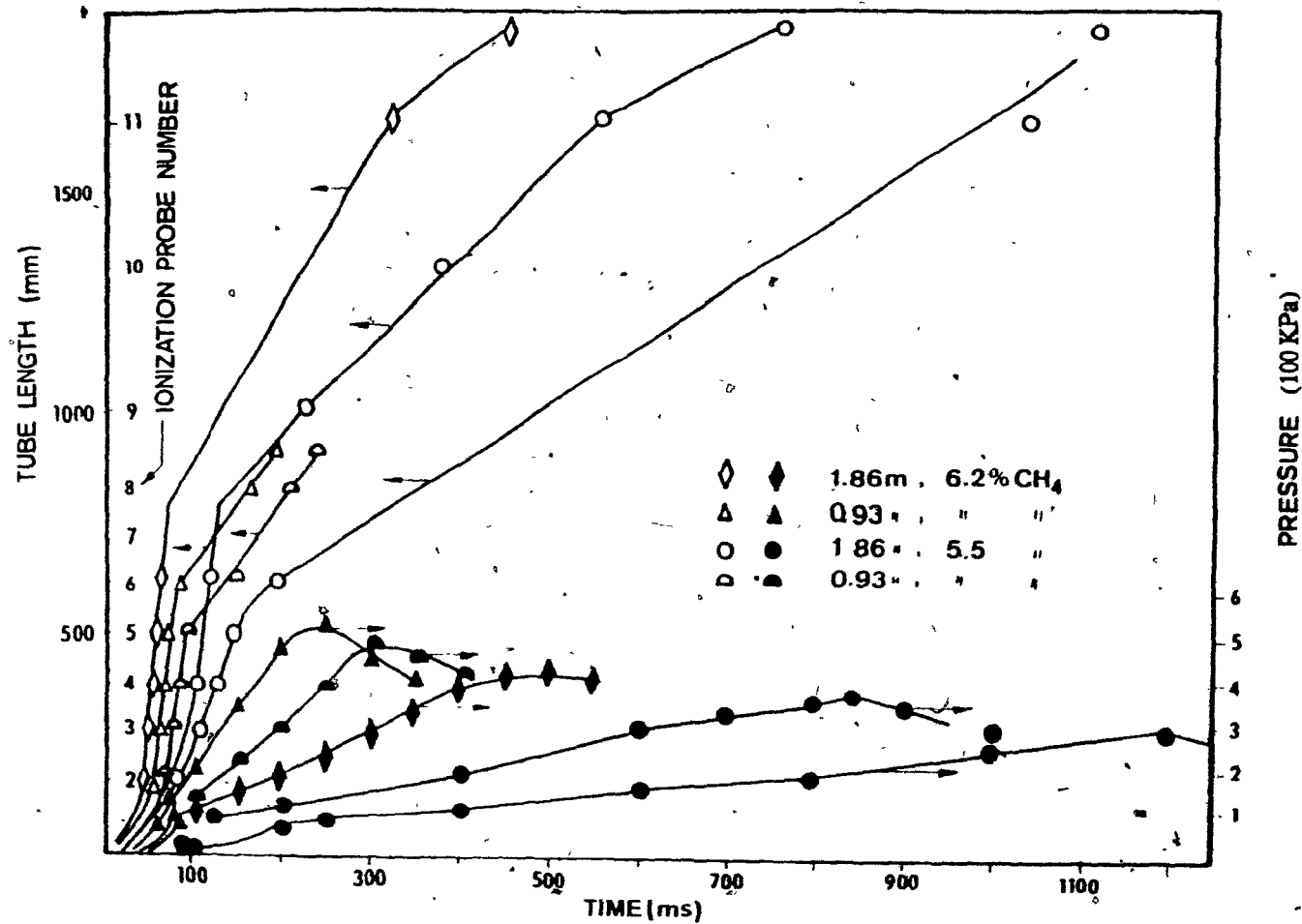


Fig.33. The pressure rise and the location of the flame front along a 0.93 meter and 1.86 meter closed tube as functions of time at a ignition delay time of 319 ms for the flame propagation in the methane- air mixtures.

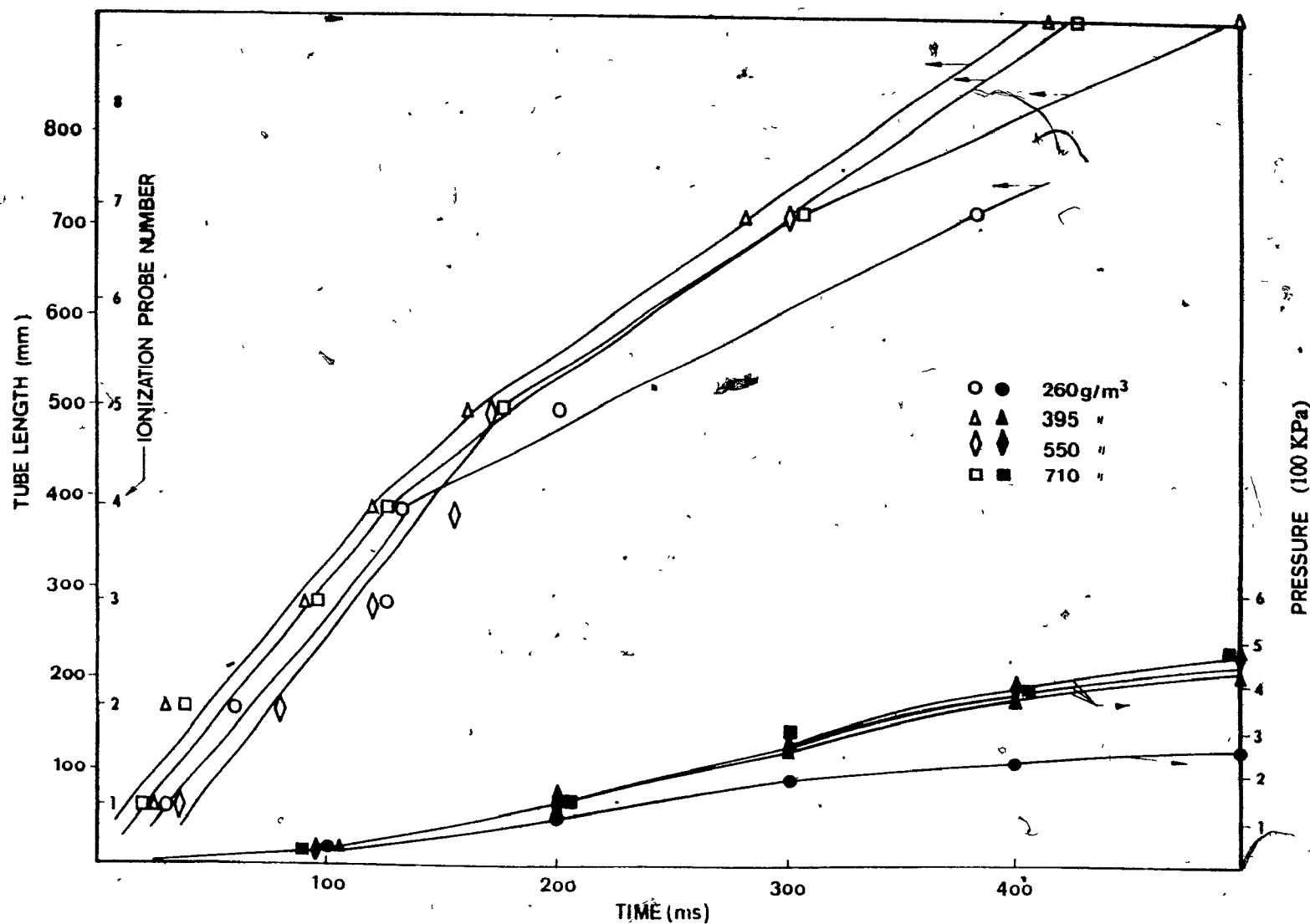


Fig.34. The pressure rise and the location of the flame front along a 0.93 meter tube as a function of time at the ignition delay time of 319 ms for the flame propagation in the cornstarch dust-air mixtures.

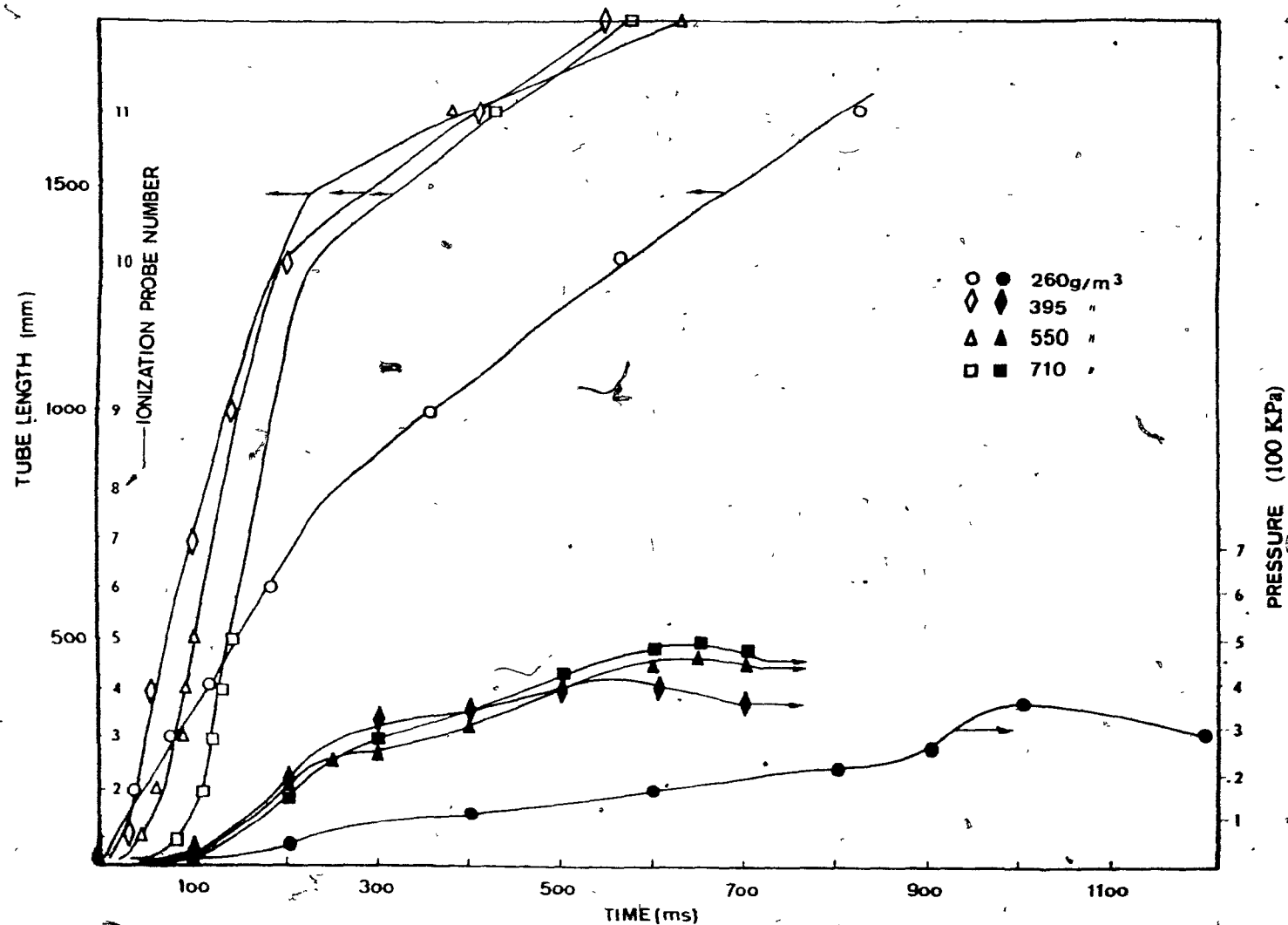


Fig.35. The pressure rise and the location of the flame front along a 1.86 meter closed tube as functions of time at the ignition delay time of 319 ms for the flame propagation in the cornstarch dust-air mixtures.

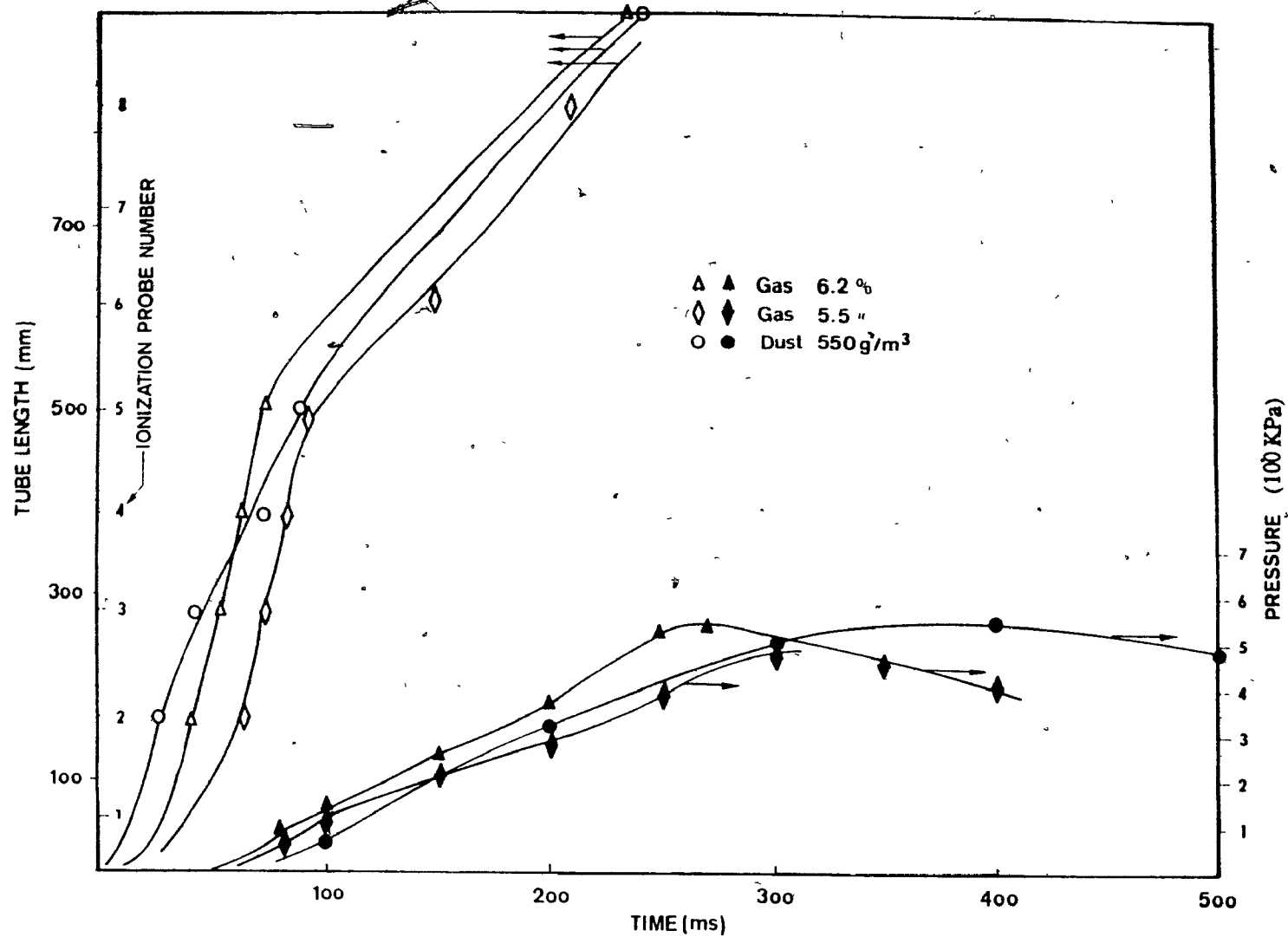


Fig.36. The pressure rise and the location of the flame front as functions of time for gas and dust flame in a 0.93 meter closed tube at the ignition delay time of 319 ms.

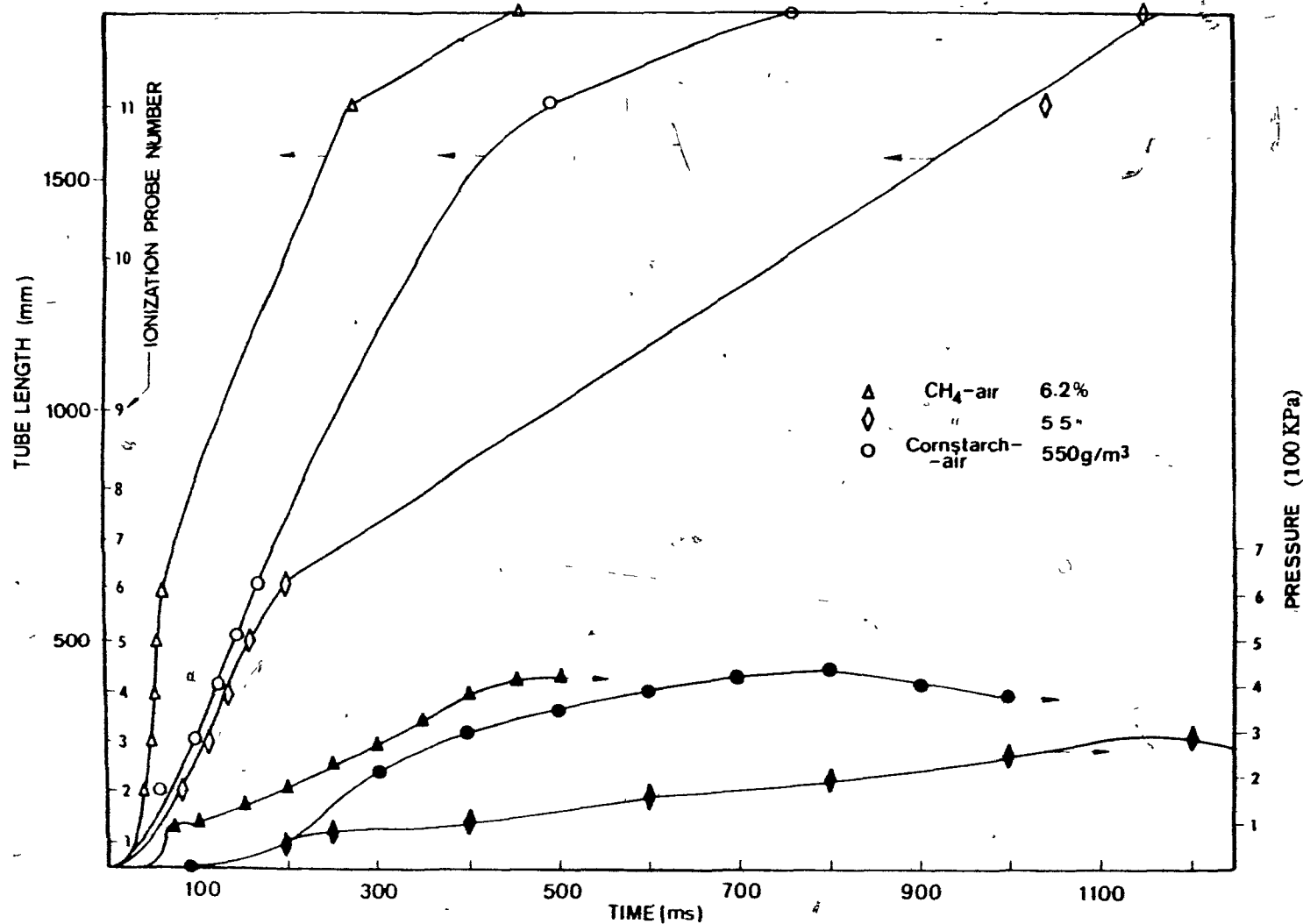


Fig.37. The pressure rise and the location of the flame front as a functions of time for a gas and dust flame in a 1.86 meter closed tube at the ignition delay time of 319 ms.

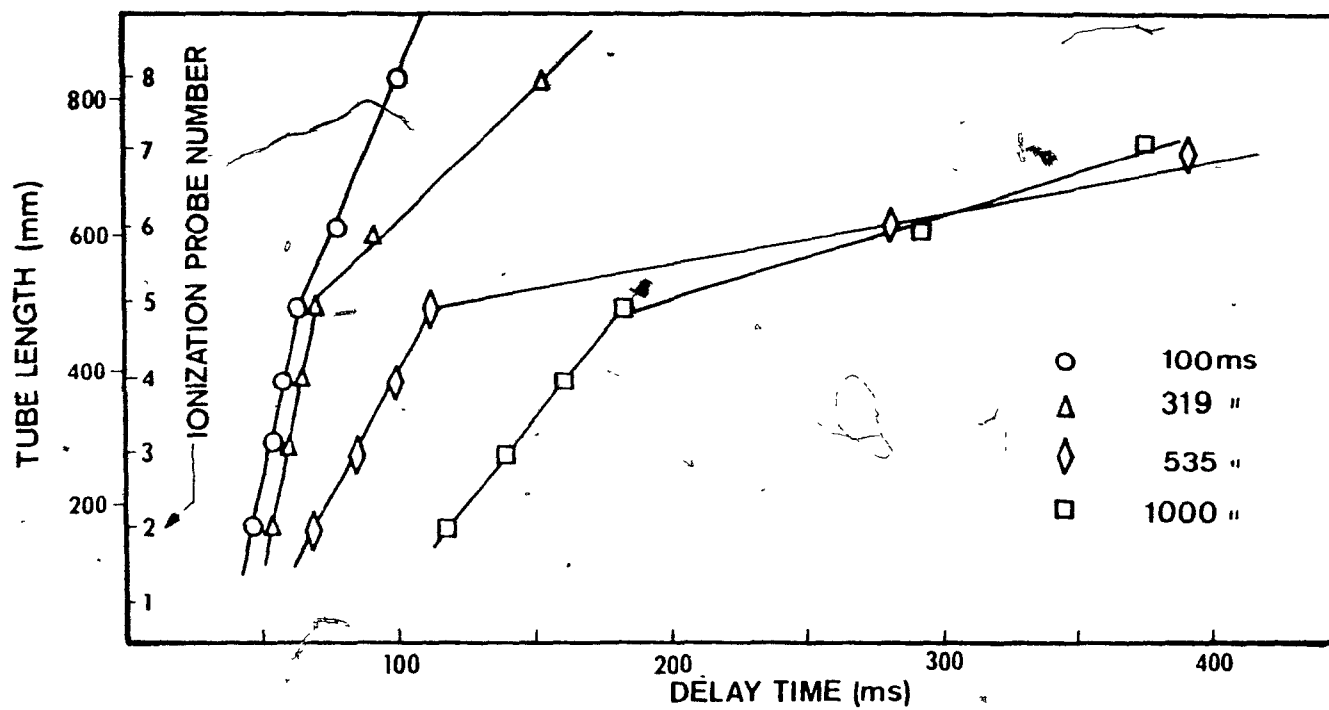


Fig.38. The influence of the ignition delay time on the flame propagation in a mixture of 6.2% CH_4 with air through a 0.93 meter closed tube.

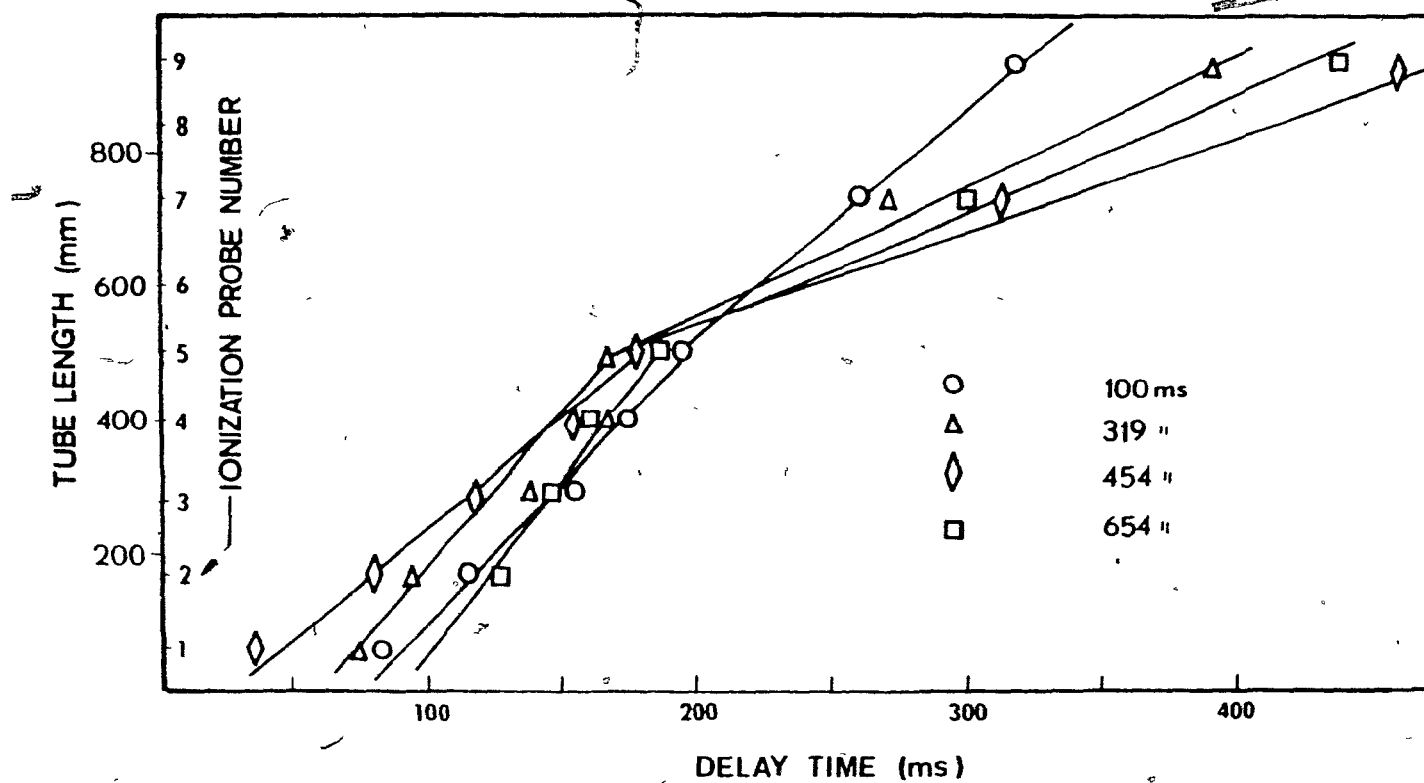


Fig.39. The influence of the ignition delay time on the flame propagation through a 0.93 meter closed tube in a cornstarch dust-air mixture with dust concentration of 550 g/m^3 .

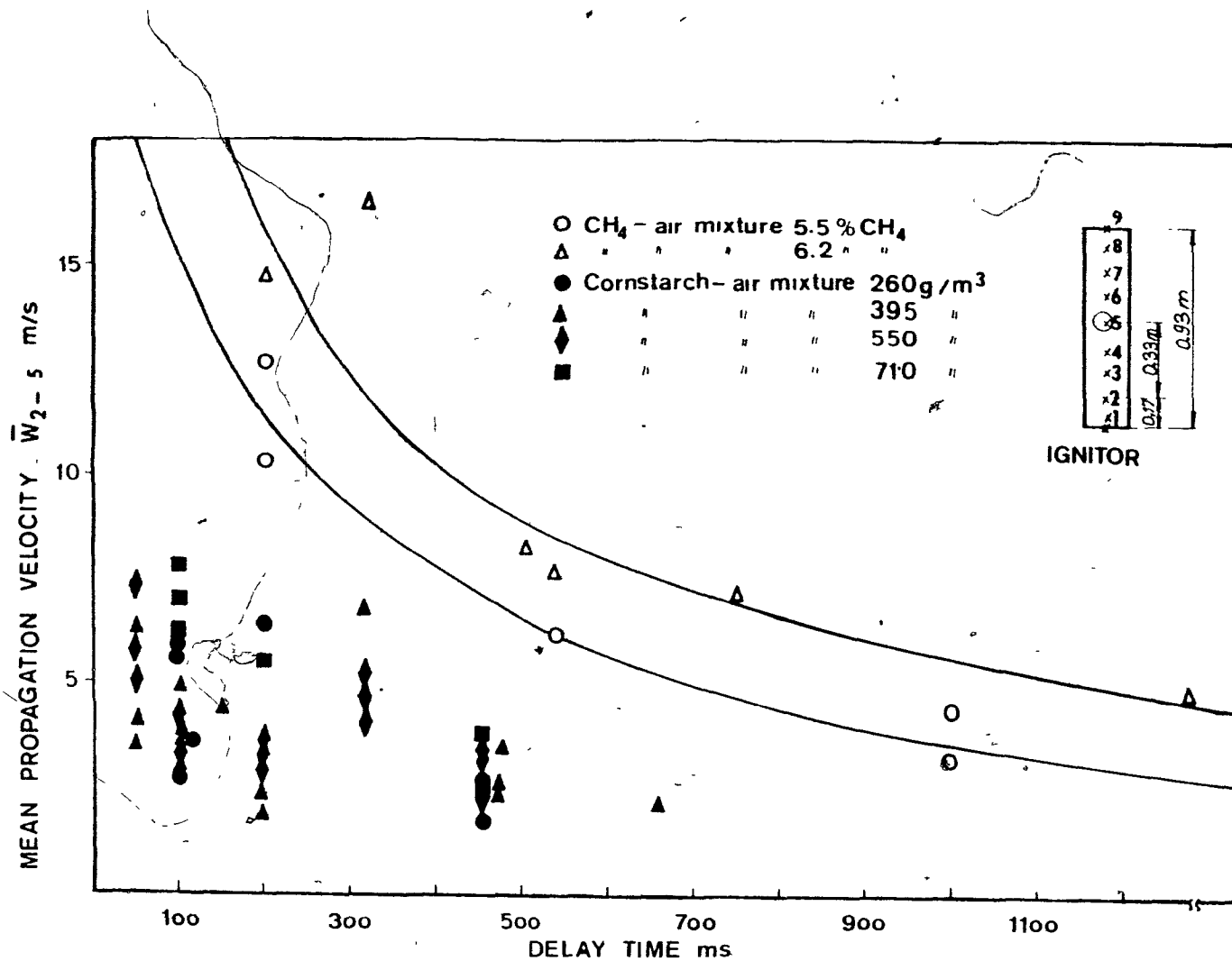


Fig.40. The mean propagation velocity of the flame front in the first stage of the flame propagation through a 0.93 meter closed tube as a function of the ignition delay time for gas and dust flame.

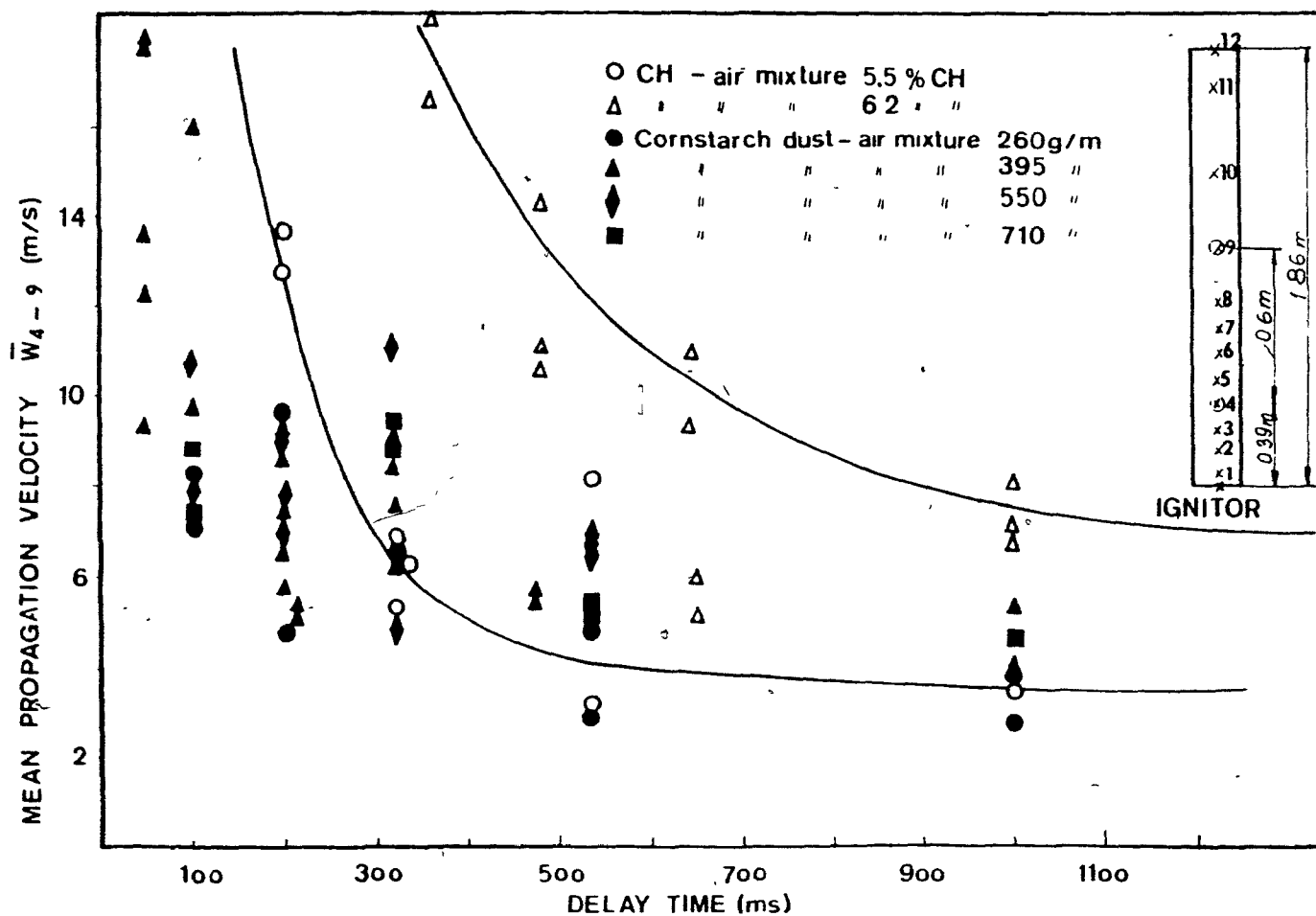


Fig41. The mean propagation velocity of the flame front in the first stage of the flame propagation through a 1.86 meter closed tube as a function of the ignition delay time for gas and dust flame.

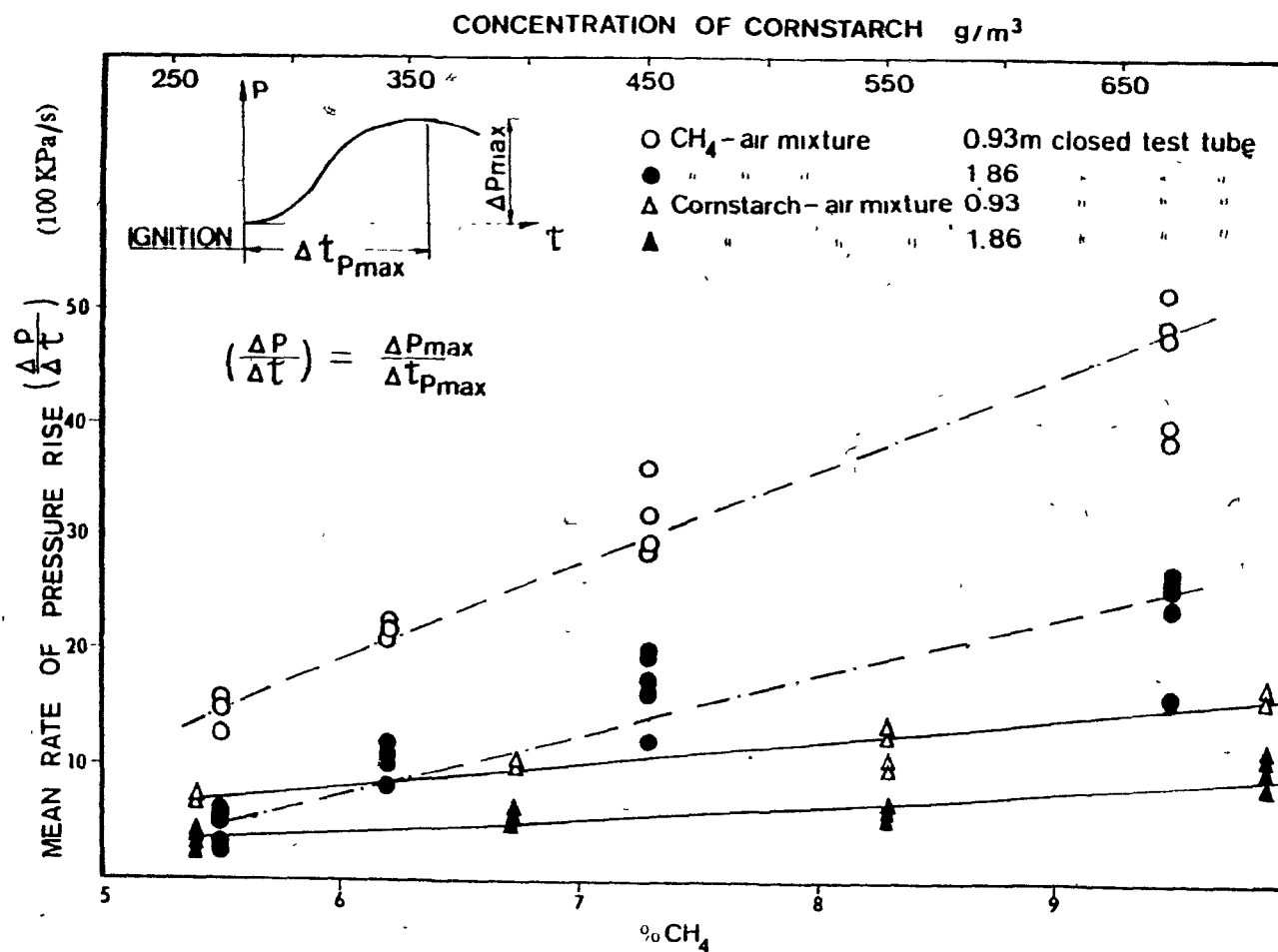


Fig.42. The mean rate of the pressure rise during the entire combustion process as a function of the mixture concentration for gas and dust flame with the ignition delay time of 319 ms.

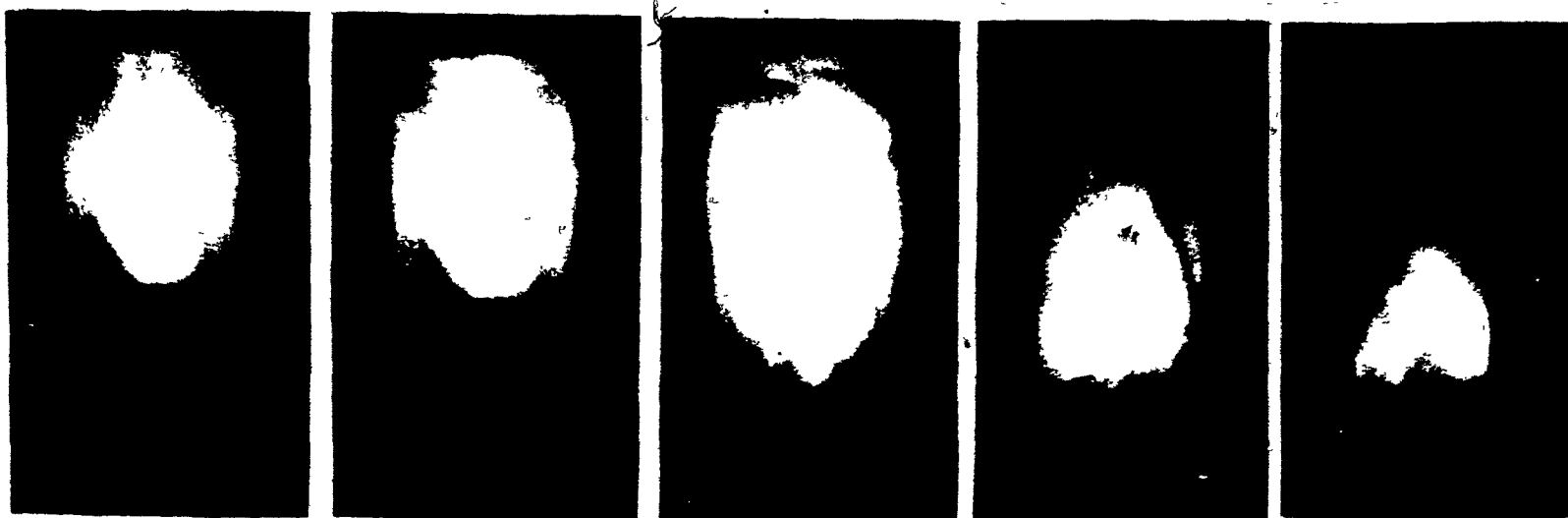


Fig.43. A sequence of flames extracted from a movie of cornstarch dust-air flame propagating downward from an open end of a rectangular duct (178mm x 178mm x 1000mm). Ignitor with 0.6 grams black powder, 30 ms time interval between frames with initial frame 20 ms after ignition. Ignition delay time = 430 ms, Cornstarch dust concentration = 560 g/m³.

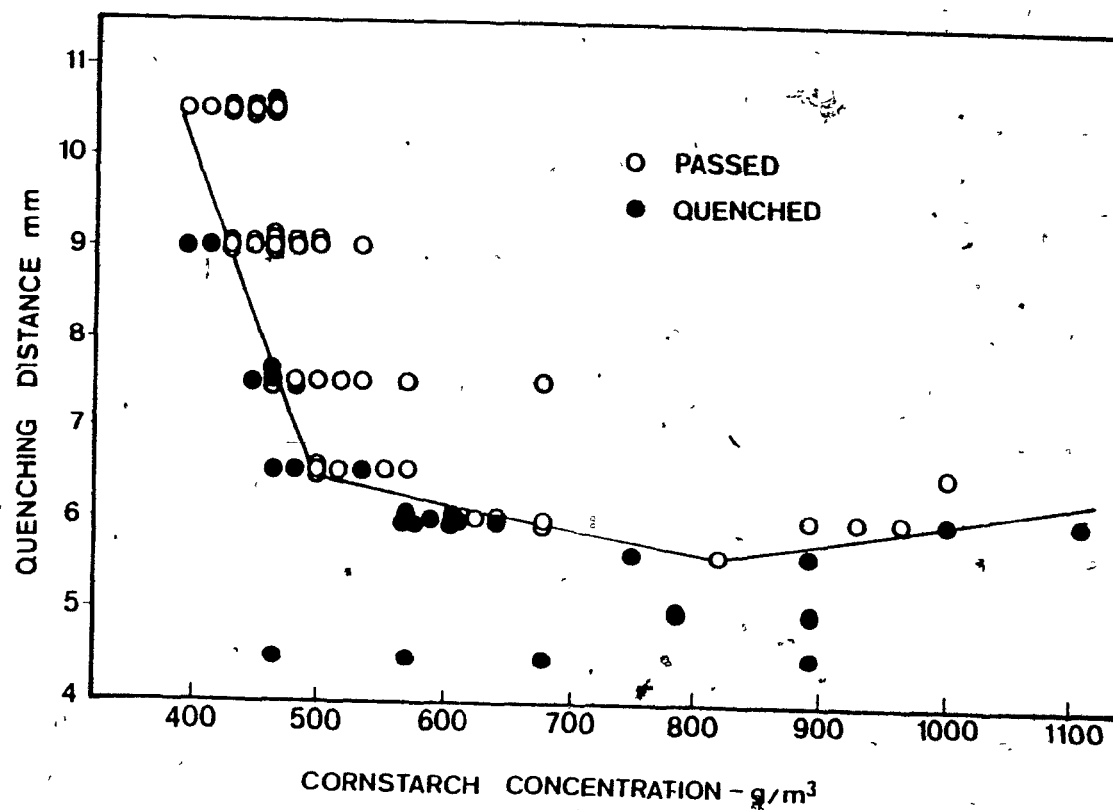


Fig.44. The quenching distance as a function of the cornstarch concentration [38].

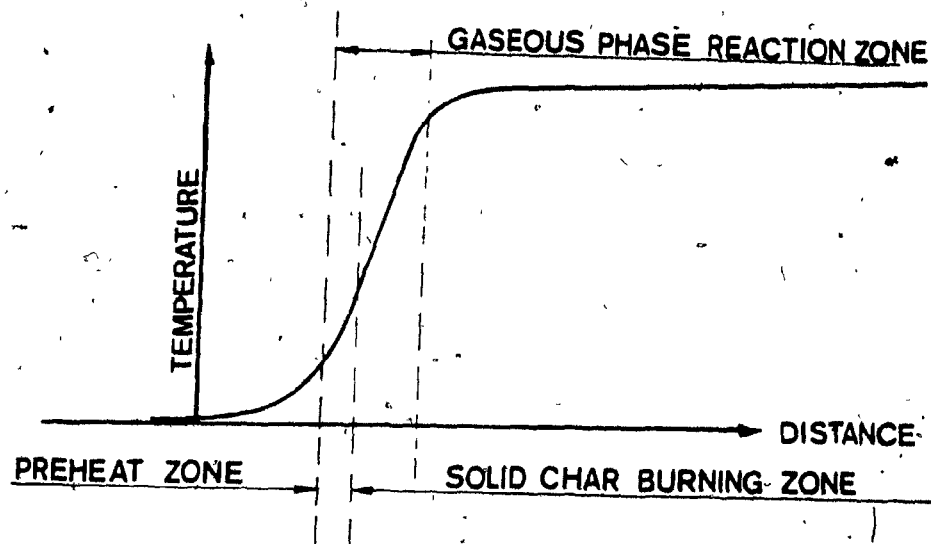


Fig.45. The structure of a premixed laminar dust-air flame.

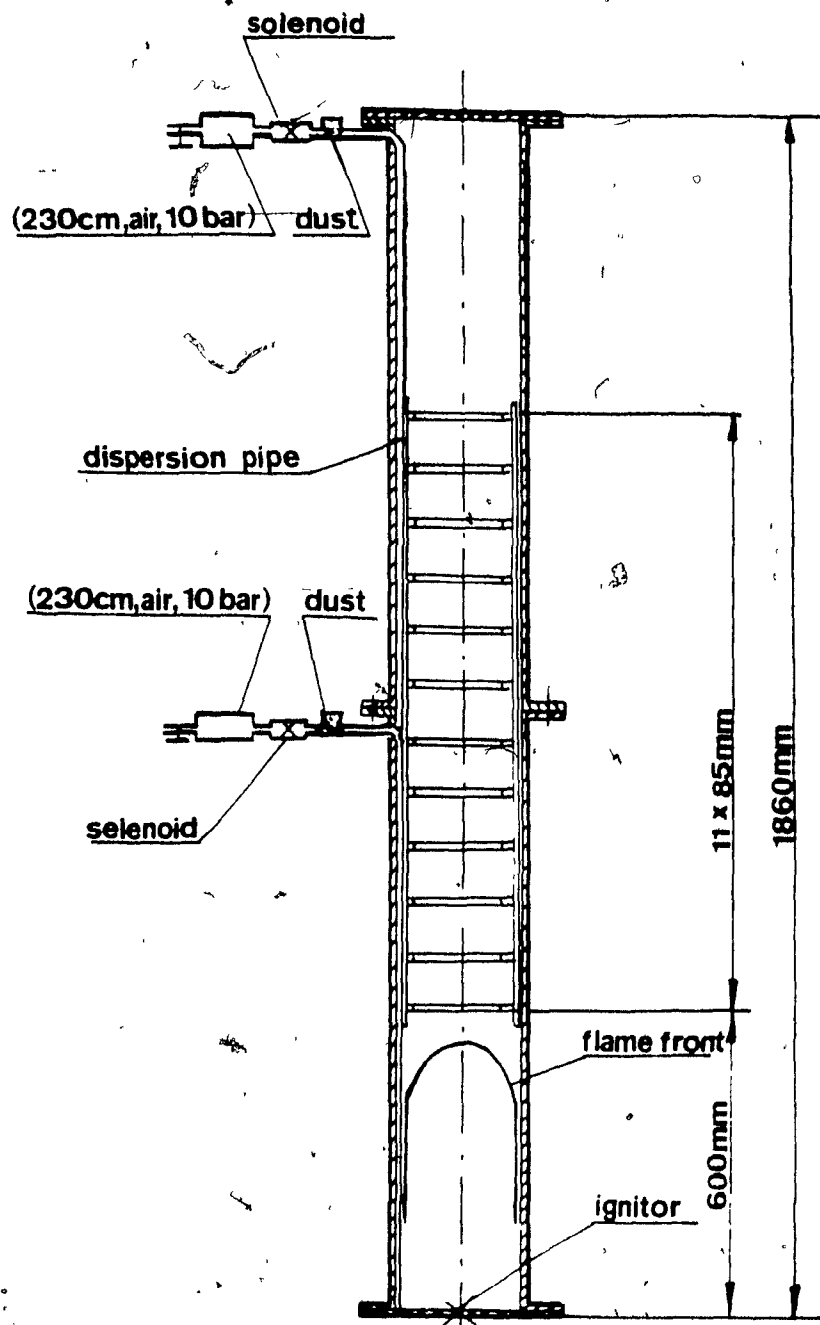


Fig.46. The side view of the obstacles location in present test tube.

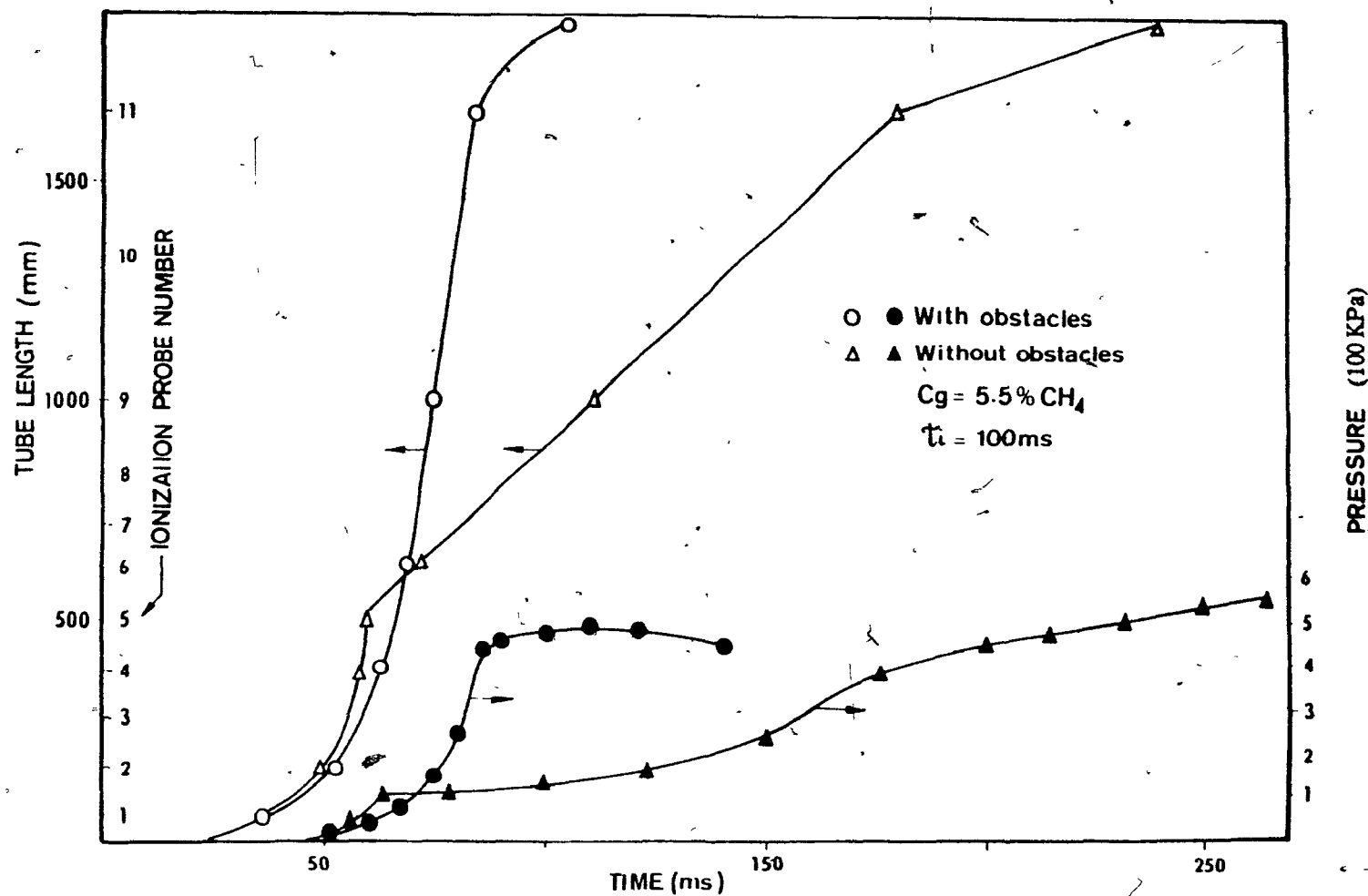


Fig. 47. The pressure rise and the location of the flame front along a 1.86 meter closed tube as a function of time with and without obstacles for the flame propagation in 5.5% methane-air mixture at the ignition delay time of 100 ms.

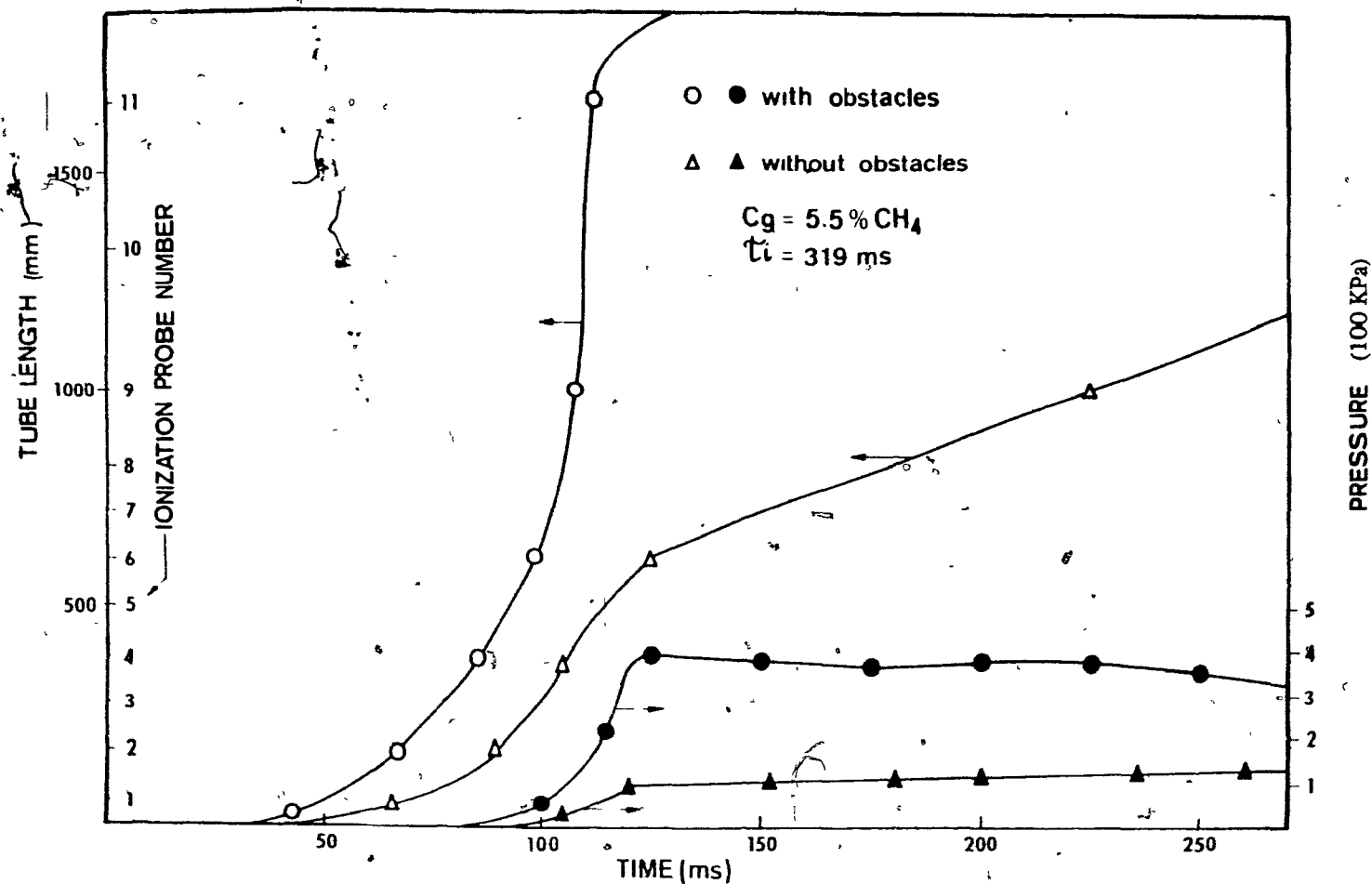


Fig.48. The pressure rise and the location of the flame front along a 1.86 meter closed tube as a function of time with and without obstacles for the flame propagation in 5.5% methane-air mixture at the ignition delay time of 319 ms.

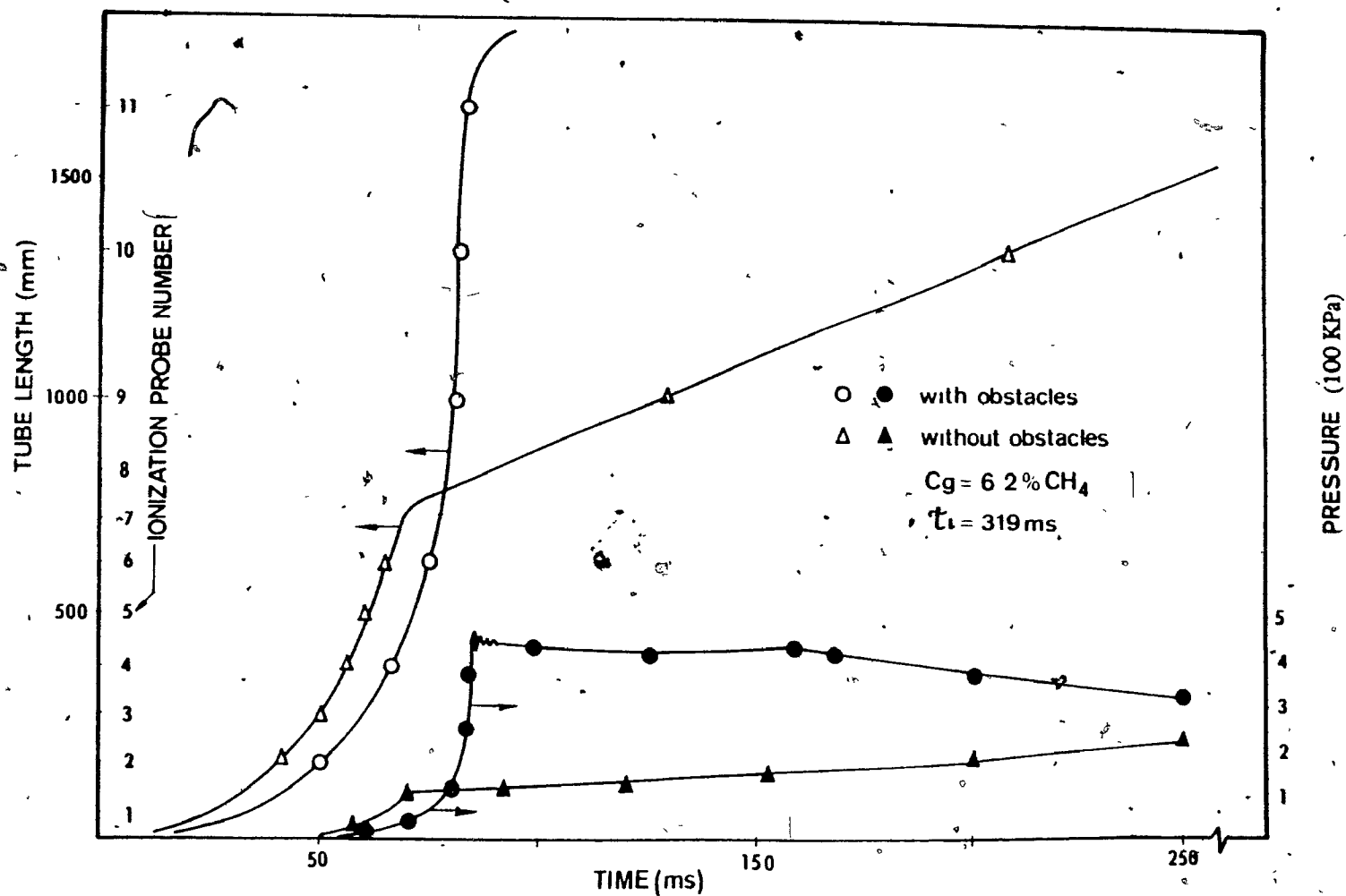


Fig.49. The pressure rise and the location of the flame front along a 1.86 meter closed tube as a function of time with and without obstacles for the flame propagation in 6.2% methane-air mixture at the ignition delay time of 319 ms.

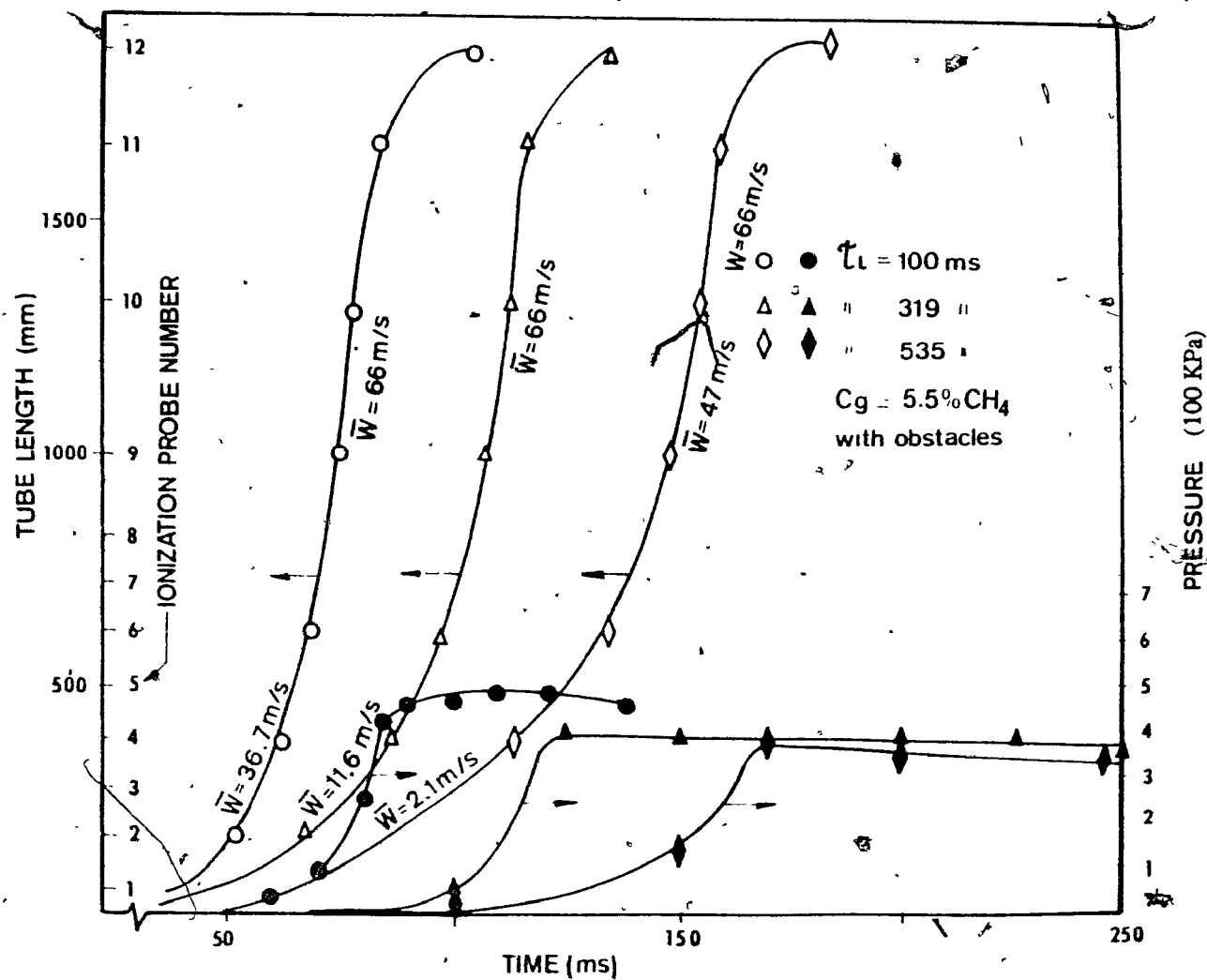


Fig.50 The pressure rise and the location of the flame front along a 1.86 meter closed tube as a function of time under the influence of obstacle-induced turbulence with various ignition delay times for the flame propagation in 5.5% methane-air mixture.

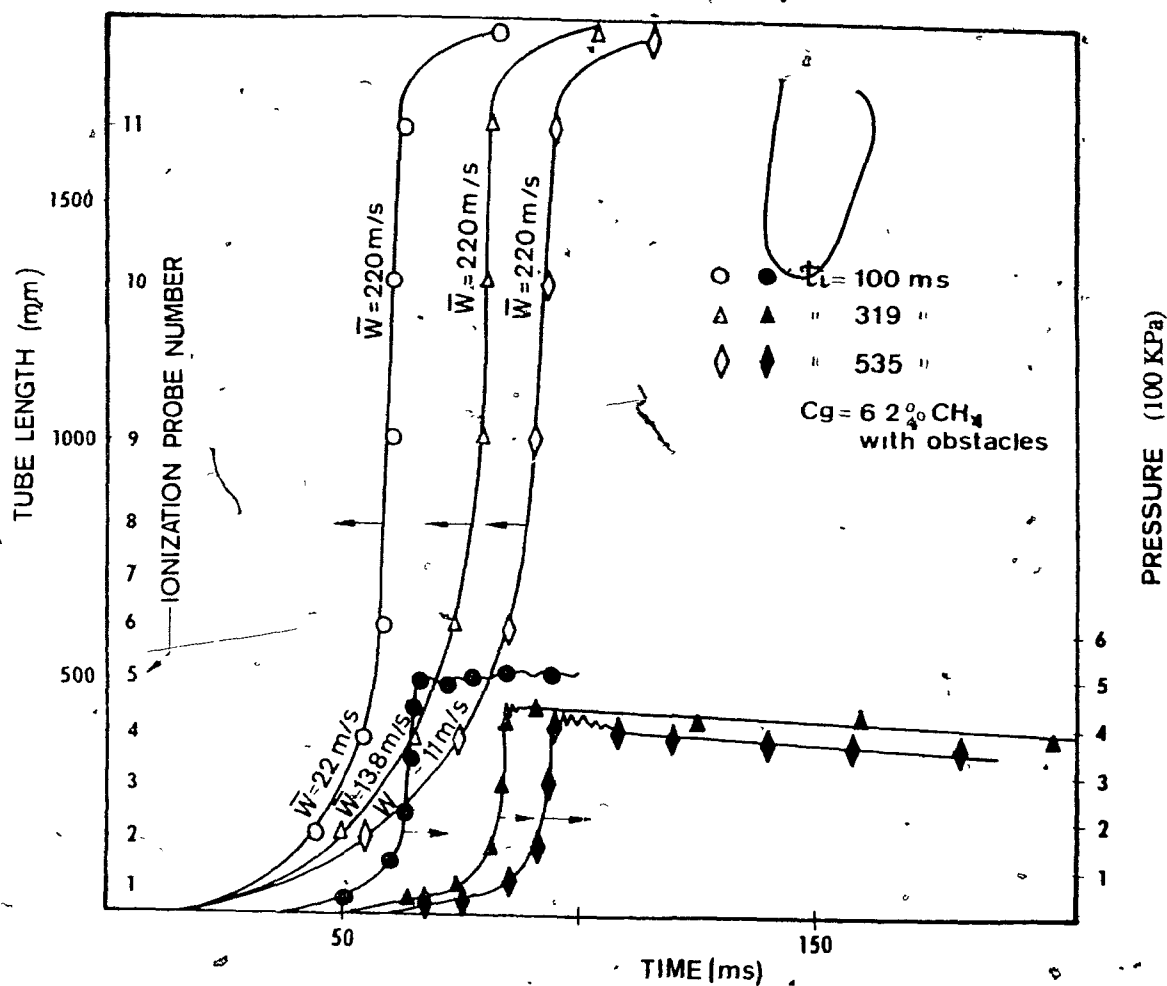


Fig.51. Pressure rise and location of the flame front along a 1.86 meter closed tube as a function of time under the influence of the obstacle-induced turbulence with different ignition delay times for the flame propagation in 6.2% methane-air mixture.

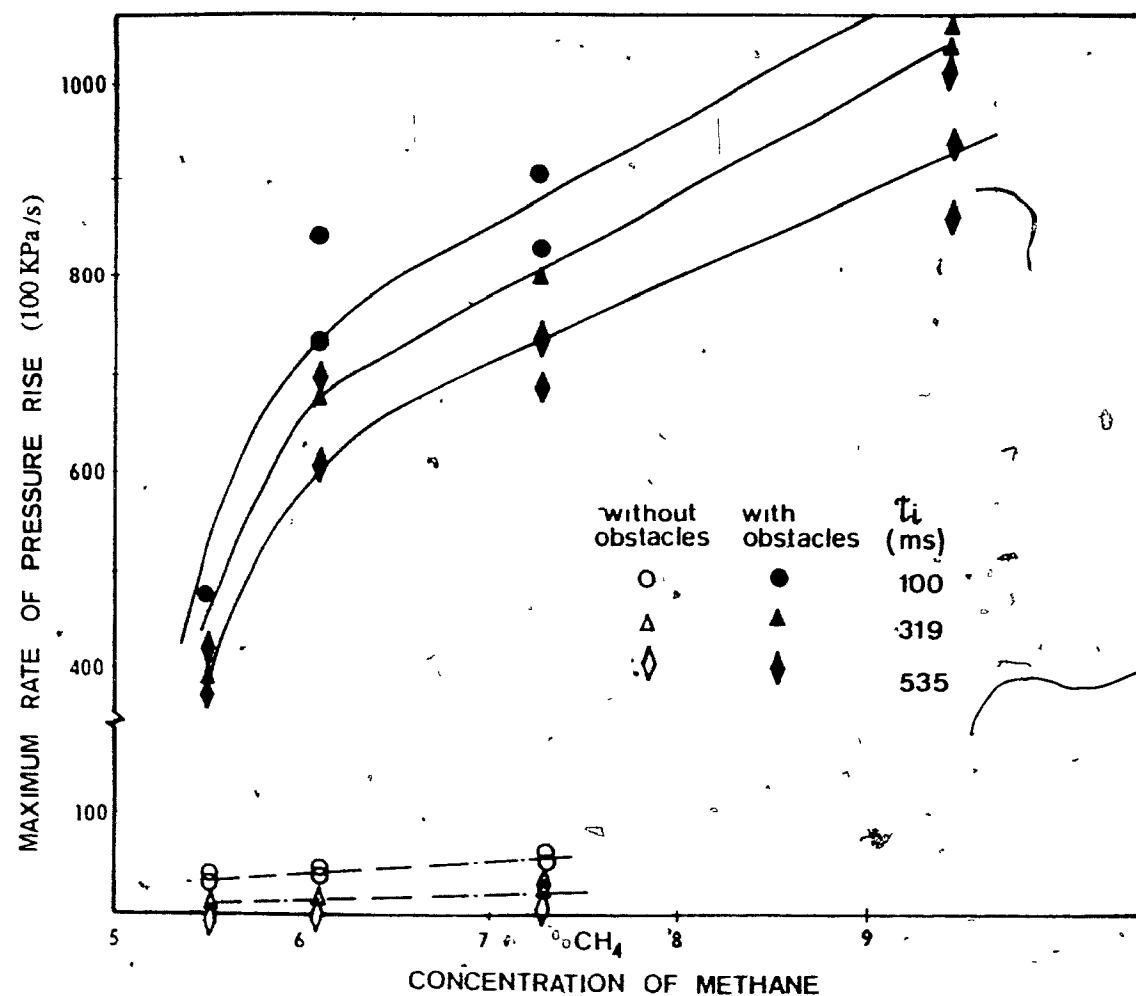


Fig.52. The influence of the obstacles on the maximum rate of pressure rise as a function of the concentration of methane in the methane-air mixtures.

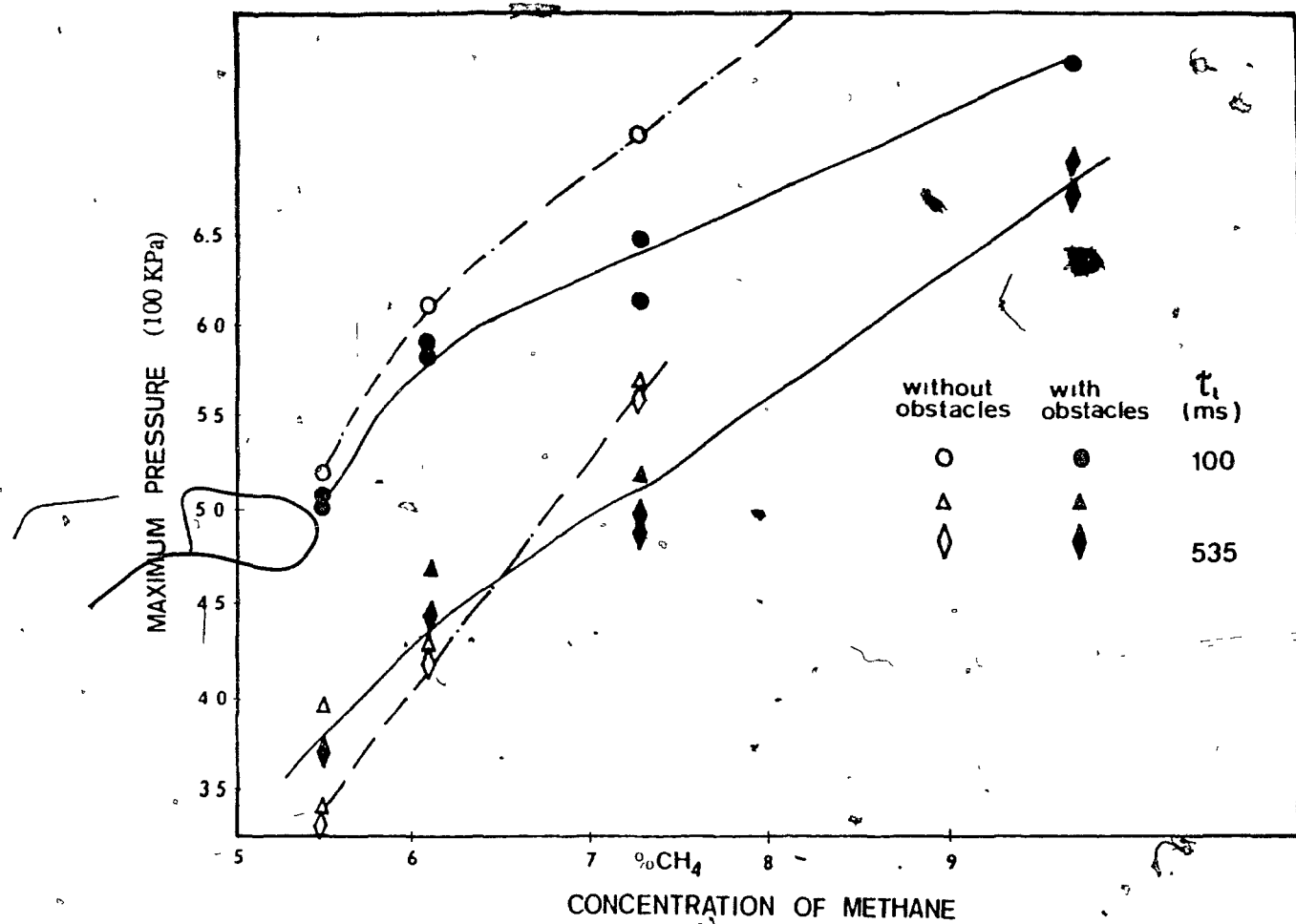


Fig.53. The influence of the obstacles on the maximum pressure rise as a function of the concentration of methane in the methane-air mixtures.

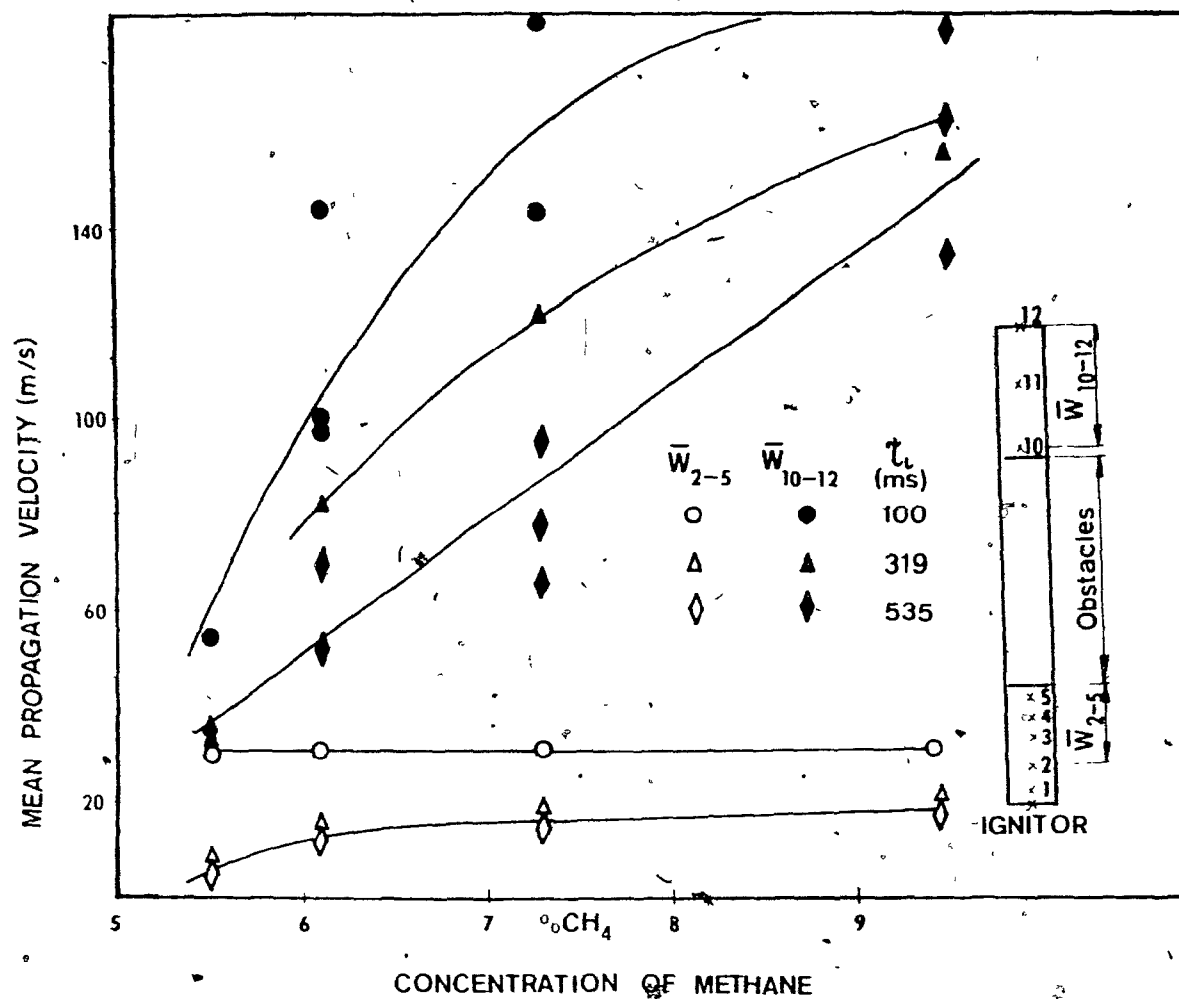
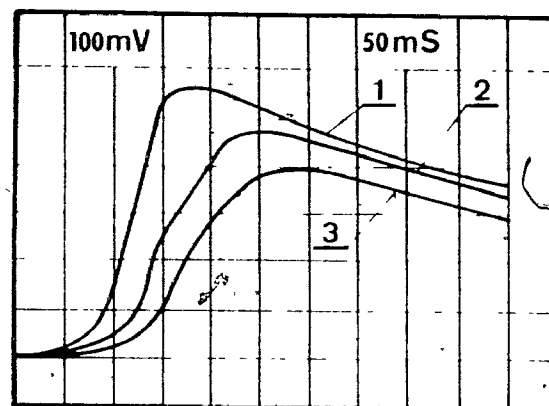
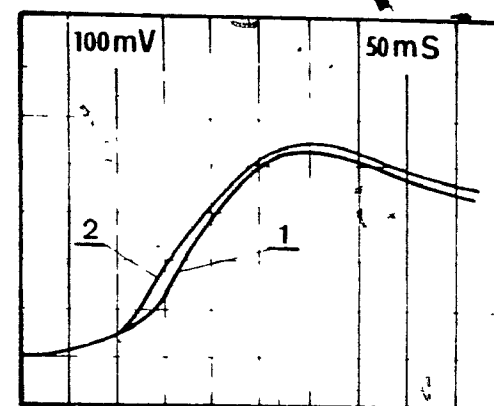


Fig.54. The influence of the obstacles on the mean propagation velocity as a function of the concentration of methane in the methane-air mixtures.



$(P_i)_{\text{reservoir}}$
(MPa) $(P_i)_{\text{test tube}}$
(MPa)

1	0.2 (air)	0.01 (air)
2	0.1 "	" "
3	0.1 "	0.008 "



$(P_i)_{\text{reservoir}}$
(MPa) $(P_i)_{\text{test tube}}$
(MPa)

1	0.2 (N_2)	0.01 (air)
2	0.1 "	" "

Fig.55. The influence of intensity of turbulence and the amount of air participating in combustion on the pressure history at the ignition delay time of 50 ms.

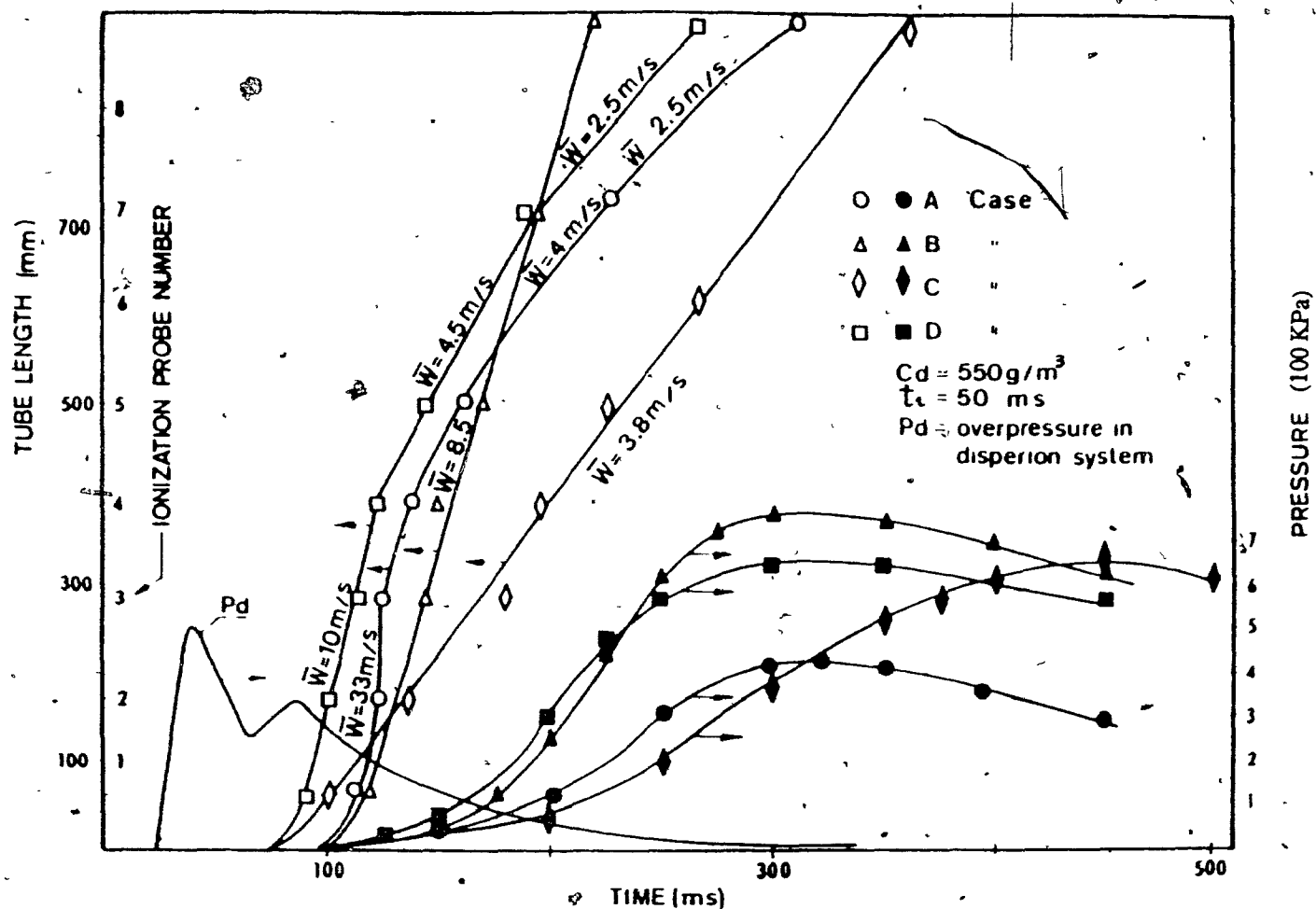


Fig 56 The reproducibility of the pressure rise and the location of the flame front along a 0.93 meter closed tube as a function of time for four experiments of combustion in a cornstarch dust-air mixture under identical procedure and at the same experimental conditions.

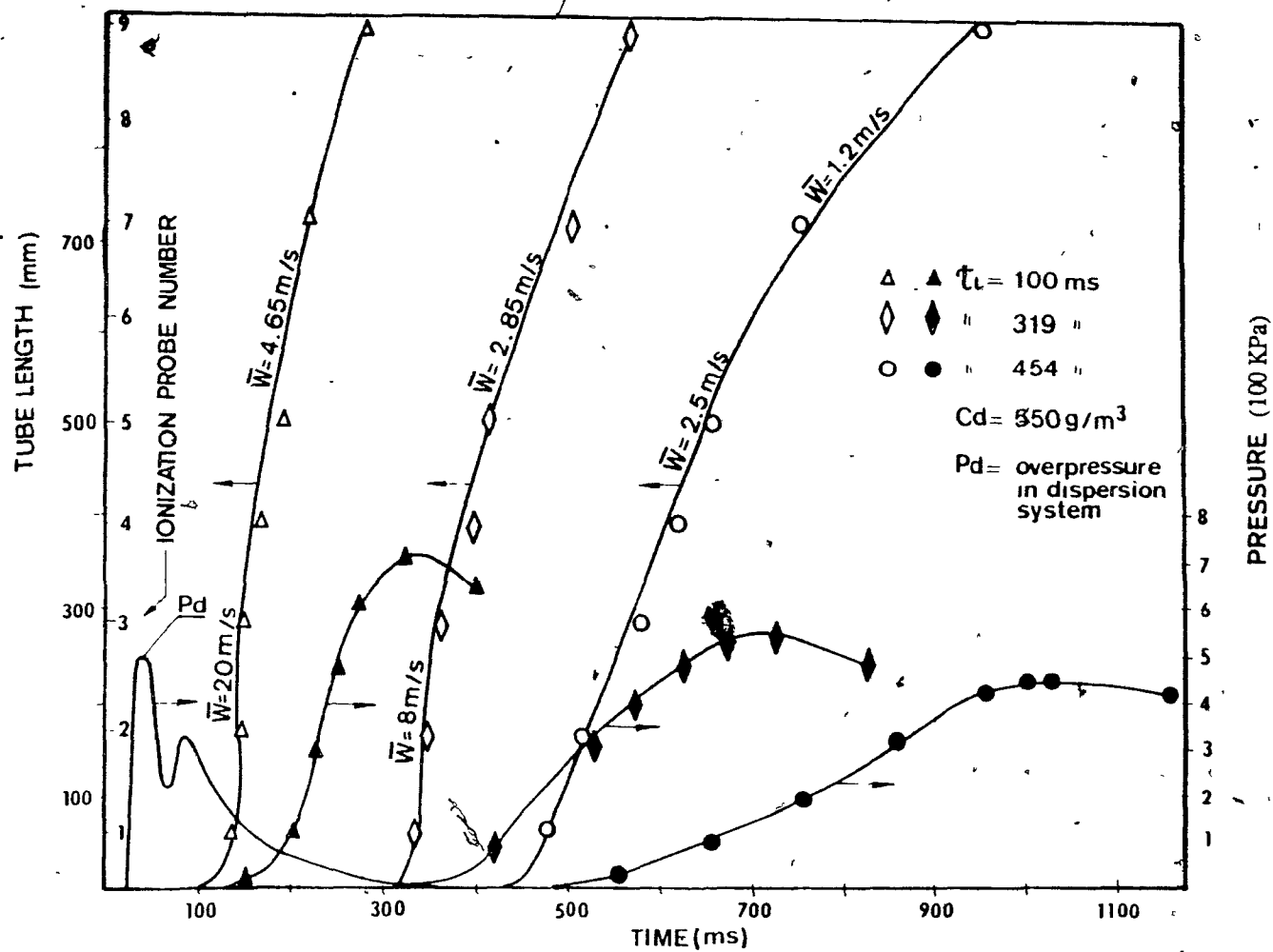


Fig.57. The pressure rise and the location of the flame front along a 0.83 meter closed tube as a function of time at various ignition delay time for a cornstarch dust-air mixture:

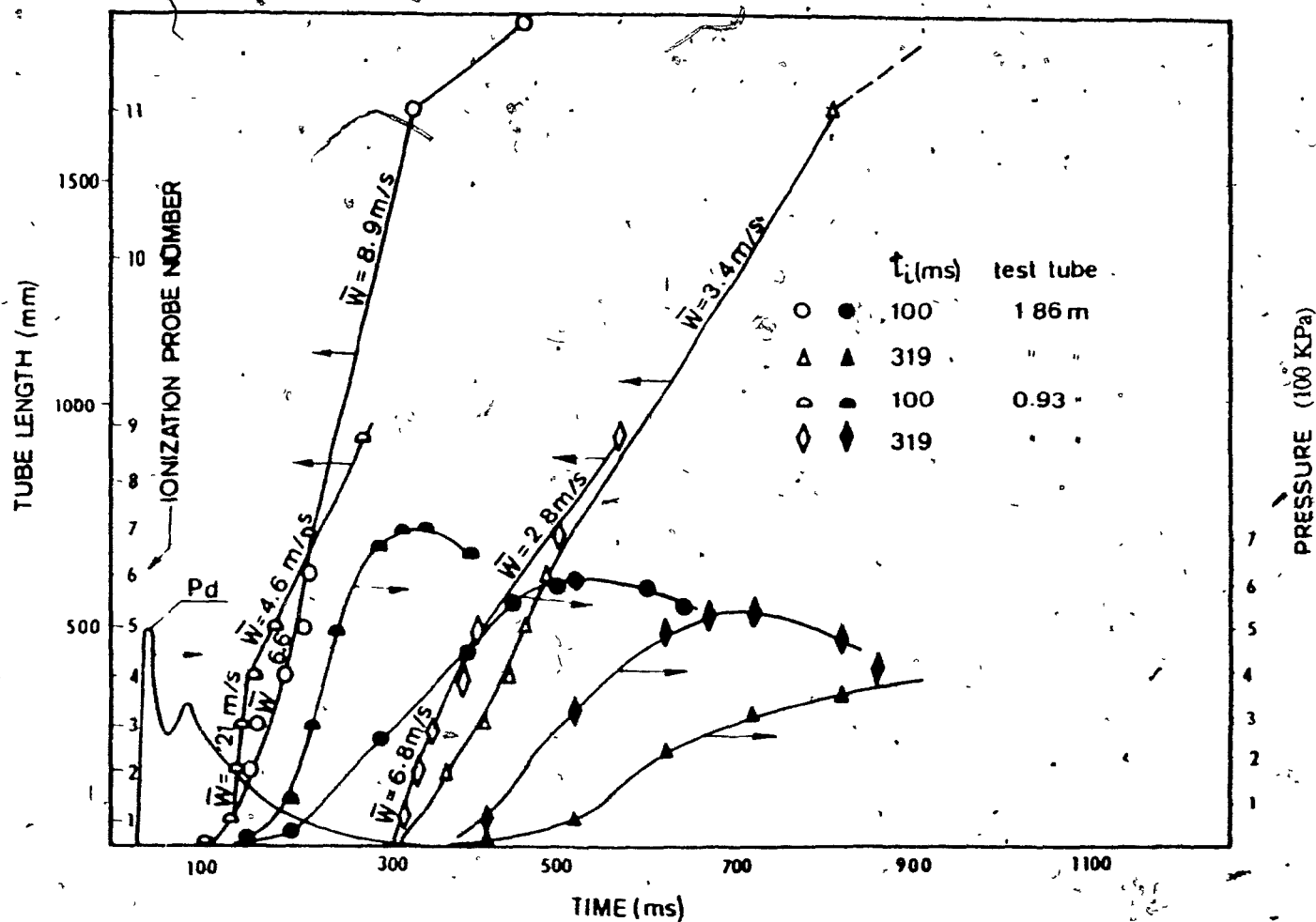


Fig.58. The pressure rise and the location of the flame front along 0.93 meter and 1.86 meter closed tube as a function of time at two different ignition delay time for combustion in a cornstarch dust - air mixture with dust concentration 550 g/m^3 .

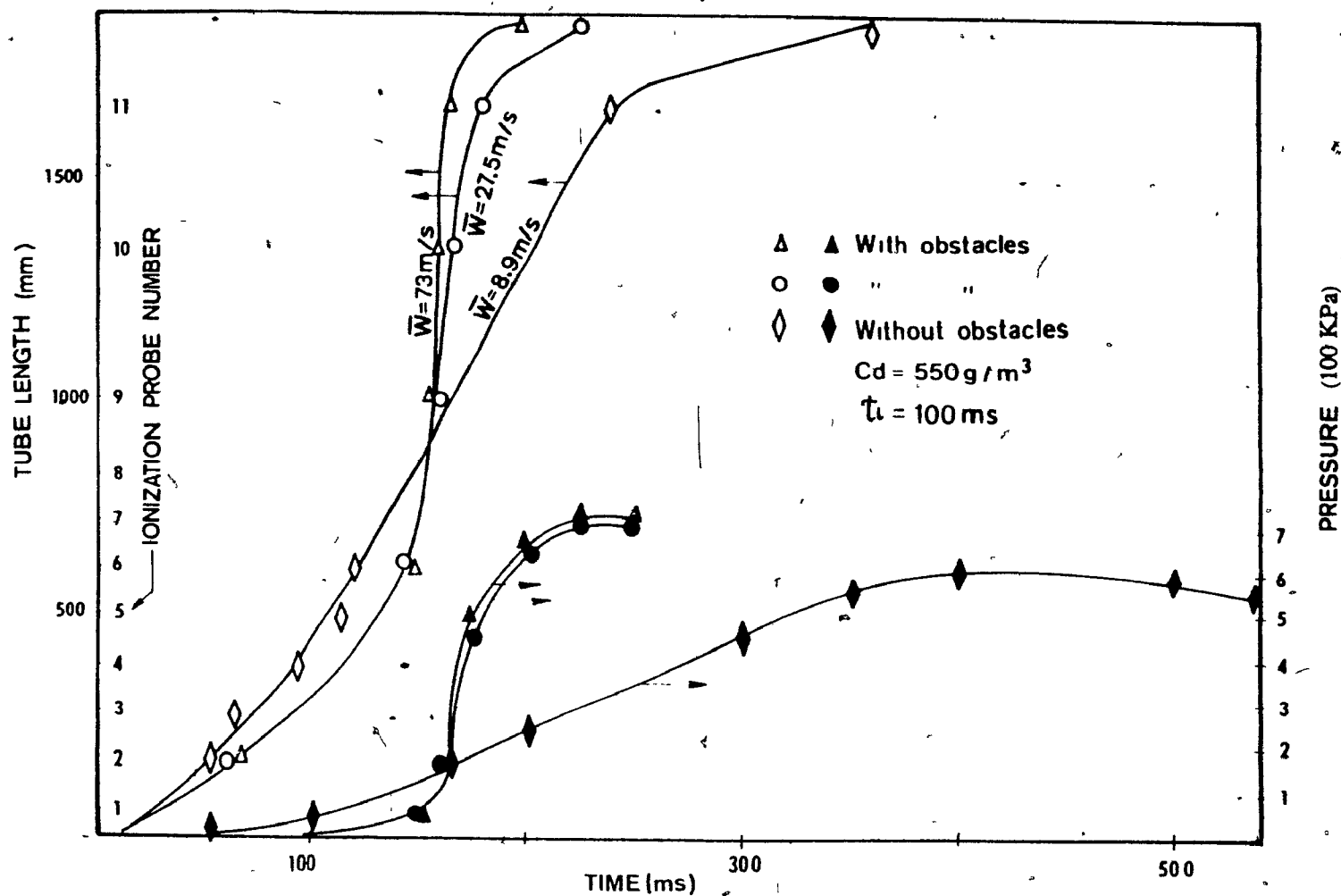


Fig.59. The pressure rise and the location of the flame front along a 1.86 meter closed tube as a function of time with and without obstacles for combustion in a cornstarch dust-air mixture at the short ignition delay time of 100 ms.

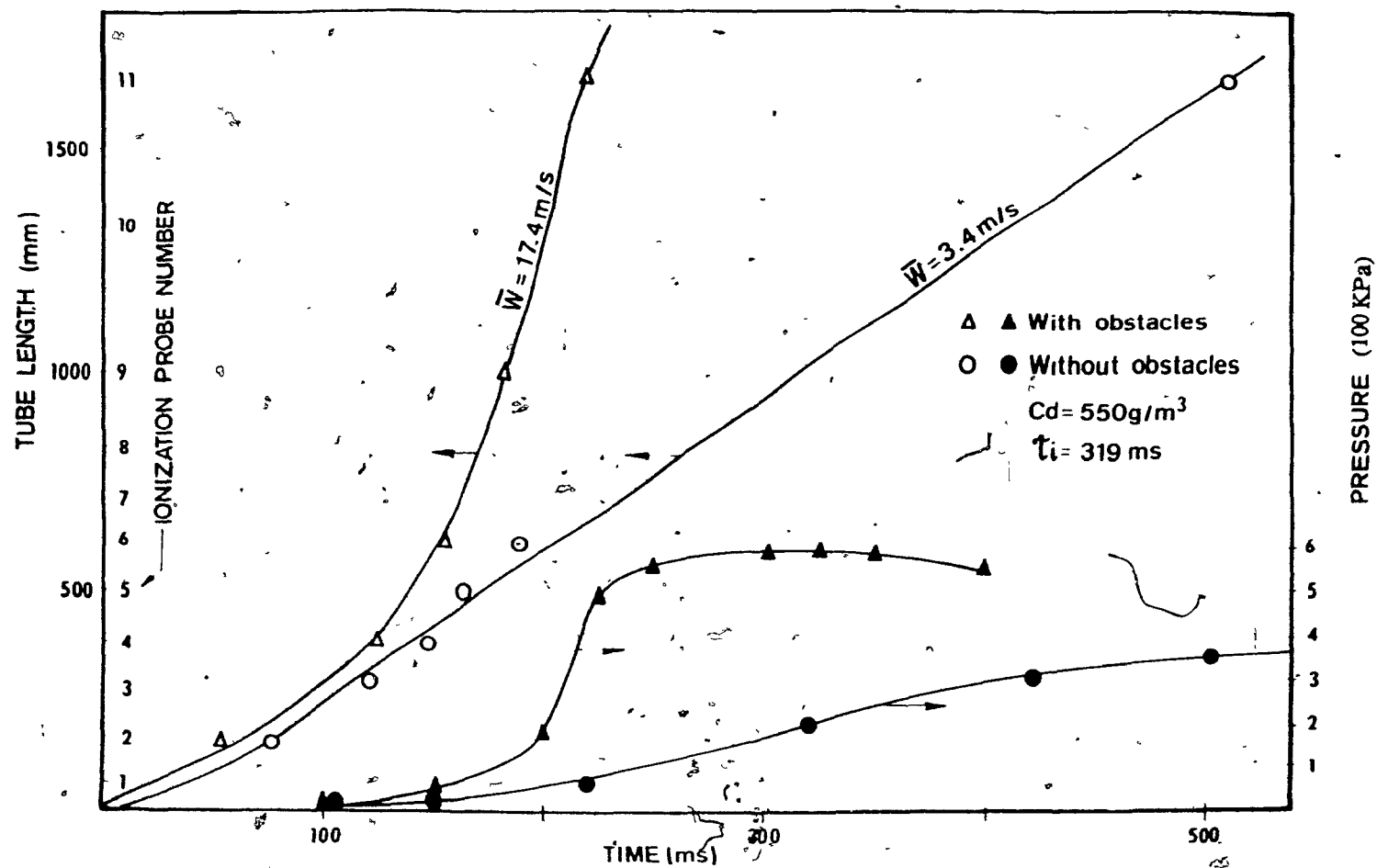


Fig.60. The pressure rise and the location of the flame front along a 1.86 meter closed tube as a function of time with and without obstacles for combustion in a cornstarch dust-air mixture at the ignition delay time of 319 ms.

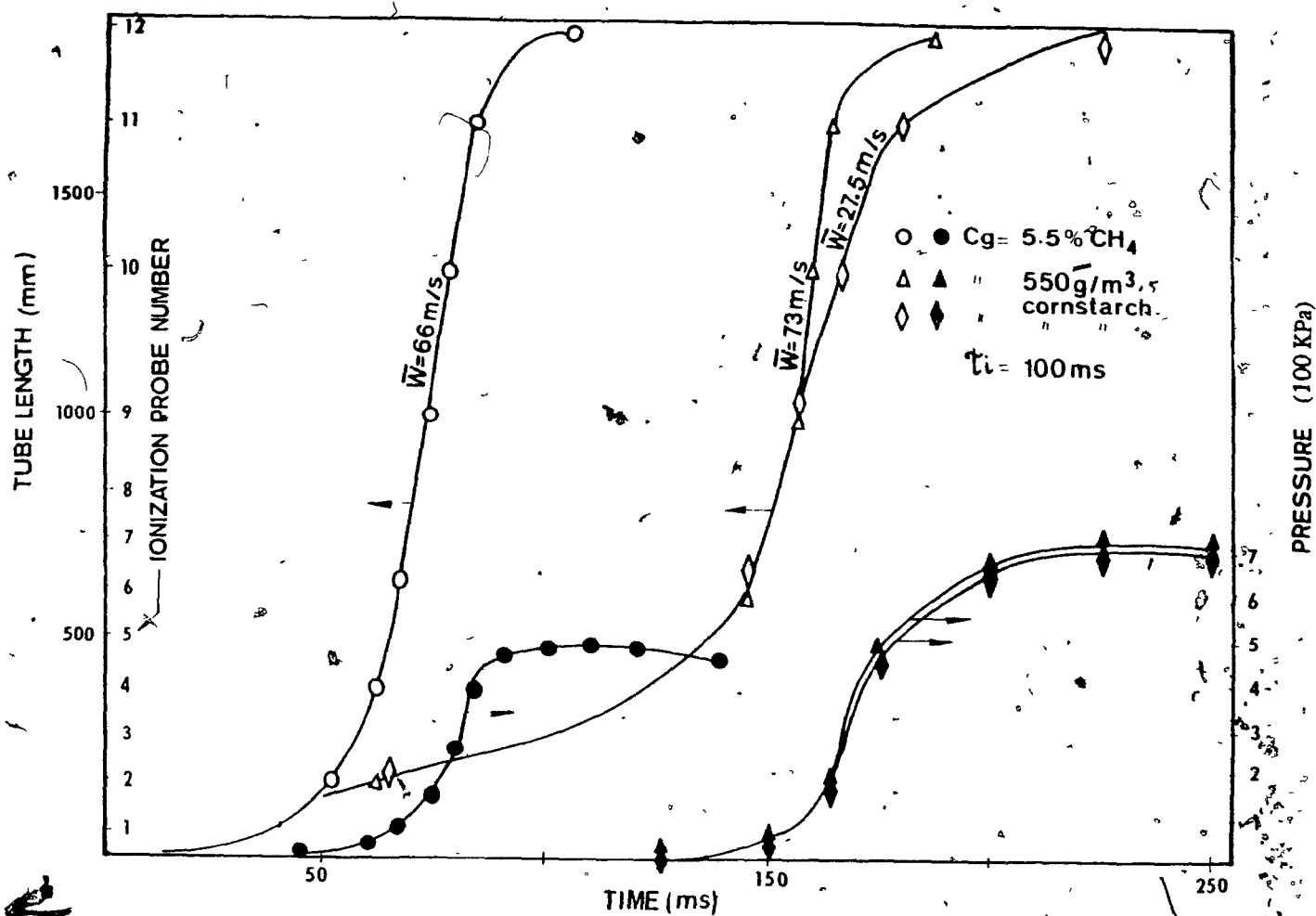


Fig 61. A comparison of the pressure rise and the location of the flame front between gas and dust flame propagating through obstacles along a 1.86 meter closed tube as a function of time at the ignition delay-time of 100 ms.

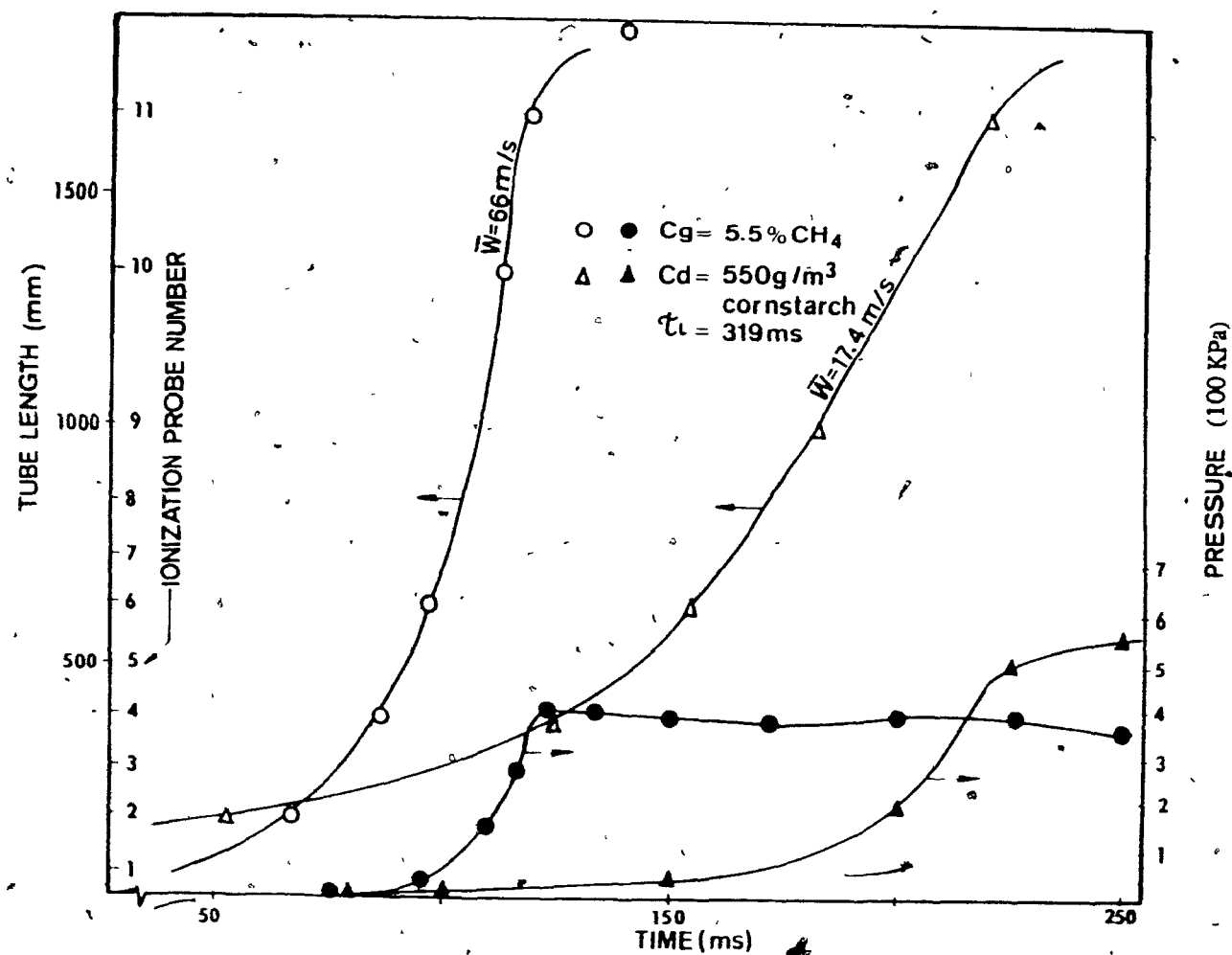


Fig.62. A comparison of the pressure rise and the location of the flame front between gas and dust flame propagating through obstacles along a 1.86 meter closed tube as a function of time at the ignition delay time of 319 ms.

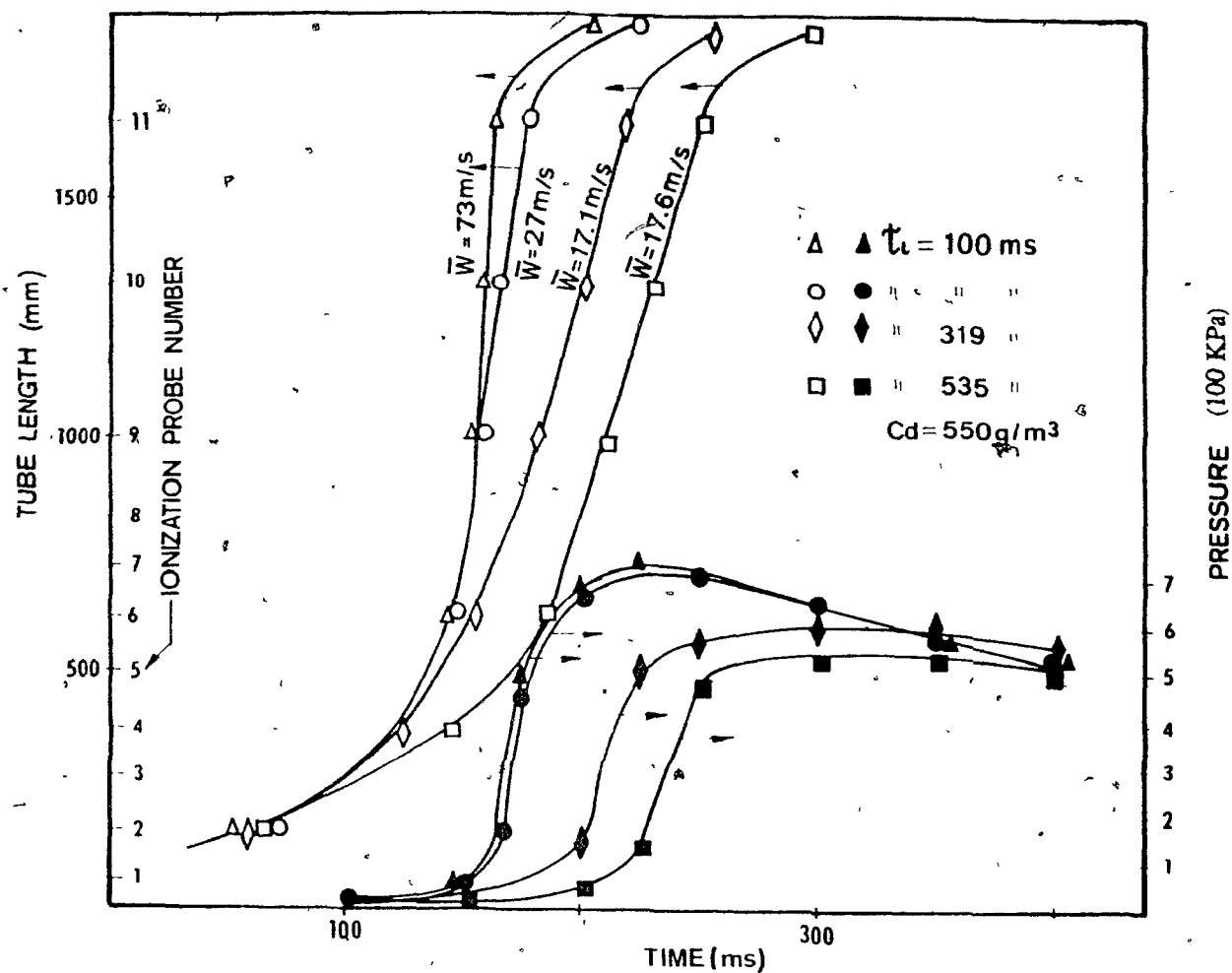


Fig.63. The pressure rise and the location of the flame front through obstacles along a 1.86 meter closed tube as a function of time for combustion in a 550 g/m^3 cornstarch dust-air mixture with various ignition delay times.

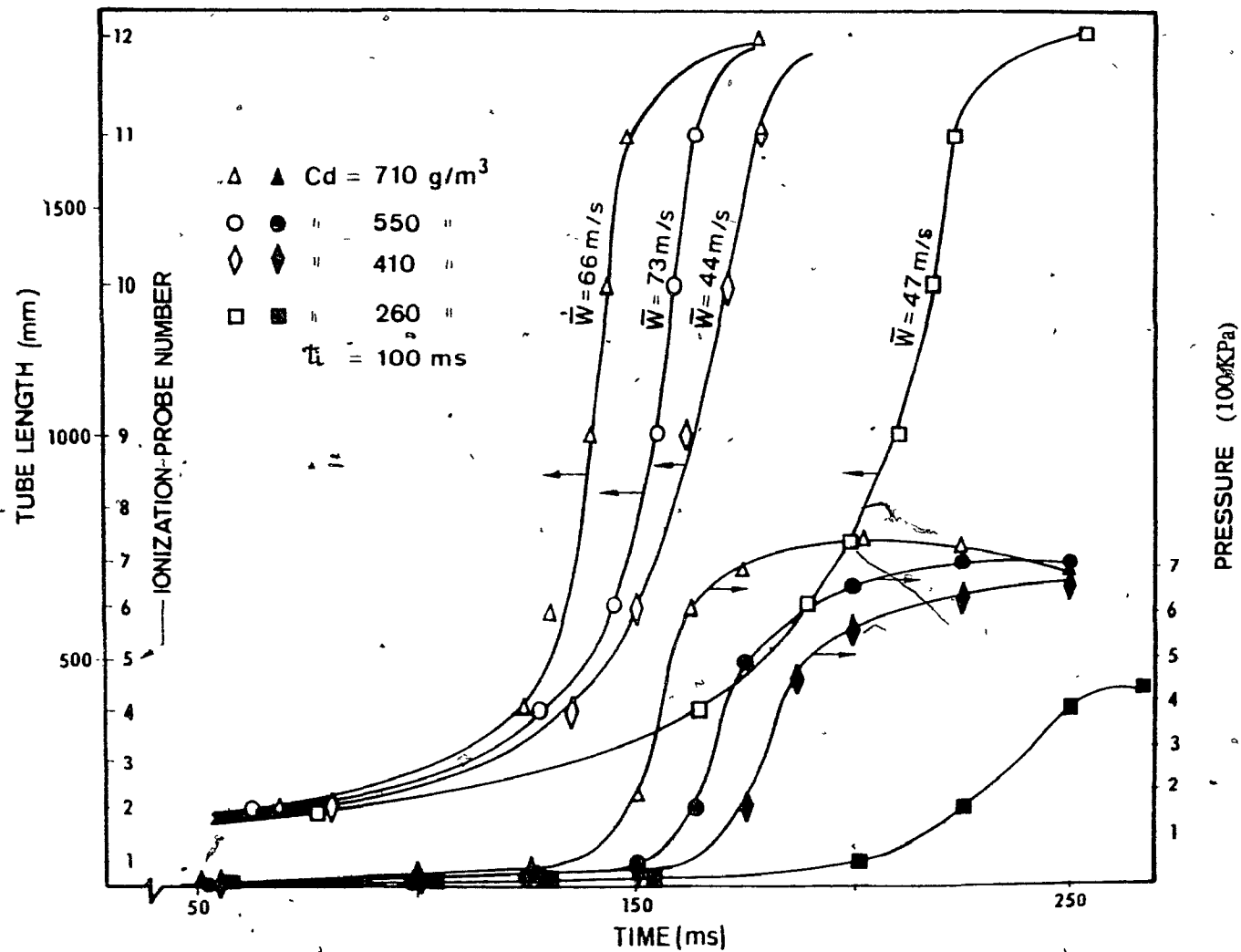


Fig.64. The pressure rise and the location of the flame front through obstacles along a 1.86 meter closed tube as a function of time for combustion in a cornstarch dust-air mixture with various concentrations at the ignition delay time of 100 ms.

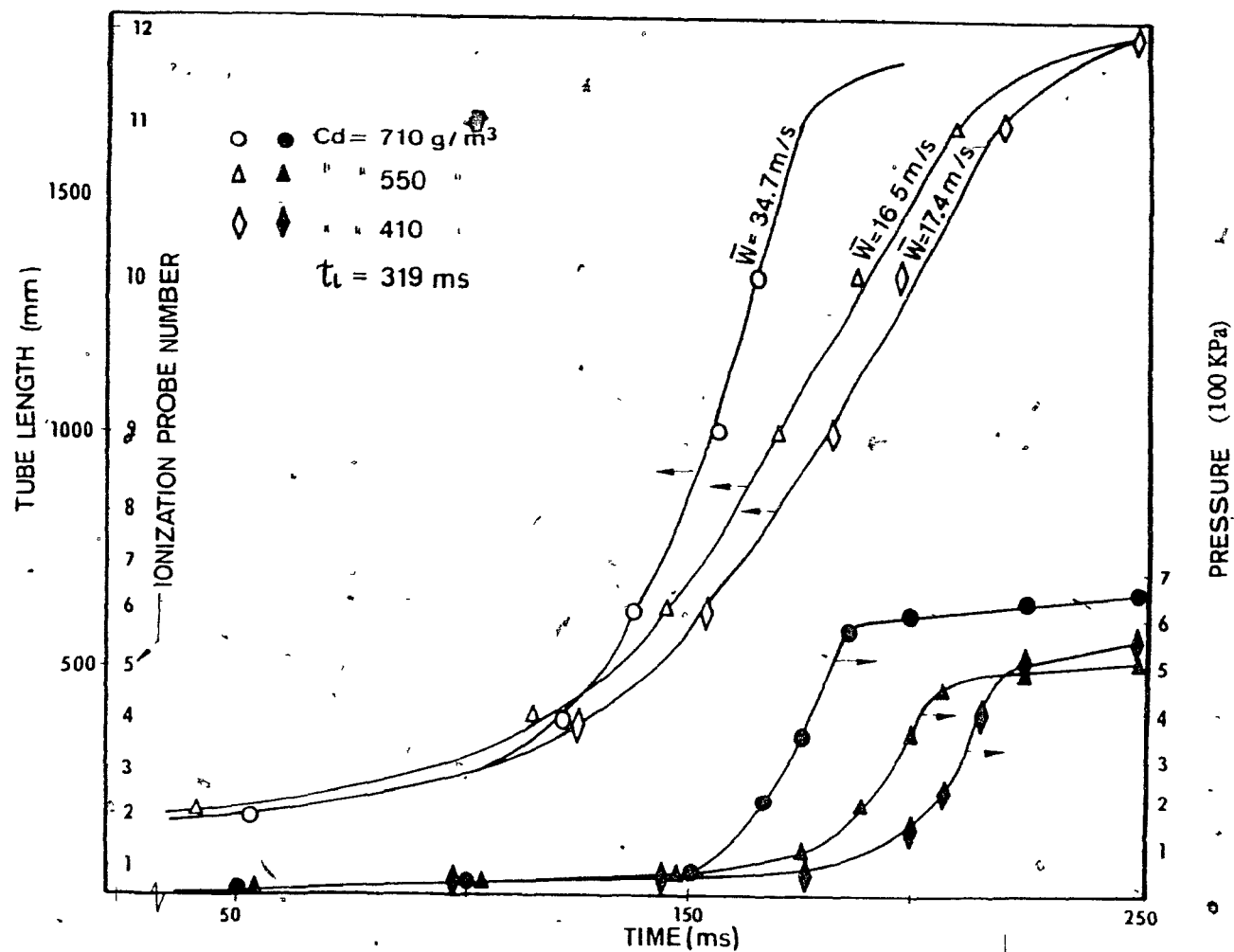


Fig.65. The pressure rise and the location of the flame front through obstacles along a 1.86 meter closed tube as a function of time for combustion in a cornstarch dust-air mixture of various concentrations at the ignition delay time of 319 ms

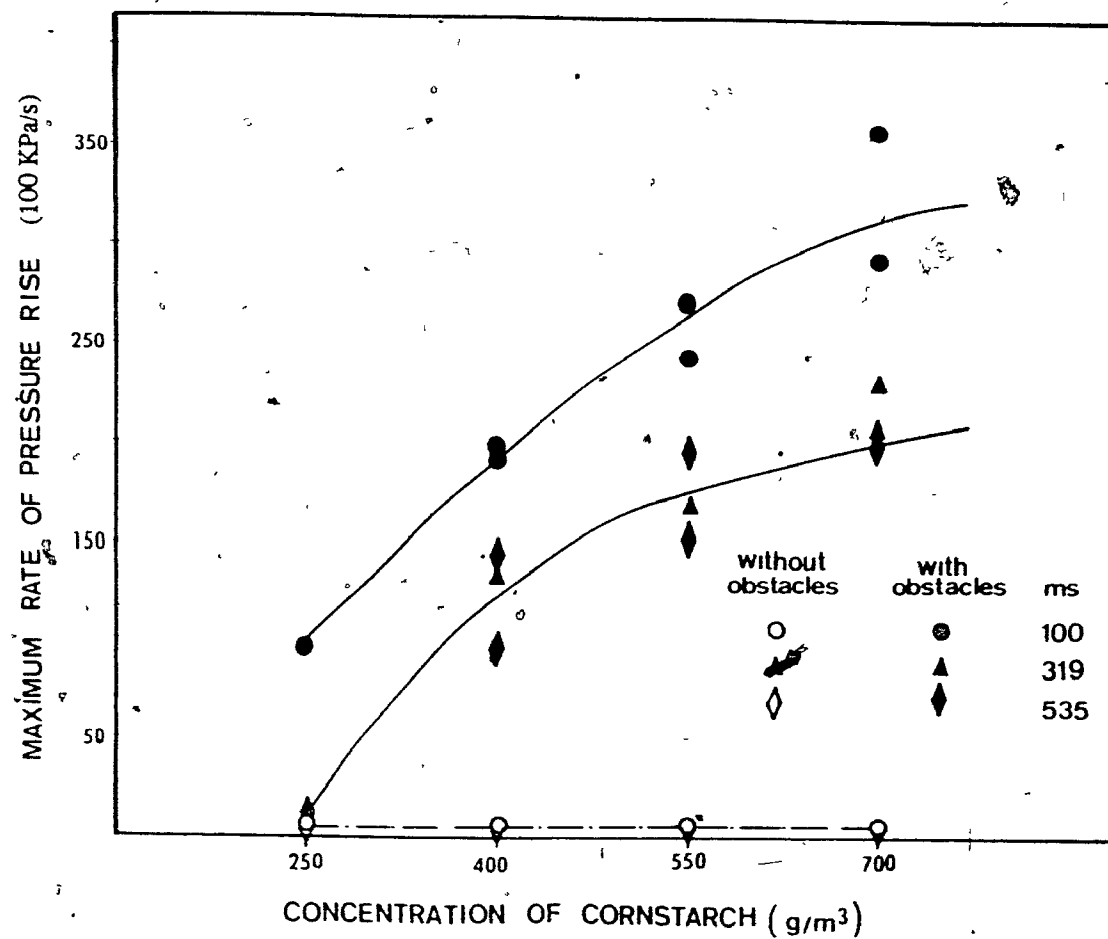


Fig 66. The influence of the obstacles on the maximum rate of pressure rise as a function of the cornstarch concentration.

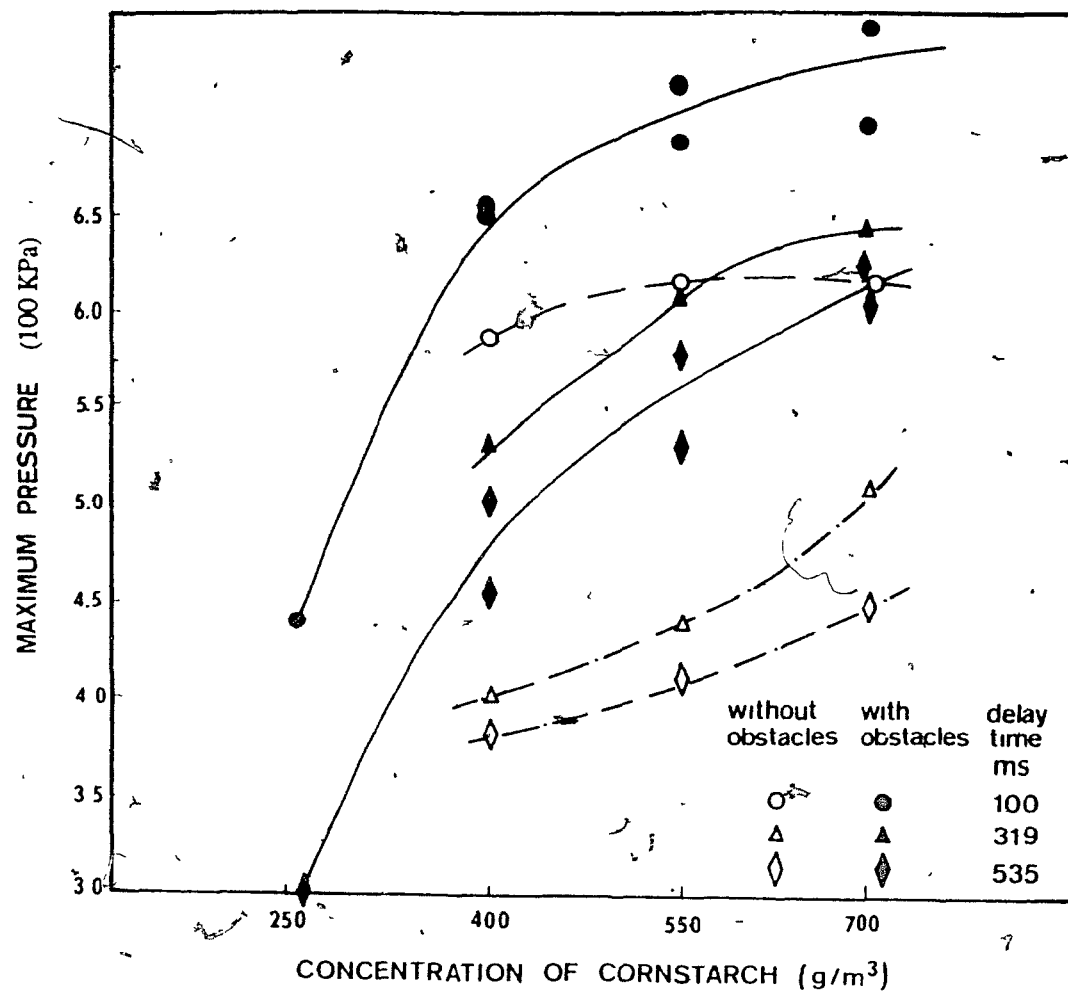


Fig 67. The influence of obstacles on the maximum pressure rise as a function of cornstarch concentration.

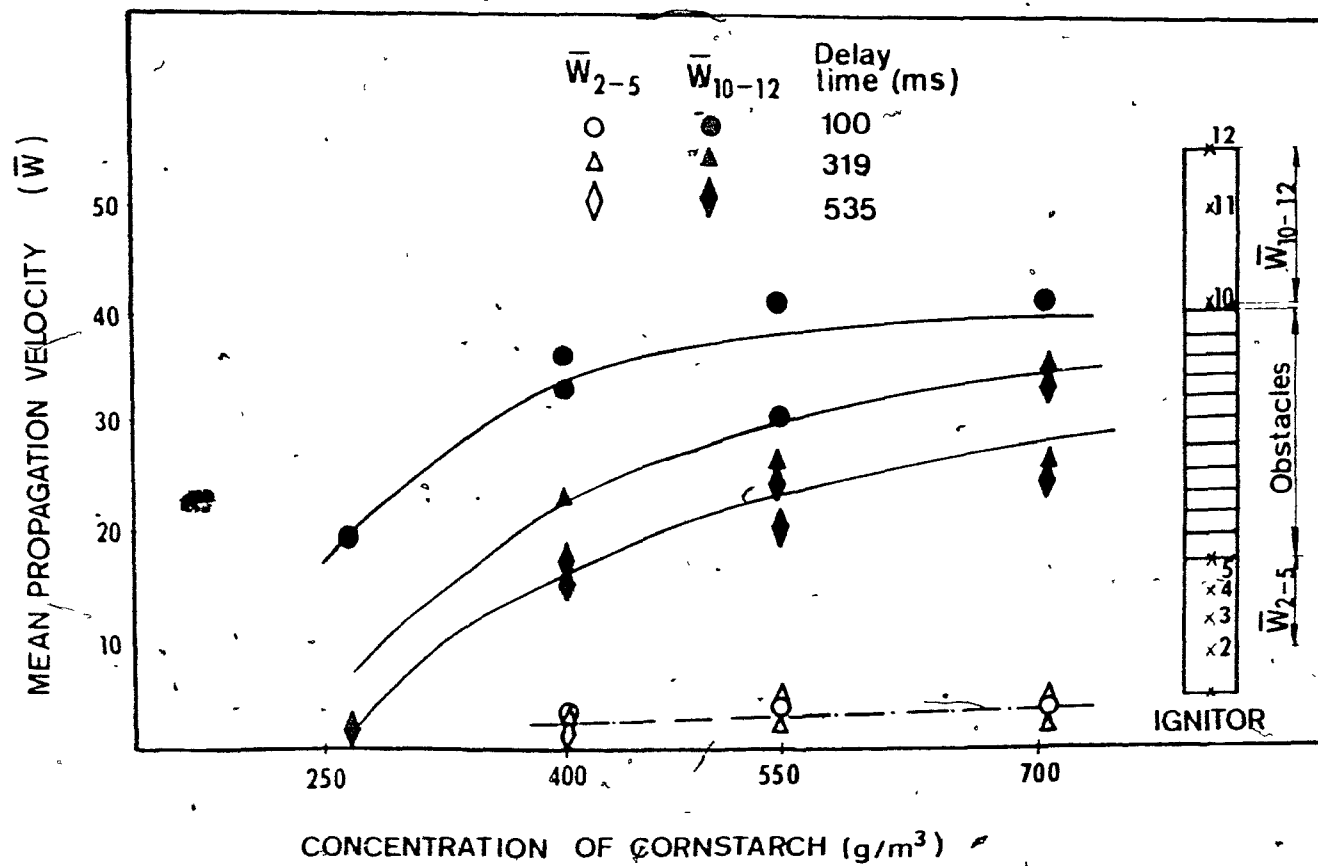


Fig.68 The influence of the obstacles on the mean propagation velocity as a function of cornstarch concentration.

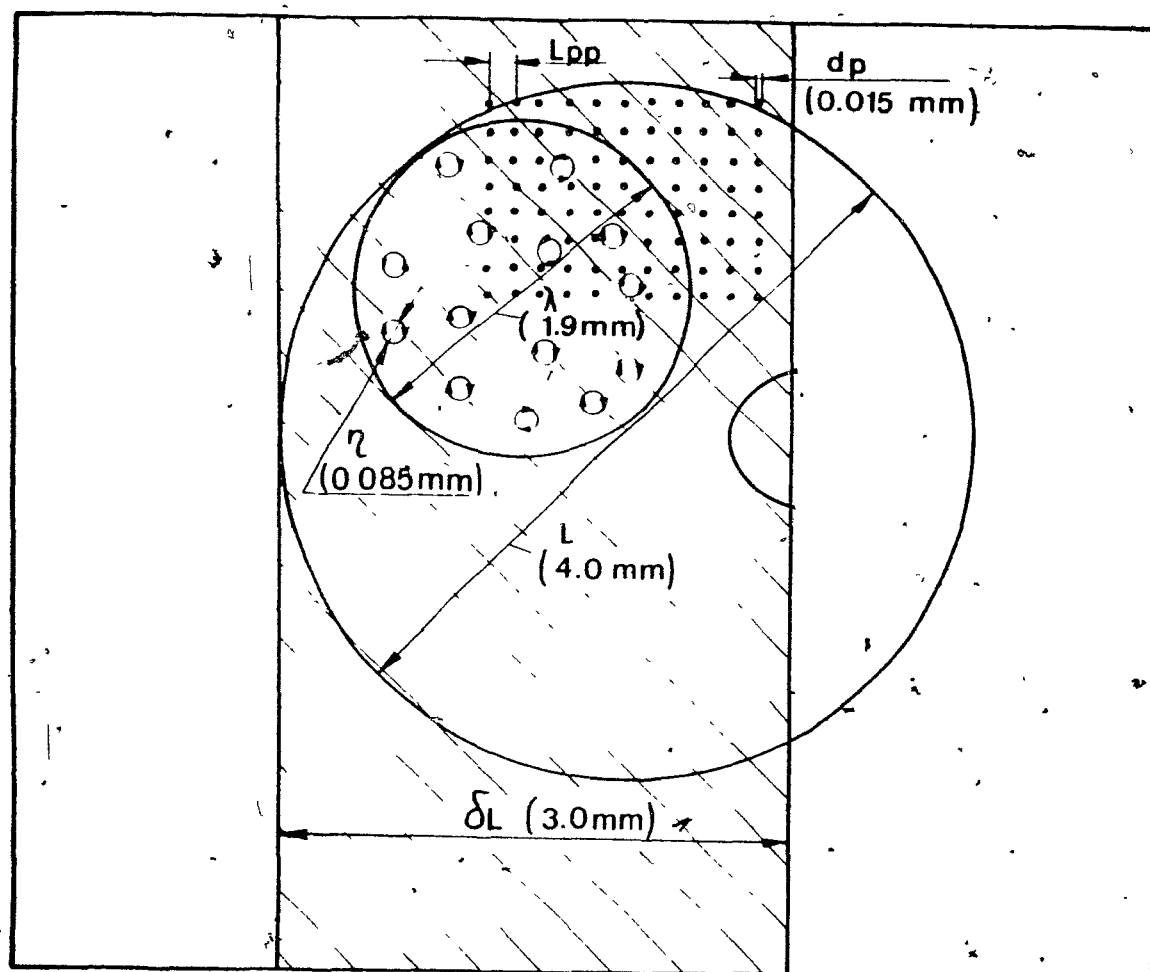


Fig.69 A comparison of lengths between dust particles, interparticle spacing and turbulent eddies

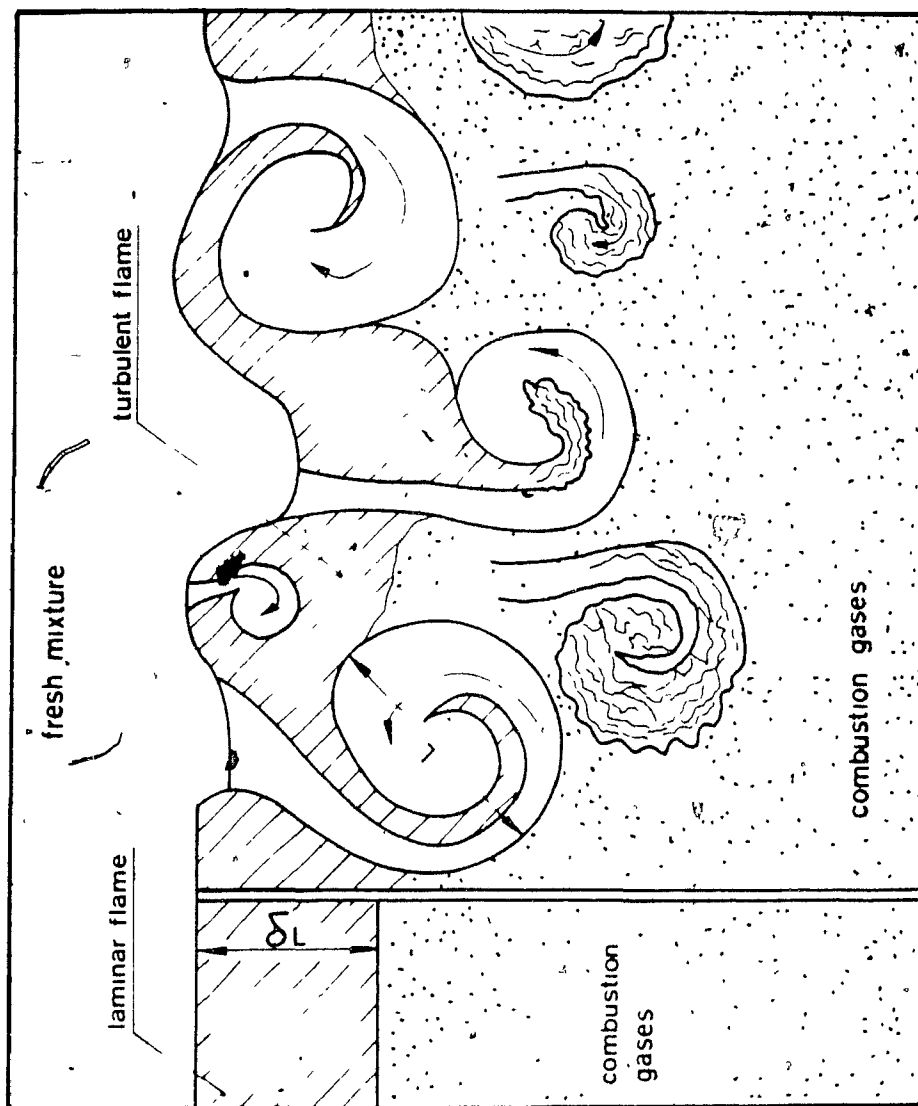
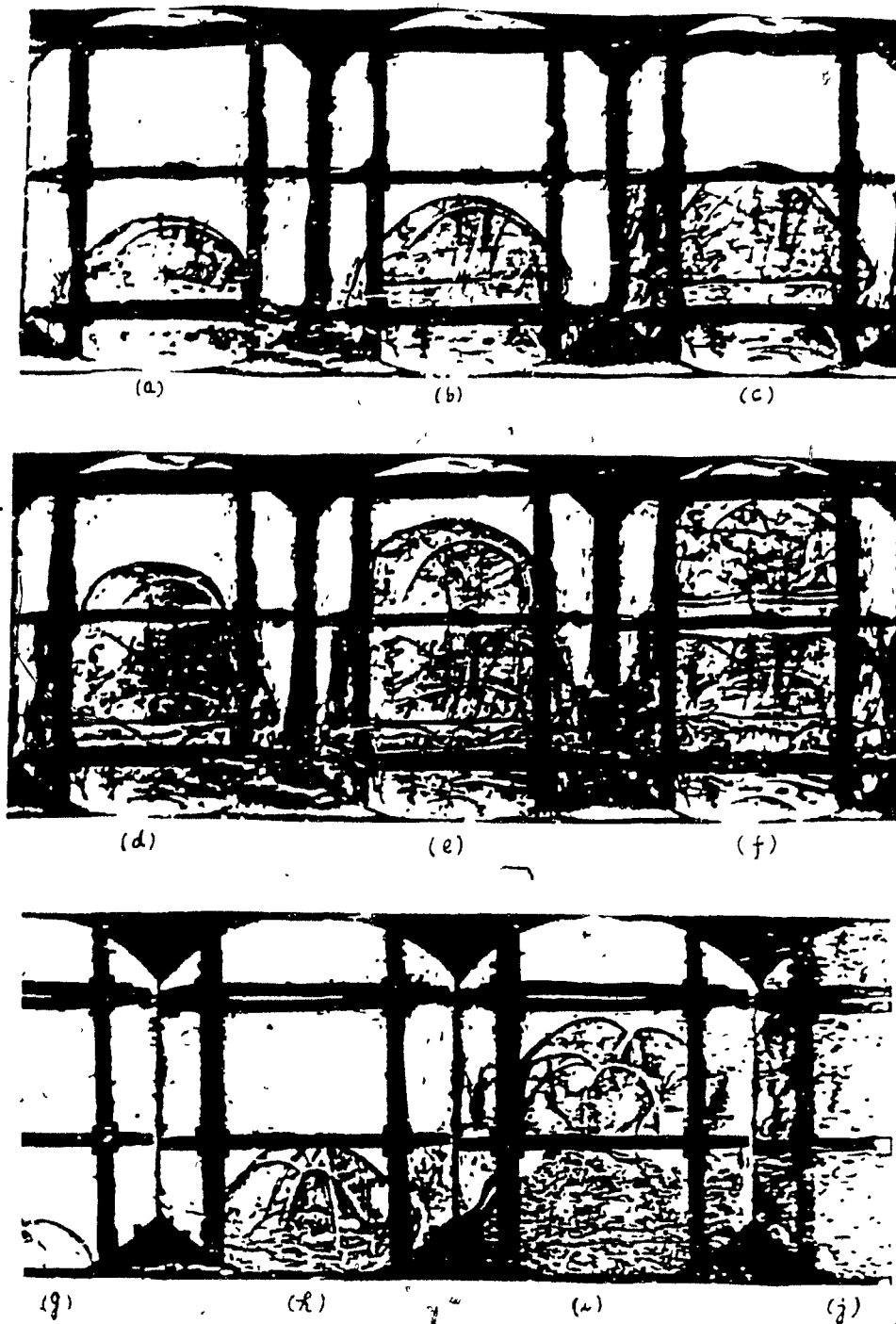


Fig.70. Physical model of a turbulent dust flame front.



Figs. a), b), c), d), e), f) are measured in the (I) part of the test tube,
Figs. g), h), i), j), are measured in the (II) part of the test tube.

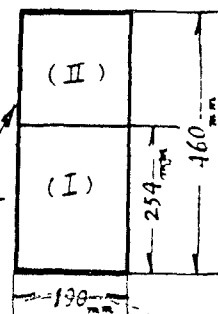


Fig.71 (a). Schlieren pictures of flame propagation in 7.3% CH_4 methane-air through obstacles from a closed end of an open rectangular duct (190mm x 190mm x 460mm), ignition at bottom end and propagation upward.

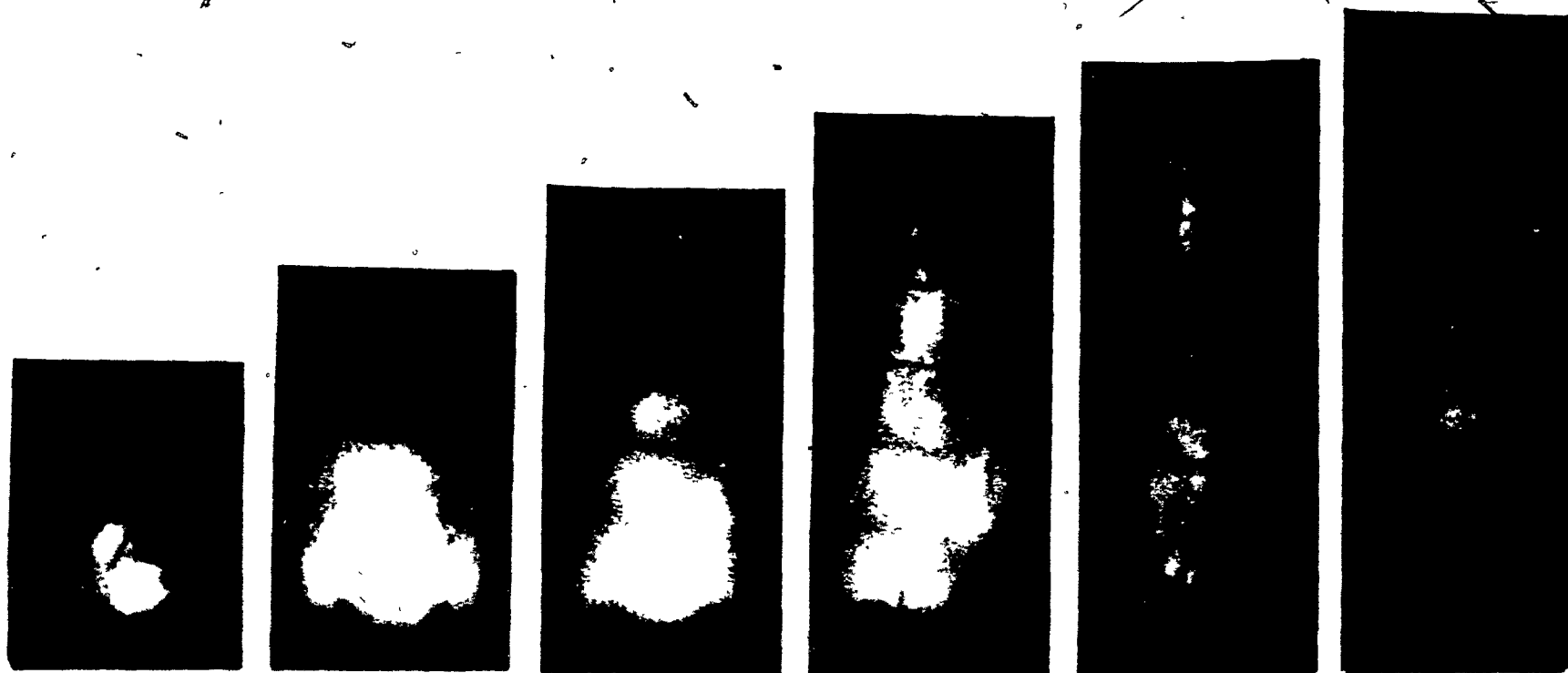


Fig.71 (b). A sequence of flames extrated from a movie of comstarch dust-air flame propagating^o through obstacles from a closed end of open rectangular duct (178mm x178mm x1000mm). Ignition with 0.6 grams black powder, 30 ms time interval between frames with initial frame 20 ms after ignition. Ignition delay time= 430 ms, cornstarch dust concentration= 560g/m³

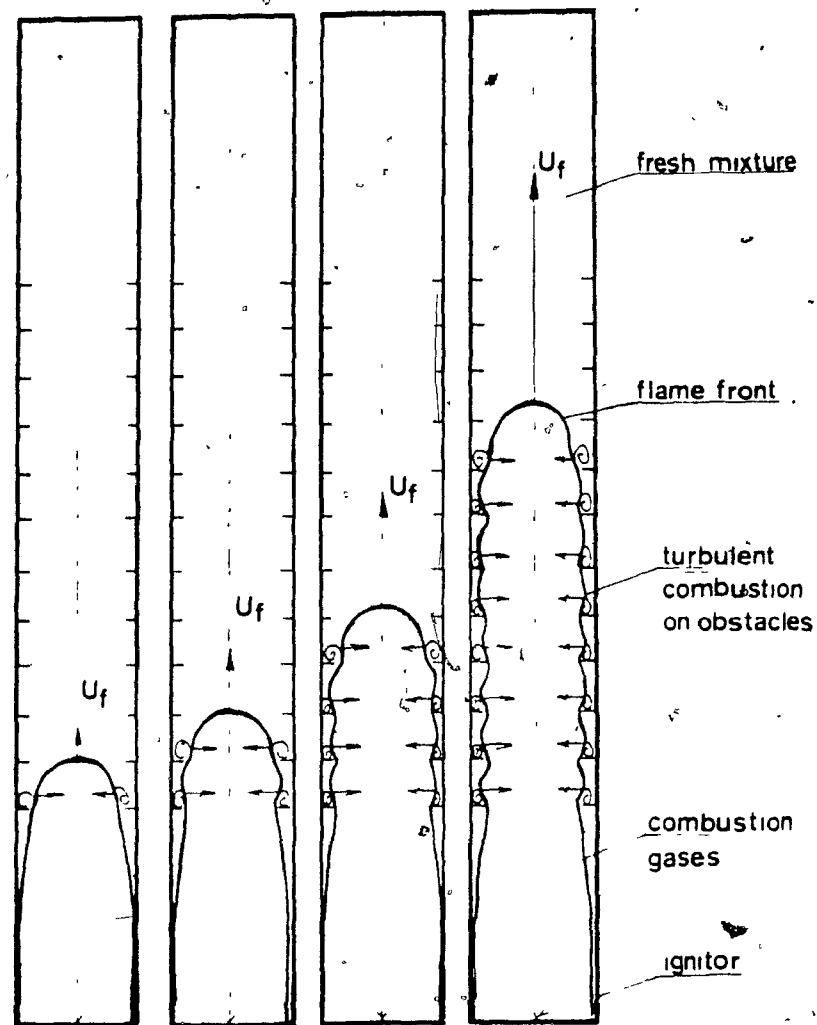


Fig.72. Mechanism of flame acceleration by obstacles.

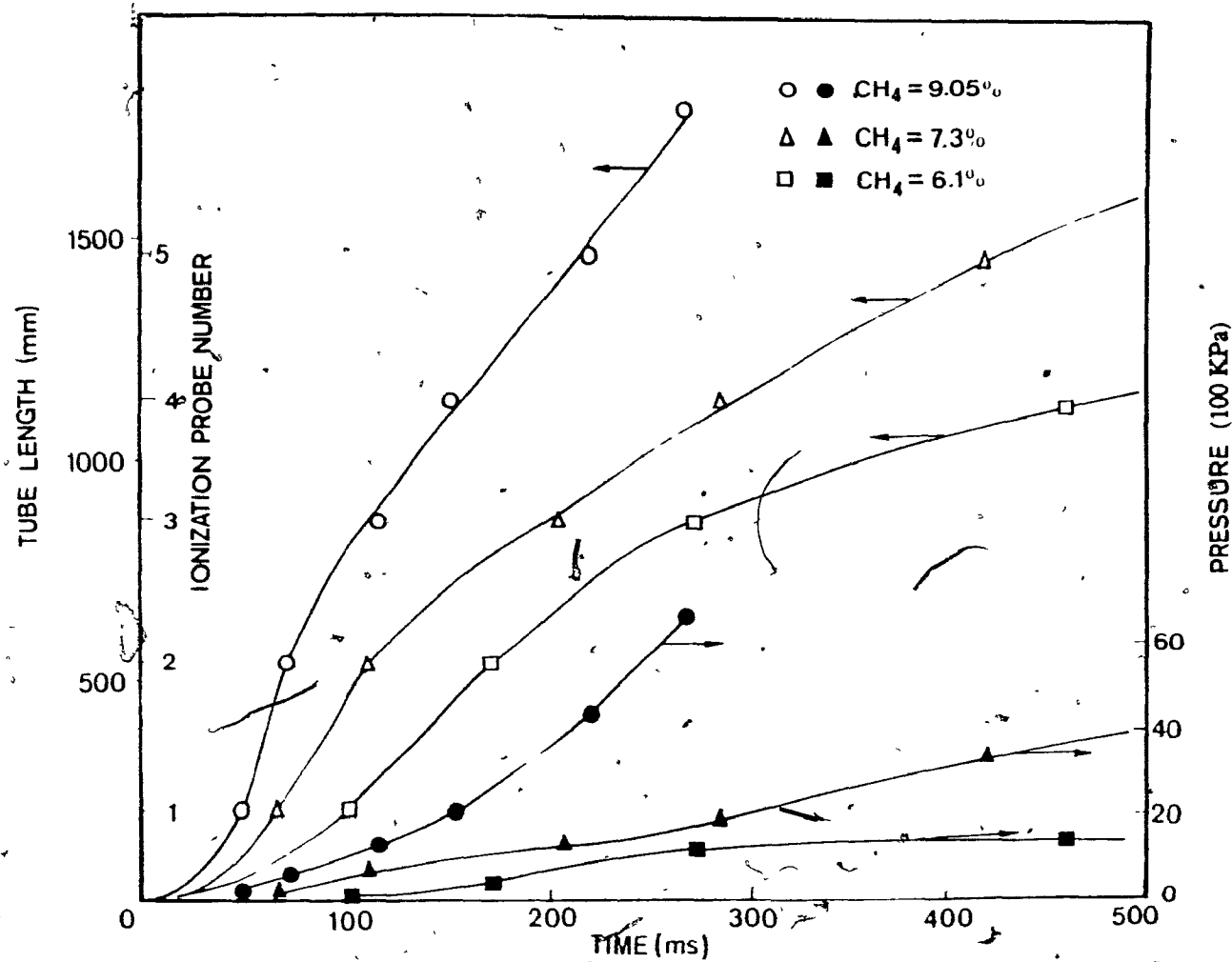


Fig B -1. The pressure rise and the location of the flame front as a function of time for various compositions of the methane-air mixture of a laminar propagation in a 1.86 meter closed tube.

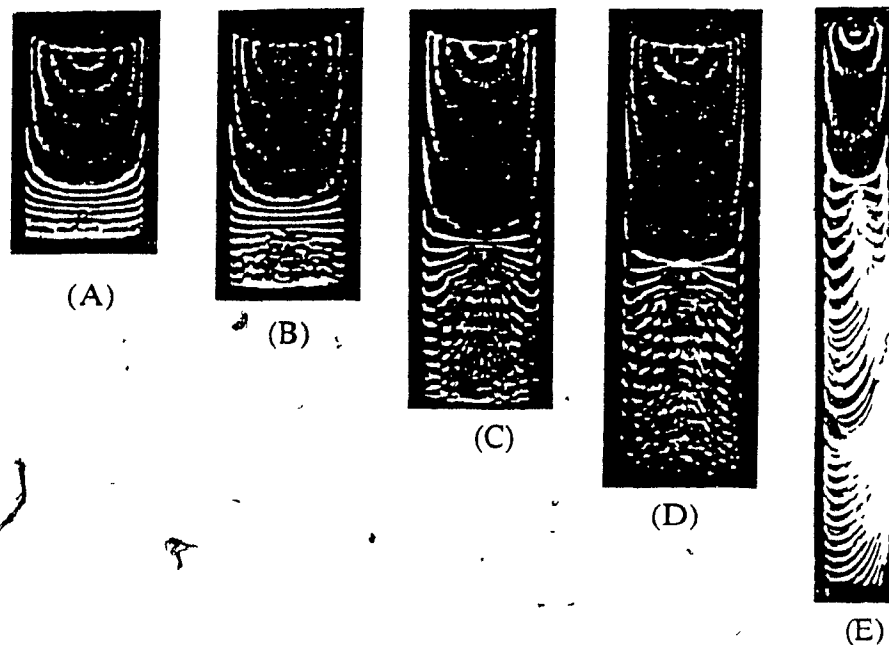
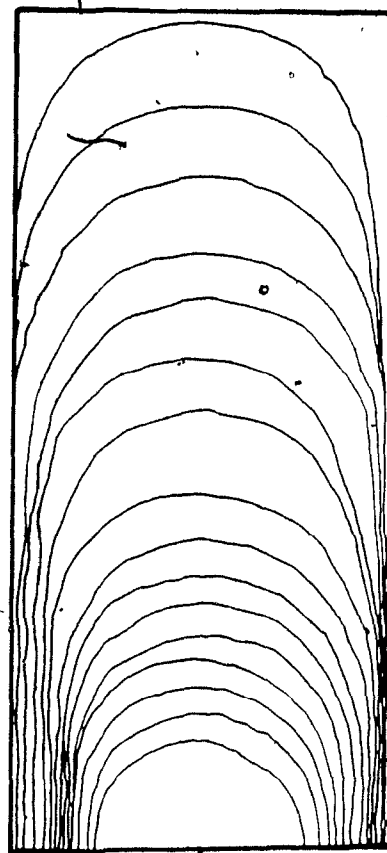
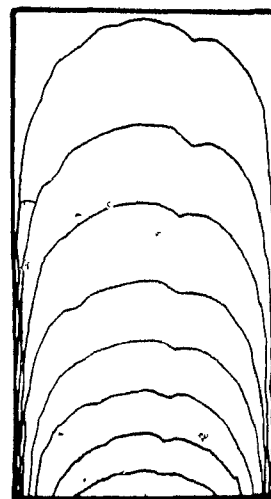


Fig. B -2(a). Tracing of flame front propagating inside a closed tube [127] in a mixture of 10 parts CO +1 part O_2 .

- (A). 50mm D x 95mm L,
- (B). 50mm D x 120mm L,
- (C). 50mm D x 170mm L,
- (D). 50mm D x 195mm L,
- (E). 25mm D x 230mm L.



IGNITOR
(a)



IGNITOR
(b)

Fig. B -2(b). Tracings of flame front propagating from the closed end of the tube (open at the top) in methane-air mixture with a concentration of 6.2% CH_4 .

(A). 178mm x 178mm x 457mm L,

(B). 127mm x 127mm x 203mm L.

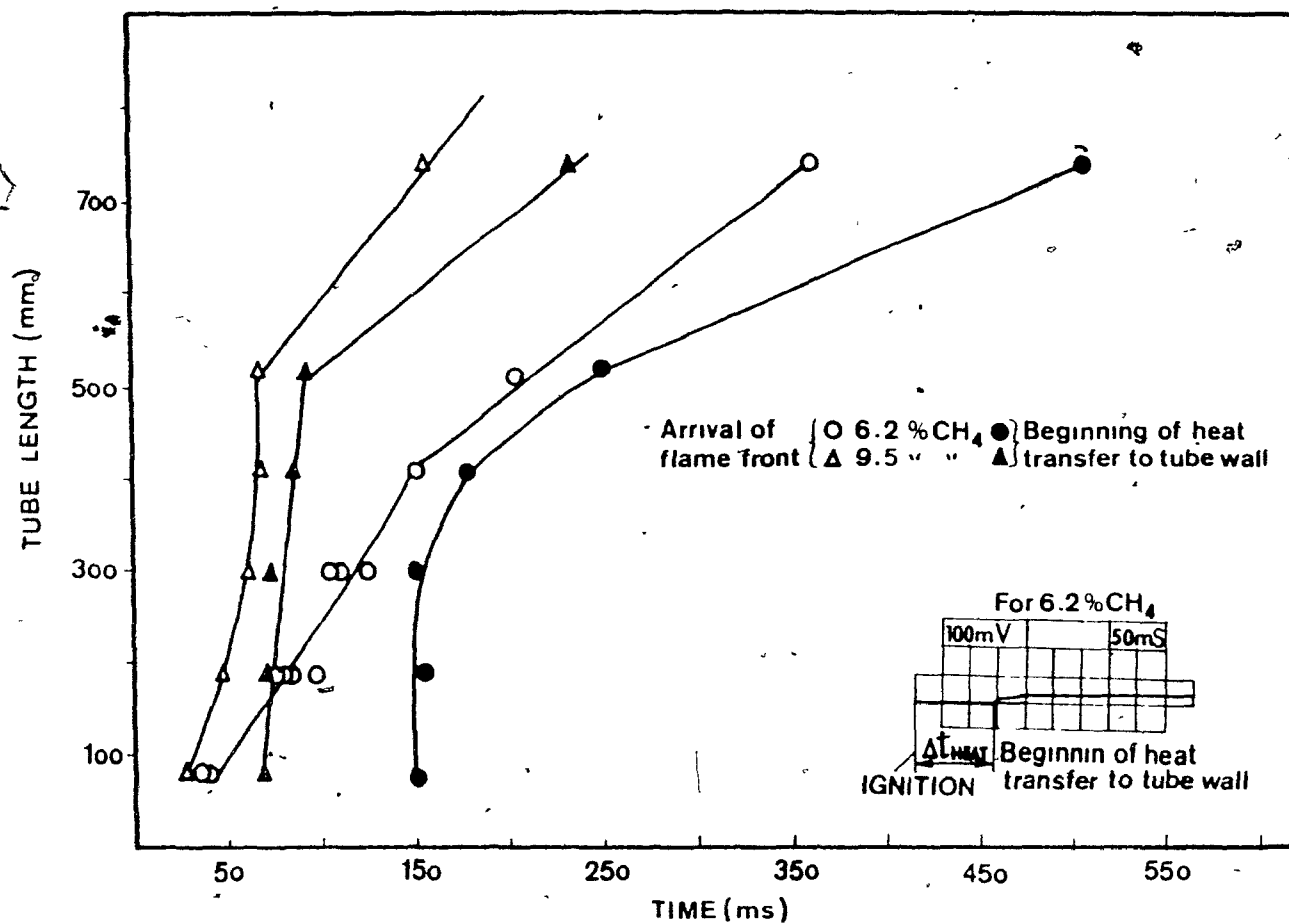
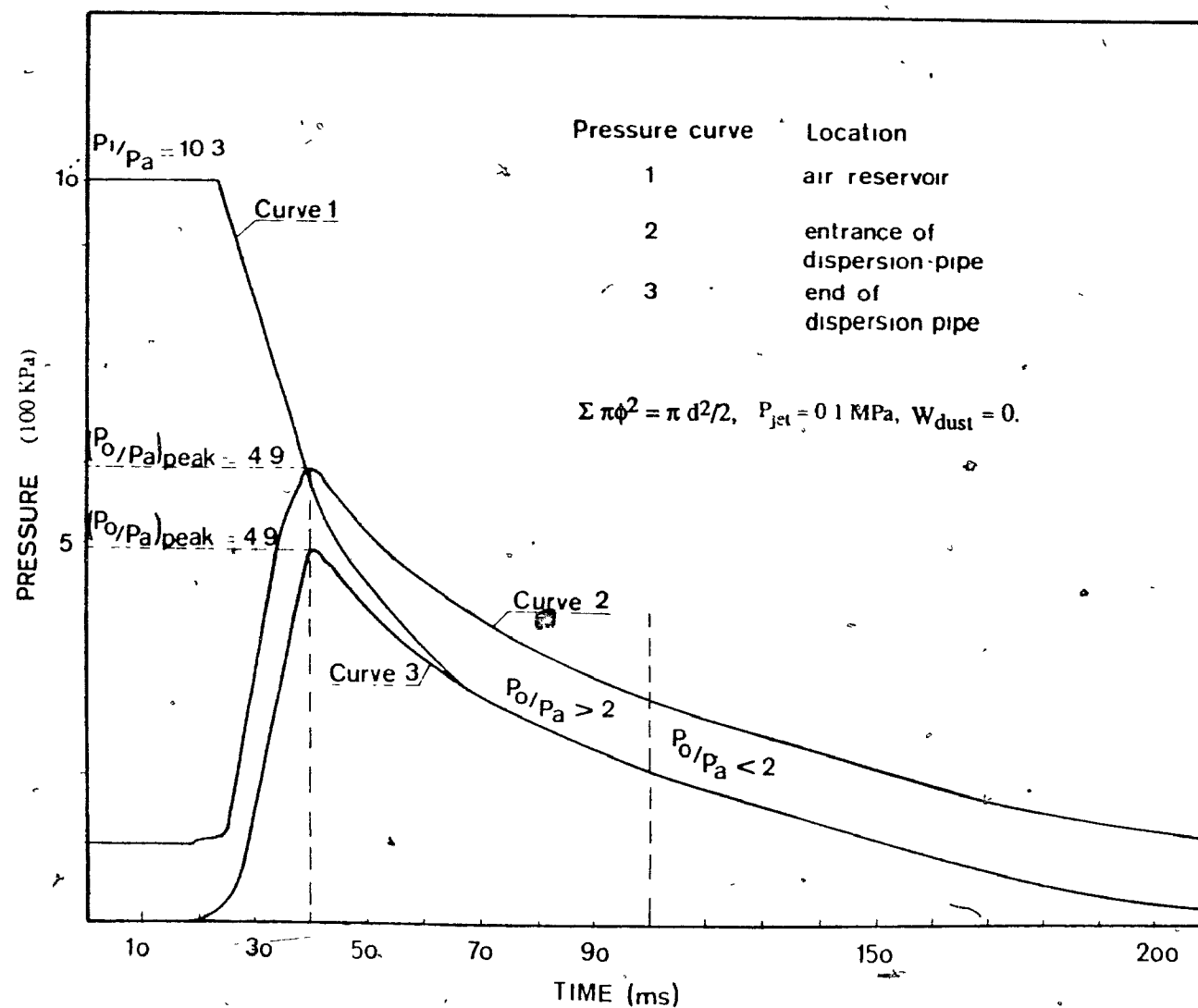
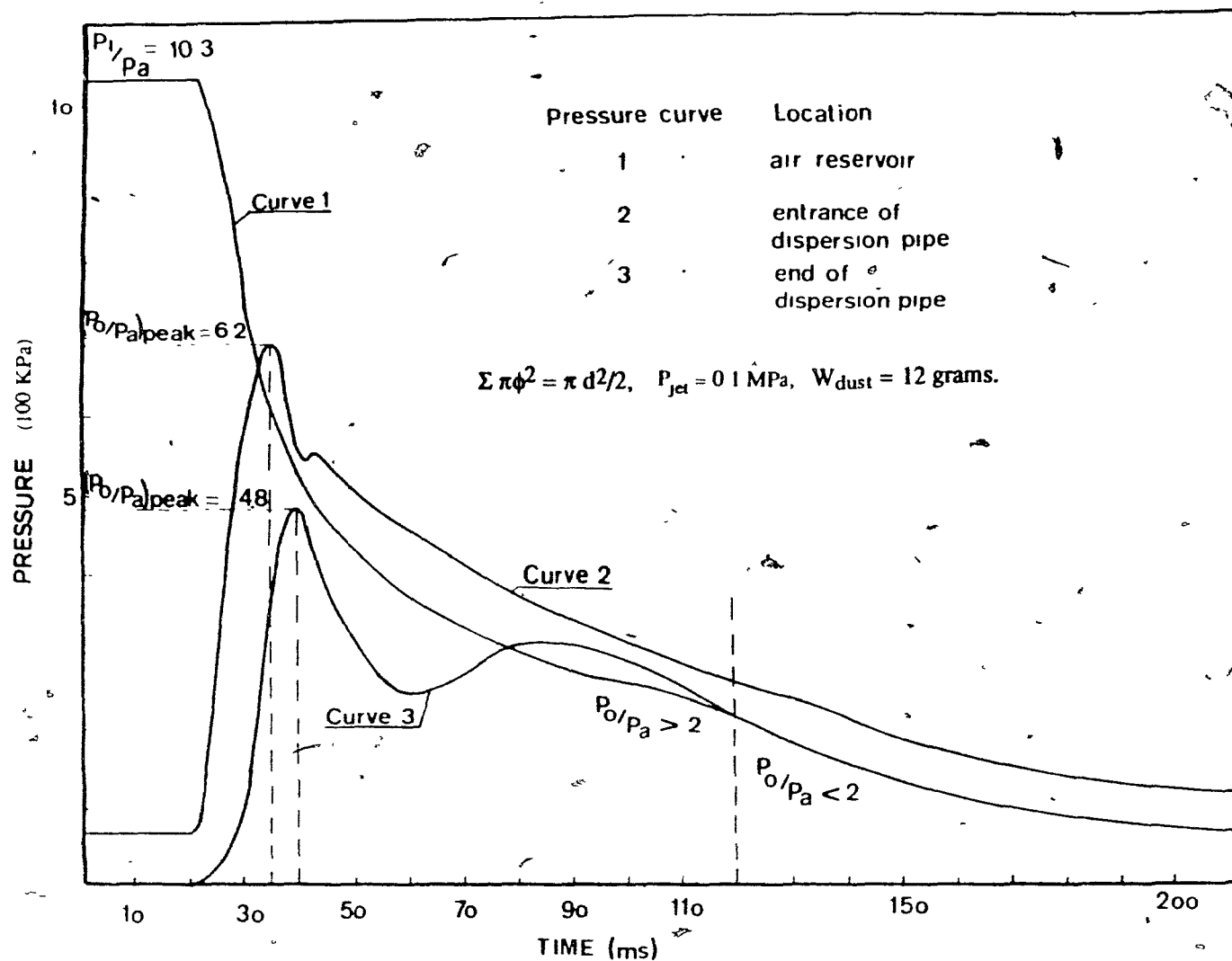


Fig. B -3. The locations of the flame front and the surface temperature rise of the wall of the test tube as a function of time for a laminar flame propagation along a 0.93 meter closed tube.



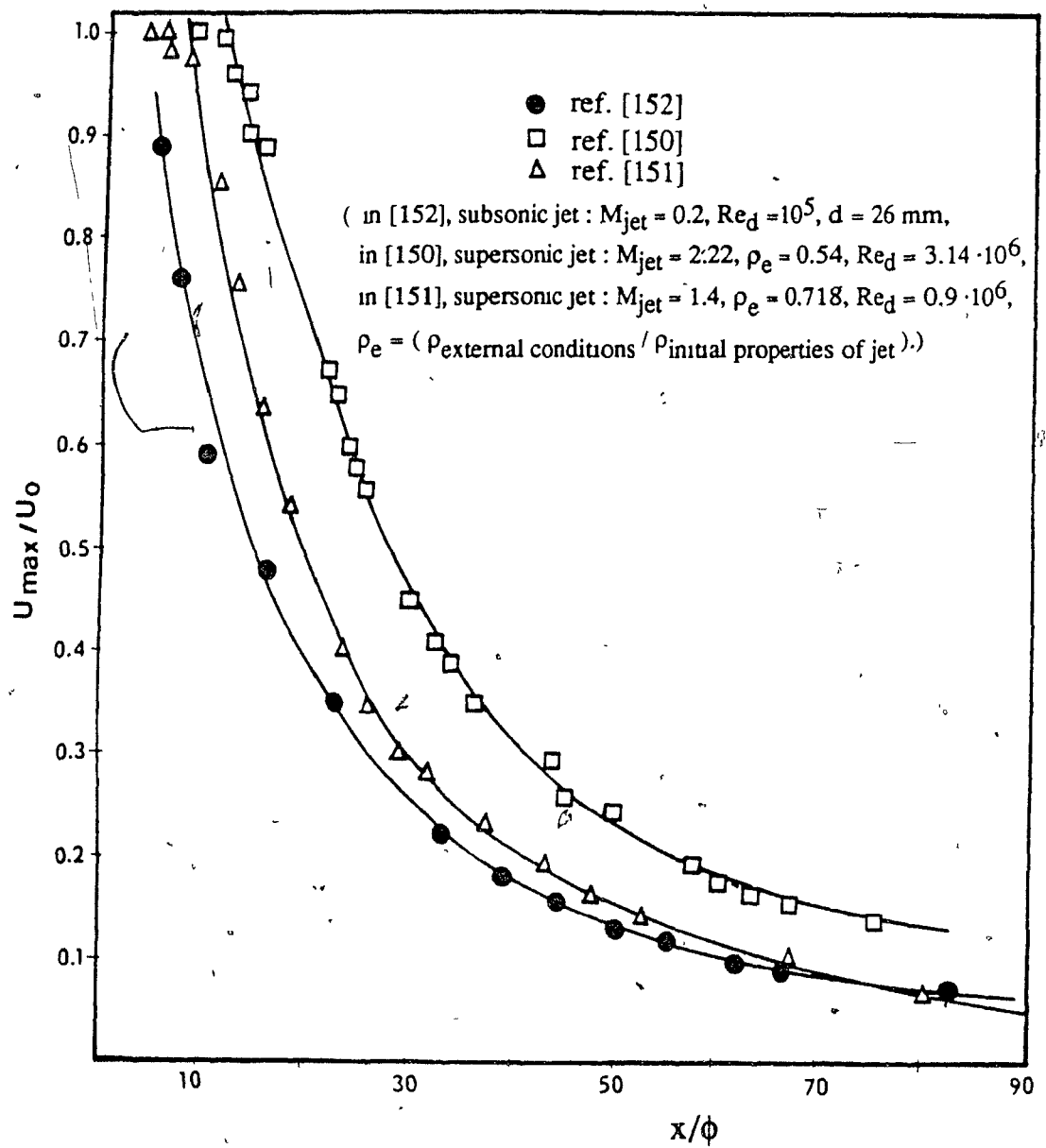
P_{jet} : initial pressure in the air reservoir, W_{dust} : initial amount of dust in the dust vessel

Fig. C -2(a). Pressure histories during discharging process of pure air in the air reservoir, in the entrance and in the end of the dispersion pipe of the dispersion system.



P_{jet} : the initial pressure in the air reservoir, W_{dust} : the initial amount of dust in the dust.

Fig C - 2(b). Pressure histories during discharging process of dust-air mixture in the air reservoir, in the entrance and in the end of the dispersion pipe of the dispersion system.



U_{max} : jet velocity along the center-line of the jet,
 U_0 : initial jet velocity along the center-line of the jet,
 x : distance along the center-line of the jet,
 ϕ : diameter of the orifice.

Fig. C -3. Jet velocity versus distance.

TABLE 1

K_{st} values measured for cornstarch dust in different closed testing apparatus ($K_{st} = (dP/dt)_{max} V^{1/3}$)

Source	$(dP/dt)_{max}$ (100 KPa sec ⁻¹)	Volume of apparatus (m ³)	$(K_{st})_{max}$ (100 KPa sec ⁻¹ m)
Kauffman et al. [21]	72.0	0.95	71 ($u = 4.2$ m/s)
" "	20.0	0.95	19.7 ($u = 0.5$ m/s)
Bond et al. [20]	50.0	0.33	34.6
Aldis et al. [46]	320.0	0.02	87.6
Bartknecht [7]	680.0	0.00123	73.0
Nagy & Verakis [9]	1864.0	0.00123	200
" "	816.3	0.00123	87.7
Field [8]	612.2	0.00123	65.6
" "	412.8	0.00906	88.1
" "	272.1	0.02832	83.0
" "	136.0	3.115	198.5
" "	110.5	6.740	208.6
" "	55.3	13.375	132.4
Current Investigation	10 - 20	.0264 *	5 - 10 ($u' < 10$ cm/s)
" "	60 - 80	.0264 *	30 - 40 ($u' \approx 0.6$ m/s)
" "	200 - 300	.0264 *	100 - 150 (obstacles)

* Ignited at the closed end of test tube. This case can be considered approximately double length of flame propagation ($2V^{1/3}$) comparing to the center ignition ($V^{1/3}$)

TABLE 2

The characteristics of laminar dust flames measured in
different open testing apparatus

Source	Name of fuel	d_p (μm)	δ_l (cm)	U_l (cm/s)	$(D_q)_{min}$ (cm)	E_{min} (mJ)
Ballal [16]	coal (20% volatile)	30		8		
Ballal [16]	coal (40% volatile)	30		15		
Slezak et al. [18]	Pittsburgh coal	50		34		
Smoot et al. & Horton et al. [72]	Pittsburgh coal	33	1.0	16 - 33		
Milne & Beachey [28]	" "	10 - 20	1.0	10 - 15		
Strehlow et al. [33]	" " "	10 - 90		4 - 14		
Cassel et al. [46]	aluminium	0 - 40		19 - 25		
Cassel et al. [71]	" "	< 5		15 - 22.5		
Ballal [16]	" "	30		18		
Mason & Wilson [77]	lycopodium	/	0.2	14 - 25		
Ballal [16]	magnesium	/		23		
Jarosinski et al. [38]	cornstarch	15			0.55	
" "	aluminium flakes	15 x 0.1			1.05	
" "	atomized aluminium	7.5 - 9.5			1.05	
" "	bituminous coal	< 5			2.5	
Proust & Veyssier [70]	cornstarch	~20		15 - 30	0.6	
Eckhoff [37]	aluminium flakes	10 x 0.1				0.3 - 0.9
" "	wheat grain	55				12
" "	lycopodium	/				9
Bradley [104]	CH ₄ 6%		0.23	17 (adiabatic)		
" "	CH ₄ 5.3%		0.5	~12 (adiabatic)		
Jarosinski et al. [38]	CH ₄ 6%				0.4 - 0.6	
" " "	CH ₄ 5.3%				0.6 - 0.9	
Lewis & Elbe [106]	CH ₄ 6% / 5.3%					9 / 19

TABLE 3
The correction of nominal dust concentration

Dispersion system	Initial amount of cornstarch in dust vessel (g) Nominal dust concentration (g/m ³)	Amount of dust left in dispersion system (g)	Amount of dust dispersed into test tube (g) Real dust concentration (g/m ³)	Amount of dust collected from bottom flange of test tube (g)	Amount of dust stuck on the tube walls (g)
IV $P_{jet} = 0.1 \text{ MPa}$	8 / 315	1.43	6.6 / 260	4.6	2.0
	12 / 472	2.0	10.0 / 394	8.3	1.7
	16 / 630	2.0	14.0 / 551	12.3	1.7
	20 / 787	2.0	18.0 / 709	15.2	2.8
II $P_{jet} = 0.1 \text{ MPa}$	8 / 315	0.9	7.1 / 280	4.8	2.3
	12 / 472	0.9	11.1 / 437	9.0	2.1
	16 / 630	0.9	15.1 / 595	12.0	3.1
	20 / 787	0.9	19.1 / 752	15.7	3.4

IV $\sum \pi \phi^2 = \pi d^2/2$, uniform initial axial distribution of dust concentration

II $\sum \pi \phi^2 = \pi d^2/2$, non-uniform initial axial distribution of dust concentration

TABLE 4

**The decay feature of mean flow velocity (corresponding to Fig.5)
and rms turbulence velocity**

Ignition delay time (ms)	50	100	150	200	300	400	500	600	700	800	900	1000
Mean flow velocity (cm/s)	600	400	300	240	180	150	100	75	60	50	40	<40
RMS turbulence velocity (cm/s)	60	40	30	22	20	15	10	7.5	6	5	4	<4

$$\text{RMS turbulence velocity} = (u'/\bar{u}) \times \bar{u}$$

The ratio of $u'/\bar{u}$ is obtained from measurements of comparison of Fig.7 and Fig 8,
and the value of this ratio is considered as constant during turbulence decaying process.

TABLE C

**The characteristics of the process during the pressure discharging
through the entire dispersion pipe**

Table C-1 : $\Sigma \pi \phi^2 = \pi d^2/2$, (d : diameter of dispersion pipe, ϕ : diameter of dispersion orifice.)

P_{initial} (in the air reservoir) (100 KPa)		10 3	10 3	10.3
W_{dust} (initial amount of cornstarch in dust vessel) (grams)		0	12	12
t (solenoid valve activation) (ms)		22	22	22
t (pressure starts to raise in dispersion pipe) (ms)	Entrance	22	22	22
	End	24	25	28
t (pressure arrives to peak value in dispersion pipe) (ms)	Entrance	40	35	36
	End	40	40	41
t (pressure decreases to critical value P _c / P ₀ in dispersion pipe) (ms)	Entrance	100	120	130
	End	100	130	150
P_{max} (in dispersion pipe) (100 KPa)	Entrance	5 0	4 8	6 2
	End	4 8	3 7	4.7

TABLE C

The characteristics of the process during the pressure discharging
through the entire dispersion pipe

Table C -2 : $\Sigma \pi \phi^2 = \pi d^2$, (d : diameter of dispersion pipe, ϕ : diameter of dispersion orifice.)

P_{initial} (in the air reservoir) (100 KPa)		10.3	10.3	10.3
W_{dust} (initial amount of cornstarch in dust vessel) (grams)		0	12	20
t (solenoid valve activation) (ms)		24	23 ^s	22
t (pressure starts to raise in dispersion pipe) (ms)	Entrance	26	23	22
	End	29	28	30
t (pressure arrives to peak value in dispersion pipe) (ms)	Entrance	34	37.5	50
	End	36	37	75
t (pressure decreases to critical value P_0/P_c in dispersion pipe) (ms)	Entrance	55	80	90
	End	45	70	75
P_{max} (in dispersion pipe) (100 KPa)	Entrance	4.1	4.8	4.8
	End	2.9	3.6	3.7