## Studies of Flame Instabilities in Hele-Shaw Cell



### Samouil Balevski

### Department of Mechanical Engineering, McGill University

Thesis supervisor: Professor J.M. Bergthorson

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### Abstract

Methane and propane flames at various equivalence ratios were recorded in a Hele-Shaw cell using a highspeed camera. Methane flames were then seeded with silicon carbide particles using a particle dispersion system to investigate the effects of inert particles on flame stability. In particular, the effect on thermo-diffusive instabilities was studied by measuring the average flame speed, the number of cells formed and the size of these cells using in-house MATLAB codes. A laser and oscilloscope setup were used to measure the transmittance of the mixture in the cell, a measure of the concentration of particles in the flow. The Arrhenius law states that the areanormalized average flame speed decreases as the concentration of inert particles increases because of a lower temperature of reaction. However, results indicate that as a flame becomes more thermodiffusively unstable, the flame surface area increases leading to high-temperature convex regions which can overcome the Arrhenius law and lead to no substantial change in the average flame speed. Furthermore, an increase in the concentration of inert particles leads to the formation of a higher number of cells. However, there is not enough numerical evidence of the effect on the average cell size due to limitations of the MATLAB codes which were used to track the cells in the flame front. In conclusion, the addition of inert particles increases the thermo-diffusive instability in a flame leading to a substantial increase in the formation of cellular structures resulting in a higher number of cells formed. Furthermore, the average flame speed for methaneair flames is effectively independent of the concentration of inert solid silicon carbide particles.

### Abstrait

Des flammes de méthane et de propane à divers rapports d'équivalence ont été enregistrées dans une cellule Hele-Shaw à l'aide d'une caméra haute vitesse. Des particules de carbure de silicium sont introduits dans des flammes de méthane en utilisant un système de dispersion de particules pour étudier les effets des particules inertes sur la stabilité de la flamme. En particulier, l'effet sur les instabilités thermo-diffusives a été étudié en mesurant la vitesse moyenne de la flamme, le nombre de cellules formées et la taille de ces cellules en utilisant des codes MATLAB développés localement. Un laser et un oscilloscope ont été utilisés pour mesurer la transmittance du mélange dans la cellule. La loi d'Arrhenius stipule que la vitesse moyenne de la flamme normalisée en fonction de la surface diminue à mesure que la concentration de particules inertes augmente en raison d'une température de réaction plus basse. Cependant, les résultats indiquent que lorsqu'une flamme devient de plus en plus instable sur le plan thermo-diffusif, la surface de la flamme augmente, conduisant à des régions convexes à haute température qui peuvent s'affranchir de la loi d'Arrhenius et ne pas entraîner de modification substantielle de la vitesse moyenne de la flamme. De plus, une augmentation de la concentration de particules inertes conduit à la formation d'un nombre plus élevé de cellules. Cependant, il n'ya pas assez de preuves numériques de l'effet sur la taille moyenne des cellules en raison des limites des codes MATLAB utilisés pour suivre les cellules dans le front de flamme. En conclusion, l'ajout de particules inertes augmente l'instabilité thermo-diffusante dans une flamme, ce qui entraîne une augmentation substantielle de la formation de structures cellulaires, ce qui entraîne un nombre plus élevé de cellules formées. De plus, la vitesse moyenne de la flamme pour les flammes air-méthane est effectivement indépendante de la concentration de particules de carbure de silicium solides inertes.

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Perhaps the single most important lesson I have learned throughout this experience is that in the world of scientific research, you may plan all you want, but in the end, you never truly know where you might end up.

### **Chapter 1**

### Introduction

The process of combustion is ubiquitous both in industry and in everyday life and is of foundational importance to society.

$$C_x H_y + O_{2(g)} \to CO_{2(g)} + H_2O_{(g)} + Heat$$
 (1)

Combustion, or burning, is an exothermic chemical reaction between a substance and oxygen which emits a large amount of energy to its surroundings as heat and light, forming oxides as products. The reaction time of combustion is exceedingly sensitive to temperature, going from an effectively infinite reaction time at T < 500K down to the order of  $10^{-6}s$  econds at around 2500K. The combustion of hydrocarbons is illustrated in Equation 1.

The exploitation of the rapid high energy release from the combustion of hydrocarbons kickstarted the Industrial Revolution in the 18<sup>th</sup> century. Human civilization benefitted from a huge leap in technological and industrial advancement which led to vast improvements in social and economic developments at that time. Today, nearly 300 years later, humanity utilizes combustion to provide its vehicles with the energy required to propel themselves across large distances on land, sea, and even through air. Electric power is also generated through combustion of fuels for storage and its subsequent transportation to factories, households, and other buildings to maintain the economic, industrial, technological prosperity of all nations and the quality of life of their citizens. Without combustion, human civilization as we know it would cease to exist.

As combustion dominated the field of power generation, research was done in developing more elegant and more efficient engines to generate an increasing amount of power in the hopes of eventually perfecting this wondrous technology.

During combustion, a flame is produced in the form of a self-perpetuating reaction wave across a fuel-oxidizer mixture. The visible part of the flame, the flame front, results from the luminescence [1] of radicals produced in the intermediate steps of the reaction and from the incandescence [2] due to the thermal electromagnetic radiation of solid particles in the flame.<sup>1</sup> As the flame propagates towards the unburnt mixture, energy generated from the initial combustion reaction is transferred to the new reactants in the form of heat, raising their temperature and sustaining the propagation of the reaction across the medium. However, instabilities can be formed in the flame front throughout its formation and propagation which may negatively impact the combustion process and threaten the structural integrity of the combustion chamber. For instance, rocket motors form an environment in which high levels of vibrations can develop which may lead to large pressure fluctuations in the injection chamber thus damaging the motor. This is precisely what happened in the Rocketdyne F-1 and Titan-II rockets when their engines were damaged by pressure variations caused by the excitation of the combustion chamber walls. As the walls were self-excited from the heat released during combustion, acoustic oscillations developed and were amplified to the point where significant increases in pressure occurred [3]. Thus, as researchers increase their understanding of flame instabilities, their formation and evolution, safer and more efficient engines can be developed with lower risks of failure.

<sup>&</sup>lt;sup>1</sup>Particles at a temperature greater than absolute zero emit energy in the form of thermal radiation. Incandescence occurs when solid particles are heated above the Draper point (798 K) where part of the radiation falls within the visible spectrum [2]. At that point solid particles such as soot begin to glow in a red-orange color. However, the blue color of hydrocarbon flames stems from luminescence, coined by Q.C. Lum [1], which is a distinct method of light emission not resulting from heat. CH Radicals produced in the intermediate steps of the combustion reaction emit light in the visible spectrum due to quantized transitions when excited. [45]

All flames have a variety of inherent instabilities that can develop during combustion. These include hydrodynamic, thermo-diffusive, and thermoacoustic instabilities.

#### 1.1 Hydrodynamic instabilities

Hydrodynamic instabilities occur in premixed flames due to the thermal expansion of the gas produced by the combustion process. This expansion of the products results in a density gradient at the flame front between the burnt and unburnt mixtures.



*Figure 1: Wrinkling of the flame front and deviation of flow lines due to thermal expansion* 

Hydrodynamic instabilities, also known as Darrieus-Landau instabilities, were first discovered by Georges Jean Marie Darrieus in 1938 when he recognized that thermal expansion of gases would deviate flow lines across the flame front towards the normal of the flame. A representation of a hydrodynamic instability can be seen in

Figure 1 where a series of convex and concave regions form as the flame front propagates at a constant normal speed of  $U_L$  into the unburned mixture [4]. For clarity, only regions on the reactant side of the flame front will be discussed as to avoid confusion when referring to concave and convex portions of the flame. The flame speed is usually much smaller than the local speed of sound and so the combustion process is deemed a deflagration [5]<sup>2</sup>. This results in a very low

 $<sup>^{2}</sup>$ A deflagration defines a combustion process whose flame propagation through a medium occurs at subsonic speeds. This is opposed to a detonation in which the flame front is supersonic, generating a shock wave leading to a significant increase in pressure which is often highly destructive in nature [5]. A combustion wave is deemed a detonation or a deflagration by looking at where the final conditions of the system fall on a Hugoniot curve as determined by the Rankine-Hugoniot equations. These equations describe the independent relations between conditions upstream and downstream of the combustion wave [47].

Mach number  $M = \frac{U_L}{c}$ , where *c* is the speed of sound, which permits the approximation of the gas flow as quasi-incompressible [6]. Thus, as the flow lines converge in the concave regions and diverge in the convex regions, the unburned gases must speed up or slow down respectively by conservation of mass due to the change in area. Darrieus deduced this flow divergence and the velocity gradients produced would increase the wrinkling of the flame [7].

$$\sigma = \frac{S_L}{\lambda} \cdot \left( \frac{E}{E+1} \sqrt{\frac{E^2 + E - 1}{E}} - 1 \right)$$
(2)

At around the same time, Lev Landau independently predicted that the growth rate of hydrodynamic instabilities,  $\sigma$ , depended on the wavelength of the perturbation  $\lambda$ , and on the ratio of the densities of the unburnt and burnt gas, that is the gas expansion ratio  $E = \frac{\rho_u}{\rho_b}$  [8]. In fact, he showed that the rate of growth of an instability is inversely proportional to its wavelength as given in Equation 2 where  $S_L$  is the laminar burning velocity.

It is noteworthy to mention that the flame speed also depends on the local curvature of the flame front. This is characterized by the Markstein number  $M = \frac{\mathcal{L}}{\delta_L}$  where  $\mathcal{L}$  is the Markstein length<sup>3</sup> and  $\delta_L$  is the characteristic laminar flame thickness [9]. The Markstein length is associated with the total flame stretch which quantifies the deformation in the flame front due to its motion and the nonuniformities in the flow field [10].

Although hydrodynamic instabilities occur in all flames, there are several factors which can stabilize them. For instance, gravity has a pronounced effect which can either enhance or

<sup>&</sup>lt;sup>3</sup> The Markstein length can be expressed in terms of the Zel'dovich number, which provides a measure of the activation energy of a chemical reaction [10].

reduce stability. For flames propagating downwards, gravity has a stabilizing effect on long waves. On the other hand, flames propagating upwards are further destabilized by gravity leading to unconditionally unstable flames [10] [11].

#### 1.2 Thermo-diffusive instabilities

Thermo-diffusive instabilities result from an imbalance between heat diffusivity and mass diffusivity of the limiting species during combustion and can either suppress or enhance the wrinkling of the flame as determined by the hydrodynamic effects described in the previous section.

$$Le = \frac{\alpha}{D_i} = \frac{k}{\rho c_p D_i} \tag{3}$$

This thermo-diffusive effect is related to the Lewis number, *Le*, which is defined as the ratio of the thermal diffusivity,  $\alpha$ , over the mass diffusivity of the deficient reactant, *Di*, as can be seen in Equation 3, where *k* is the heat conductivity,  $\rho$  is density, and  $c_p$  is the specific heat capacity [12].



Figure 2: Preferential diffusion of limiting reactants [13]

If the diffusivity of the deficient reactant differs from that of the excess reactant, preferential diffusion of the former occurs as described in Figure 2 leading to a local increase in concentration

of the limiting reactant in the convex portions and a decrease in the concave portions [13]. This can cause local flame extinction resulting in the propagation of multiple flame fronts.

Experiments show that as the Lewis number moves away from some critical value  $Le \sim 1^4$ , the imbalance between heat and mass diffusivities leads to the formation of a variety of instabilities. The type of instability depends on whether the Lewis number becomes greater or lower than this critical value.



*Figure 3: Physical mechanism describing the increase or decrease in cellular instability [13]* 

At Le < 1 cellular instabilities similar to the wrinkling caused by hydrodynamic effects begin to appear while at Le > 1 these cellular instabilities disappear and are replaced by oscillatory instabilities [14].

Figure 3 describes how the formation of cellular instabilities is favored at Le < 1. In terms of cellular instabilities, thermal diffusivity has a stabilizing effect on the flame. Concave regions provide a higher surface area than convex ones from which heat can be transferred to the unburnt mixture. This favors an increase in the flame speed in concave regions, allowing it to potentially

<sup>&</sup>lt;sup>4</sup> The critical Lewis number is not always equal to 1, as will be shown later, as it depends on variables such as the Reynolds number. For the present analysis however, the critical Lewis number is considered to be approximately equal to 1.

catch up to the convex portion and return to a more uniform flame speed distribution. On the other hand, mass diffusivity has a destabilizing effect as it can increase the concentration of limiting reactants in convex regions, promoting the formation of high temperature convex regions which lead to local flame acceleration<sup>5</sup>, favoring further wrinkling of the front. Thus, when the thermal diffusivity of the limiting reactant is less than its mass diffusivity, the low rate of heat transfer cannot overcome the destabilizing effect of the latter. This results in a net acceleration of the flame at the convex regions and a deceleration at the concave ones enhancing wrinkling of the flame and leading to an earlier onset of cellular instability than if the flame was destabilized only by hydrodynamic effects [15]. Conversely, if the thermal diffusivity is higher than the mass diffusivity, the increased rate of heat transfer in the concave region combined with the reduced flame temperature at the convex region, due to weakly diffusing reactants, succeed in balancing the distribution of the flame speed. This leads to a more stable propagation until hydrodynamic instabilities dominate and eventually result in cellular instability [15].

$$Ze = \frac{E_a(T_b^o - T_u)}{RT_b^{o^2}} \tag{4}$$

As Lewis number becomes greater than 1, cellular instabilities are no longer favored. Instead, pulsating instabilities can now develop at sufficiently large Lewis and Zeldovich numbers, where the Zeldovich number Ze is a measure of the activation energy of a chemical reaction. The Zeldovich number is defined in Equation 4 where  $E_a$  is the overall activation energy,  $T_b^o$  is the

<sup>&</sup>lt;sup>5</sup> This is due to the Arrhenius law which will be described later in the text.

adiabatic flame temperature,  $T_u$  is the unburned mixture temperature, and R is the universal gas constant [16].

$$Ze(Le-1) > 4(1+\sqrt{3}) \approx 10.9$$
 (5)

The Sivashinsky criterion describing the onset of pulsating instabilities is given by Equation 5 [17]. For many gaseous flames, the Lewis and Zeldovich numbers are not sufficiently large to satisfy the criterion, leading to rare observations of pulsating flames. On the other hand, pulsations have been shown to appear in lean aluminum dust clouds, where very high Lewis numbers can be achieved due to the low mass diffusivity of solid particles [12]. As the Lewis number is increased sufficiently, decaying pulsations are the first to appear. With further increases in Lewis number, regular pulsating flames develop followed by pulsating flames accompanied by spiral patterns and ending at fully spiral flames at higher Lewis numbers [12]. Pulsations occur when the propagation of the flame is disturbed by a lack of the limiting reactant due to low reactant diffusion rates. This results in periods of intense combustion followed by an apparent extinguishing of the flame [12].



*Figure 4: Visual Comparison of the stability in various types of flames at*  $Le \ge 1$  *and* Le < 1

While instabilities can develop both at Lewis numbers greater or lesser than 1, at Le > 1 a smoother flame front free of cellular structures can be acquired as shown in Figure 4 [18] [19] [20].

#### 1.3 Thermoacoustic instabilities

Thermoacoustic instabilities are briefly introduced for the sake of completion. These instabilities result from the unsteady heat released from the flame front which creates acoustic waves that reflect from the enclosure back into the flame, further generating waves in a feedback loop. The formation and propagation of these acoustic waves result in pressure fluctuations throughout the enclosure which may severely damage the combustion chamber [21]. Thermoacoustic instabilities are a natural product of the overall dynamics of the system and need not be generated by external forces; the unsteady nature of the heat release amplifies the feedback mechanism [22]. This phenomenon is illustrated in Figure 5 [23].



Figure 5:Schematic of the feedback nature of Thermoacoustic instabilities

#### 1.4 A note on instabilities

Since all three types of instabilities occur due to independent physical mechanisms, the overall instability in a flame will result from a mixture of hydrodynamic, thermo-diffusive, and thermoacoustic instabilities.

A significant problem exists when attempting to differentiate between hydrodynamic and thermo-diffusive instabilities at Le < 1 as both mechanisms lead to cellular-like flame development. To study purely thermo-diffusive instabilities, hydrodynamic ones must be filtered out. One way of doing this would be to remove the density gradient between the burned and unburned sides of the flame. However, this is problematic since all burned particles experience a thermal expansion due to an increase in temperature. This is especially true for gases which expand significantly more than liquids or solids. Although this is true, studies in stability can be done within the context of a constant-density approximation where appropriate [10]. Nonetheless, one way of distinguishing between hydrodynamic and thermo-diffusive instabilities is by classifying them in terms of the scale of interest. Thermo-diffusive instabilities dominate on the scale of the hydrodynamic length associated with the combustion vessel [10] [24].

#### 1.5 Research in the field

In the 1940s, after Darrieus and Landau determined that flames would suffer a destabilizing effect due to thermal expansion, they concluded that all flames were inherently unstable, and that stabilization was impossible [10]. This conclusion proved inconsistent with experimental observations of stabilized planar laminar flames conducted by Mallard and le Chatelier in 1883 [25]. In reality, Darrieus and Landau disregarded diffusion effects which incited Markstein to add an intrinsically diffusive curvature correction to the analysis of flame stability [26]. This correction allowed a stabilization of short-wavelength disturbances, thus resolving the inconsistency.

Studies of thermo-diffusive effects on laminar flames were conducted by Barenblatt, Zeldovich and Sivashinsky where planar flames were determined stable for  $Le \approx 1$  in the absence of hydrodynamic effects [27] [28]. In their work, observations of cellular formation and oscillating instabilities led them to the conclusion that sufficient deviations from unity had a pronounced effect on stability. Strengthening and weakening of reaction rates at convex and concave regions of the flame front led to cell formation while low reactant diffusion rates were the cause of oscillating instabilities. In recent years, self-wrinkling flame fronts formed by weak turbulence and background noise have been observed by Creta, Fogla and Matalon [29].

Considerable work has been done across the years in terms of modeling combustion instabilities. In 1978, a model describing the motion of a flame sheet as well as the effects of axial pressure waves on the dynamics of gaseous reactants and products was developed by Marble and Candel [30]. They stipulated that low frequency oscillations in large utility powerplants could be caused by the unsteady response of the flame front. Furthermore, extensive research has been done using a fully non-linear hydrodynamic model through the study of the weakly nonlinear Michelson-Sivashinsky equation, which describes hydrodynamic instabilities in premixed turbulent combustion, in the context of weak thermal expansions [31]. Along the lines of premixed turbulent combustion, Williams developed the G-equation which can describe the instantaneous position of the flame [32]. More recently, work by Brookes, Cant, Dupere, and Dowling has been done in assessing the accuracy of Computational Fluid Dynamics (CFD) in predicting the onset and nature of self-excited combustion instabilities [33].

In the field of metal combustion, in 1984, work on hydrodynamic instabilities in aerosols

was performed by Korolchenko and Poletaev, where they demonstrated the enhancement of instability due to particle lag within the flow [34]. Around that time, experiments in open tubes detailing the formation of thermoacoustic instabilities were performed by Goroshin [35]. Further work by Tang and Goroshin led to the observation of cellular instabilities in fuel-rich mixtures of iron burned in an oxygen-argon mixture [36]. Recently, work by Julien led to observations of pulsating and spiraling flame propagations in fuel-lean aluminum flames. He showed that pulsating frequencies are largely independent on oxygen concentration and inert gas used in the oxidizer mixture but are strongly dependent on aluminum concentrations [12] [14]. He also demonstrated that the thermal diffusivity of the mixture had no substantial effect on the average flame speed of the pulsating flame.

#### 1.6 Motivation and objectives

There is still much work to be done in further understanding the nature of flame instabilities and their effects on flame front development and propagation. Furthermore, advancements in the development of metal fuel combustion technologies require a firmer theoretical foundation on metal flame theory and how it relates to the already established gas flame theory.

Thus, the purpose of this research is to recognize the effect of solid inert particles on gas flame stability to pave the way for research on flames with solid chemically reactive particles such as aluminum powders. Hence, how does the addition of solid inert particles, such as silicon carbide, influence the stability of gas flames in terms of cellular formation? The focus, therefore, will be on investigating the average flame speed of the flame front, the number of cells developed and the average size of these cells.

In the next section, a hypothesis will be presented concerning the expected results of this research. In Chapter 2, an apparatus description will be provided for the setup used throughout the

experiments as well as a presentation of the data acquired. In Chapter 3, a thorough analysis of the acquired data will be developed. In Chapter 4, a conclusion summarizing the results will be presented in addition to remarks on future research in the field. Finally, an appendix is provided to supplement the main text.

#### 1.7 Hypothesis

Solid inert particles are much denser than liquids and gases. When a methane-air mixture is seeded with inert solid silicon carbide particles, the highly dense solid particles increase the density of the new two-phase mixture. From Equation 3, Lewis number is defined as

$$Le = \frac{\alpha}{D_i} = \frac{k}{\rho c_p D_i} \tag{6}$$

Thus, as solid inert particles are added to the mixture, there is an increase in the  $\rho c_p$  term in Equation 6. That is, as silicon carbide is added and the mixture's density increases, the thermal diffusivity of the mixture decreases. Moreover, there is no change in the mass diffusivity of the limiting reactant as the inert particles do not participate in the chemical reaction. This results in a decrease in the Lewis number. As shown in Figure 4, as Lewis number decreases below 1, cellular structures begin to form. Thus, it is expected that as more silicon carbide particles are added, the decrease in Lewis number will be more pronounced leading to greater thermo-diffusive instability expressed as an increase in the number of cells in the flame front. It is also expected that as the number of cells increases, cells will split into smaller cells faster and lead to a decrease in the average size of these cells as smaller cells become more dominant.

On the other hand, the decrease in thermal diffusivity causes the temperature of the unburned mixture to increase more slowly as heat flows through it. This should lead to a lower overall temperature of the mixture during combustion resulting in a lower reaction rate as dictated by the Arrhenius Law which should result in slower flame propagation speeds.

$$k = A e^{\frac{E_a}{RT}} \tag{7}$$

The Arrhenius law, as seen in Equation 7, states that the rate constant of a chemical reaction is dependent on the absolute temperature of the reaction. In this equation, k is the rate constant, T is the absolute temperature, A is the pre-exponential factor,  $E_a$  is the activation energy of the reaction, and R is the universal gas constant.

Thus, as silicon carbide particles are added, the average flame speed is expected to decrease.

## **Chapter 2**

## **Setup and Data Acquisition**

#### 2.1 Experimental setup

The following experiments are all conducted in a Hele-Shaw cell built by previous undergraduate students working for the Alternative Fuels Lab at McGill University. A Hele-Shaw cell, as seen in Figure 7, is a quasi-2-dimensional setup where powders are stored in a piston and then dispersed from below into the test cell. An actuator feeds the piston into a dispersion system composed of a gas inlet and an air knife.



#### Figure 6: Schematic of the Hele-Shaw Cell

In the case of gas flames, a fuel such as methane mixes with air in a solenoid valve before passing through the inlet of the dispersion system where it picks up the powder from the piston. The new

solid-gaseous mixture then diffuses up through the diffuser, entering the test cell and exiting the cell at the exhaust. Once the flow of the mixture reaches steady-state conditions, a current is passed through tungsten wires planted at the exhaust of the cell, igniting the wires which subsequently ignites the mixture. The flame then propagates from the top of the cell to the bottom of the cell where it quenches. A cut-off plate is activated at the bottom of the cell to withhold fuel from the flame to prevent it from propagating through the diffuser and into the gas lines. A high-speed camera is setup to capture a video of the flame as it propagates for further numerical analysis.

For this thesis, some improvements are made to the experimental setup. A particle concentration system is implemented and tested by shining a laser through the cell and into a photo diode detector. This detector would measure the amount of light recovered from the laser after passing through the cell, compare it to the initial light emitted, and give a measure of the concentration of solid particles in the cell. Minor changes are also made for easier operation of the cell. This includes the optimization and re-adjustment of the spring-loaded cutoff plate to decrease friction between individual components which initially prevented the plate from moving smoothly. Moreover, a retractable platform is created for setting up three tungsten wires for ignition, among other minor improvements.

#### 2.2 Data acquisition

A variety of tests are done on methane-air flames, propane-air flames, and methane-air flames seeded with silicon carbide particles at various equivalence ratios as can be seen in Figures 8-12. Other types of flames are also tested and are given in Appendix A1.

An equivalence ratio is defined as the ratio of the actual fuel-air ratio to the stoichiometric fuel-air ratio, where the fuel-air ratio is defined as the ratio of the amount of air to the amount of

fuel in the mixture. Stoichiometric combustion occurs when all the oxygen is consumed in the reaction and there is no molecular oxygen  $(O_2)$  in the products.

$$FAR = \frac{m_{fuel}}{m_{air}} \tag{8}$$

$$\varphi = \frac{m_{fuel}/m_{air}}{(m_{fuel}/m_{air})_{st}} = \frac{n_{fuel}/n_{air}}{(n_{fuel}/n_{air})_{st}}$$
(9)

Fuel-air ratios and equivalence ratios are given by Equations 8 and 9 respectively.

Lewis numbers for the various mixtures are not calculated in this thesis as the process for determining thermal conductivities and mass diffusion coefficients is quite involved. These calculations require the use of complex equations such as the Chapman Enskog<sup>6</sup> equation to calculate mass diffusion coefficients of individual mixture components and then use equations derived from the Stefan-Maxwell<sup>7</sup> diffusion equations to obtain the effective diffusion coefficient [15]. Fortunately, Lewis number and critical Lewis number calculations have been done by Clarke for methane-air and propane-air flames [15]. He compared Lewis numbers determined by using the binary mass diffusion coefficient considering air as a single ideal gas with those determined by considering the diffusion of the limiting reactant into the remaining mixture. He concluded that for combustible mixtures, the mass diffusion coefficient should not be determined by treating air as a single component of the mixture, rather it should be based on the deficient species.

He also concluded that critical Lewis numbers should be defined as  $Le_{crit} \le 1 - \frac{1}{Ze}$  as

opposed to  $Le_{crit} \leq 1 - \frac{2}{Ze}$  due to the asymptotic analysis in the latter underpredicting the value

<sup>&</sup>lt;sup>6</sup> The Chapman-Enskog equation can be derived from the Boltzmann equation, which itself is quite involved [49].

<sup>&</sup>lt;sup>7</sup> The Maxwell-Stefan diffusion equations developed by Maxwell for dilute gases and by Stefan for fluids are used to model the diffusion in multicomponent systems [50].

of the critical Lewis number. Thus, Lewis numbers calculated by Clarke shall be used in the analysis of the flames obtained in this thesis.

#### 2.2.1 Methane-air flames

Methane-air flames are recorded from the lower limit of  $\varphi = 0.5$  to the upper limit of  $\varphi = 1.5$ . The propagation of these flames can be illustrated by overlapping the flame front at various frames of the captured video as can be seen in Figure 7. The flames propagate from the top of the cell to the bottom of the cell.



Figure 7: Flame front propagation of methane flames at different frames at various equivalence ratios

Lewis numbers at various equivalence ratios can be seen in Figure 8 as provided by Clarke, where  $\beta$  is the Zeldovich number.



*Figure 8: Lewis numbers and critical Lewis numbers for methane-air mixtures at 1 bar at 298 K [15].* As mentioned previously, the Lewis numbers of interest are given by the squares and triangles representing the calculation done using mass diffusion coefficients based on the deficient species. Furthermore, the critical Lewis number is given by the solid line in the graph. Thus, as can be seen in Figure 8, the Lewis number starts off at around 0.95 at fuel lean conditions and decreases as equivalence ratio increases to 1. A downward jump discontinuity to around 0.875 occurs after stoichiometry, where the Lewis number begins to increase as the mixture becomes fuel-rich. The critical Lewis number remains below the Lewis number of the mixture at all equivalence ratios, thus making the flame thermo-diffusively stable. This leads to predominantly hydrodynamic instabilities which wrinkle the flames as seen in Figure 7. Thus, the methane-air flames obtained are consistent with the Lewis numbers provided by Clarke.

Moreover, the flame seems to be hydrodynamically stable at very lean equivalence ratios

such as  $\varphi = 0.5$  with more pronounced wrinkling observed at equivalence ratios closer to stoichiometry.

As the equivalence ratio increases from fuel-lean to fuel-rich, the flame changes color. In Figure 7, for the most part, fuel-lean flames have a distinct blue color due to excited CH radicals [37]. As the equivalence ratio is increased beyond stoichiometry, more  $C_2$  radicals are excited which emit green light leading to flames whose color is a mix between blue and green.

It is also interesting to note the preferential propagation that occurs at the right wall at fuelrich equivalence ratios of 1.2 and above. It is not known exactly why this occurs, as the Hele-Shaw is leveled, but it is possible that the tungsten wires at the right side of the exhaust always ignite first leading to preferential propagation, however this does not seem like an adequate explanation of the phenomenon.

Finally, at equivalence ratios above 1.4, the flame splits into two distinct flame fronts. This is most likely caused by a difference in diffusivities between methane and air which leads to preferential diffusion of the limiting reactant, in this case air, at convex regions. This results in a sufficiently high decrease in air concentration at the concave regions which leads to local flame extinction, generating two flame fronts instead of one. It is also possible that this preferential diffusion of the limiting reactant is the cause for the preferential propagation at the right wall at an equivalence ratio of 1.2.

#### 2.2.2 Propane-air flames



Propane-air flames are recorded from the lower limit of  $\varphi = 0.6$  to the upper limit of  $\varphi = 1.7$ .

Figure 9: Flame front propagation of propane flames at different frames at various equivalence ratios

Again, as shown in Figure 9, the propane-air flame changes color as the equivalence ratio is increased. It starts at a pale blue, becomes a brighter blue, a teal, and finally ends at a green. This is expected as lean laminar premixed propane flames are characterized by their blue color, which as described before is due to excited CH radicals [38]. As the equivalence ratio approaches 1,  $C_2$  radicals become excited resulting in a teal color. With further increases in equivalence ratio, the flame becomes completely green due to a significant increase in excited  $C_2$  radicals as opposed to methane-air flames which do not achieve such a high number of these radicals.

Once more, the Lewis numbers for propane-air flames are given by Clarke in Figure 10.



Figure 10: Lewis numbers and critical Lewis numbers for propane-air mixtures at 1 bar and 298 K [15]

As can be seen in Figure 10, the Lewis number for propane-air starts at around 1.8 and decreases to 1.7 as equivalence ratio reaches stoichiometry. After stoichiometry, there is a jump discontinuity resulting in a Lewis number of 0.8 which remains constant for higher equivalence ratios. The critical Lewis number as given by the solid line is much lower than the Lewis number at fuel-lean equivalence ratios. However, as the mixture becomes fuel-rich, the critical Lewis number exceeds the Lewis number of the mixture and remains that way as the equivalence ratio increases. This means that propane-air flames should be thermo-diffusively stable for fuel-lean mixtures and become thermo-diffusively unstable at fuel-rich conditions thus leading to cellular development.

Indeed, as can be seen in Figure 9, hydrodynamic effects seem to dominate from  $\varphi = 0.7$ to  $\varphi = 1.0$ , with  $\varphi = 0.6$  being hydrodynamically stable as shown by the lack of wrinkling in the flame. On the other hand, the wrinkling of the flame seems to increase as the equivalence ratio is increased. Furthermore, as the flames become fuel rich at  $\varphi = 1.1$ , there is an observable increase in cellular structures which becomes more pronounced at higher equivalence ratios such as  $\varphi = 1.4$ . It is worth mentioning that as more cellular-like structures develop, the average size of these cells decreases.

There is a slight preferential propagation of the flame front towards the right wall which can be observed at  $\varphi = 1.5$ . It is also interesting to note that local flame extinction, similar to the one observed in very fuel-rich methane-air flames, can be seen at  $\varphi = 1.6$  and  $\varphi = 1.7$ .

#### 2.2.3 Methane-air flames seeded with silicon carbide

Methane-air flames are seeded with silicon carbide particles at various concentrations at fuel-lean, stoichiometric, and fuel-rich conditions as shown in Figures 11-13.



Figure 11:  $\varphi=0.7$  Methane-air flames seeded with Silicon Carbide particles



*Figure 12:*  $\varphi$ =1.0 *Methane-air flames seeded with Silicon Carbide particles* 



The particle concentration is determined by passing a laser through the flow and capturing the remaining light. This measures a voltage reading before and after the flow of particles.

$$T = \frac{V}{V_o} \tag{10}$$

Transmittance is defined as the ratio between the light transmitted to the receiver and the initial light that was emitted by the laser. Equation 10 describes this expression where T is the transmittance, V is the voltage measured by the receiver, and  $V_o$  is the voltage reading from the unperturbed light emitted by the laser. This transmittance can then be related to the actual concentration of particles using Beer-Lambert's law which states that there is a linear relationship between absorbance and the concentration of the absorbing species. Thus, as the concentration of particles is increased, the transmittance decreases due to a higher amount of light being absorbed and hence a lower amount of light being transmitted to the receiver.

It is important to note that different filters are used in different runs, thus some flame fronts appear too bright due to insufficient filtering leading to light saturation in the image.

By examining flames at all three equivalence ratios, it is clear that a significant change has occurred in terms of the shape of the flame front as silicon carbide particles are added. In particular, cellular instabilities develop resulting in what appears to be more thermo-diffusively unstable flames. It is interesting to note that in methane-air flames at  $\varphi = 1.3$ , as the concentration of inert silicon carbide particles increases there is a gradual decrease in the preferential flame propagation that was observed in pure methane-air flames until no preferential propagation is observed.

# Chapter 3

# **Numerical Analysis**

After recording the different flames, their average flame speed and the number and average size of cells are determined using locally-developed MATLAB algorithms. By determining the average flame speed and comparing it with known laminar burning velocities for the gases in question, a measure of the validity of the experiments can be acquired as experimental errors in equivalence ratio would negate the purpose of this thesis.

#### 3.1 Average flame speed calculations

A flame tracking code was developed in-house by Jan Palecka which tracks the boundary of the flame front at each frame of the video. This code is adapted in the analysis and improved upon to study the average flame speed using MATLAB. An example of this tracking can be seen in Figures 14 and 15 where the flame is propagating from left to right.



*Figure 14: Tracking of flame propagating from left to right at every frame (top view)* 



*Figure 15: Tracking of flame propagating from left to right at every frame (side view)* 

Once a recording of the flame is obtained, the flame-tracking algorithm can be used to approximate the flame front at every frame. It does so by binarizing the image at every frame, where a threshold value of light intensity is specified to determine whether the point is part of the flame front or not. Points in the image above this threshold are given a value of 255 in the blue portion of their RGB<sup>8</sup> value, while points below the threshold are given a value of 0. This is done to clearly distinguish between points that are part of the boundary and points that are not. Afterwards, the *bwboundaries* MATLAB function is used to trace all self-contained flame boundaries in the image, filling any holes which may be present in the boundary [39]. This process saves the positions of every point in the boundary objects and then uses this data to draw the boundary at every frame in a single plot as shown in Figures 14 and 15 to show the evolution of the flame as it propagates through the cell.

The determination of the threshold value depends on the fuel-oxidizer mixture, the equivalence ratio, the type of camera used to record the video as well as on the degree of filtering. Changes in any of these variables may have a pronounced effect on the brightness of the recorded flame front. Threshold values are manually determined by trial and error and are usually in the range of 40-90. However, there are instances where very dim flames require a threshold of 30 and very bright seeded flames require a threshold of 100 due to weak filtering. When guessing of the threshold values yields inappropriate flame front approximations, an algorithm is employed between an appropriate lower and upper bound to determine the most representative light intensity of the flame, that is the intensity with the highest number of points. This value is then used as the threshold yielding surprisingly accurate flame front approximations.

<sup>&</sup>lt;sup>8</sup> RGB stands for red, green, and blue where the RGB additive color model can recreate a broad array of colors using various combinations of these three primary colors. 255 is the maximum value for the contribution of each color.

An alternative method for flame-tracking was attempted before adapting the algorithm provided by Jan Palecka. This method can be seen in Appendix A2.

#### 3.1.1 Methane-air flames

The average flame speed is determined using a MATLAB code developed specifically for this thesis which tracks the position of the leading point at each frame and then calculates the slope of the most linear segment in the plot. See Appendix A5. The code locates the furthest point out of all flame boundary points provided by the flame-tracking algorithm and plots its location for every frame number. The code then cycles through the leading points of every frame in an attempt to find where the cell begins, where the linear portion begins, where the linear portion ends, and where the cell ends. It then uses these locations to calculate the flame speed by applying a linear regression in the linear region. Afterwards, it uses the start/end positions of the cell in conjunction with the known cell length and the video framerate to convert the flame speed from pixels/frame into cm/s.<sup>9</sup> The code also calculates the perimeter of the boundaries, by calculating the distance between individual points, to determine the area of the front using the known thickness of the cell.

The code has issues where it does not consistently identify the correct start/end points of the cell and the linear portion. Moreover, sometimes there are multiple linear regions which demand special case-by-case attention and manual fine-tuning since the code only identifies the first linear segment it comes across. In these cases, all four reference locations must be determined manually by sifting through a frame-by-frame decomposition of the flame movie.

A plot of the position of the leading point as a function of the frame number can be seen in

<sup>&</sup>lt;sup>9</sup> Movies of various framerates were recorded due to trying multiple cameras and using different modes based on the speed of the current flame. Framerates include 30 fr/s, 240 fr/s, and 1000 fr/s.



Figure 16 for methane-air flames at  $\phi = 0.9$  while the remaining equivalence ratios are provided in Appendix A3 as to not clutter the main text with a series of figures.

*Figure 16: Position of leading point for Methane*  $\varphi = 0.9$ 

There is a clear linear portion in the plots for all equivalence ratios. Thus, the speed of the leading point remains relatively constant across most of the cell. Table 1 summarizes the flame speeds of methane flames at all equivalence ratios of interest.

Equivalence Ratio	Flame Speed (cm/s)
0.6	14.068
0.7	43.364
0.8	50.860
0.9	73.958
1	82.229
1.1	66.618
1.2	90.80
1.3	121.60
1.4	115.99

Table 1: Methane-air flame speeds as a function of equivalence ratio
A graphical representation can be seen in Figure 17 where it is compared with the expected shape of the burning velocity as a function of equivalence ratio found in the literature. An uncertainty analysis is done on the results of the experiments based on the uncertainties of the machined dimensions of the Hele-Shaw cell. However, only one physical dimension, the length of the cell, was needed in the calculation of the flame speed, thus the physical error was minimized for this calculation. Based on this uncertainty analysis, the error was on the order of magnitude of 0.1% of the values plotted which is not readily visible on the error bars. This however does not account for the error induced when approximating the flame front using the flame-tracking algorithm.



*Figure 17: Theoretical laminar burning velocities and Experimental flame speeds of methane [40].* Flame speeds vary substantially with geometry, while the laminar burning velocity is an intrinsic property of the flame. The laminar burning velocity is the speed at which an unstretched laminar flame propagates through a quiescent mixture of unburnt reactants, it is dependent on the thermal diffusivity and the reaction rate of the mixture as well as on the temperature through the flame zone [41]. Thus, it is expected that the flame speeds in the Hele-Shaw cell are a few times higher than their corresponding laminar burning velocity, as stated by Ronney [42], while the shape of

the curve should remain the same.

As can be seen, an ever-increasing trend is observed in the experimental results. This discrepancy is hypothesized to be because of the change in surface area across runs. The flame wrinkles due to hydrodynamic effects, with further wrinkling and cellular development occurring for higher equivalence ratios where thermo-diffusive instabilities are more likely to develop. These instabilities lead to a significant change in area where high-temperature convex regions may form resulting in a noticeable acceleration of the flame speed at the leading point. Heat transfer rates also begin to differ across the flame front. Thus, the flame speeds should be normalized by the surface area of the flame front to account for these effects before comparing with the expected parabolic shape of the plot. A normalized plot is shown in Figure 18 where the normalized flame speed has units of  $cm^{-1}s^{-1}$ .



Figure 18: Theoretical laminar burning velocities and experimental normalized flame speeds of methane. As can be seen in Figure 18, the expected parabolic shape is retrieved after normalization. It is interesting to note that the overall trend of the normalized flame speeds is respected at all equivalence ratios except for  $\varphi = 1.1$  which is most likely due to numerical error when

approximating the flame front and its surface area. Thus, it can be concluded that the experimental setup and the accompanying experimental data acquired is valid; that the measured equivalence ratios are physically consistent.

#### 3.1.2 Propane-air flames

A similar analysis was done for propane-air flames to give further credence to the experimental setup. A plot of the position of the leading point as a function of frame number is given for  $\varphi = 0.8$  in Figure 19 while the rest are provided in Appendix A3.



*Figure 19: Position of leading point for Propane*  $\varphi = 0.8$ 

As can be seen in the plots, aside from the flames at the upper-limits, there is once again a consistently linear portion that exists in each run. A summary of the propane-air flame speeds is provided in Table 2 and graphically in Figure 20, where it is compared with the corresponding laminar burning velocity.

Equivalence Ratio	Flame Speed (cm/s)
0.6	13.90
0.7	31.84
0.8	46.09
0.9	76.50
1	80.85
1.1	85.28
1.2	90.90
1.3	79.83
1.4	57.05
1.5	40.34
1.6	22.22
1.7	10.22

Table 2: Propane-air flame speeds as a function of equivalence ratio



*Figure 20: Theoretical laminar burning velocities and Experimental flame speeds of propane [43].* Clearly, the experimentally determined flame speeds maintain the expected parabolic shape as given by the laminar burning velocities. Their magnitudes, however, are a few times higher as predicted by Ronney [42]. Thus, even without normalizing the flame speeds, it can be concluded

that the experimental results agree with expected phenomena as stated in the literature and that the subsequent analysis is therefore valid.

### 3.1.3 Methane-air flames seeded with silicon carbide

Methane-air flames at  $\varphi = 0.7$ ,  $\varphi = 1.0$ , and  $\varphi = 1.3$  are seeded with inert solid silicon carbide (SiC) particles at varying concentrations (Transmittance) however this thesis will strictly focus on methane-air flames at  $\varphi = 1.0$ . The leading point of the flame front at every run was plotted as a function of the frame number. Plots for T = 0.3961 and T = 0.7499 are given in Figures 21 and 22. The remaining plots are provided in Appendix A3. Note that transmittance will be used as a measure of the inert particle concentration as the Beer-Lambert calibration was unsuccessful. Recall that transmittance is inversely proportional to particle concentration; the lower the transmittance, the higher the concentration. See Appendix A4 for details on particle concentration.



*Figure 21: Position of leading point for methane-air*  $\varphi = 1.0$ , T = 0.3961



*Figure 22: Position of leading point for methane-air*  $\varphi = 1.0$ , T = 0.7499

Again, there is a distinct linear portion in the plots where the flame speed is constant. Table 3 summarizes the flame speeds at different values of transmittance while Figure 23 describes the relationship graphically as compared to the non-seeded case.

Transmittance	Flame Speed (cm/s)
0.3382	41.29
0.3961	50.47
0.3998	89.11
0.4177	57.92
0.6834	85.99
0.6874	88.06
0.7388	77.10
0.7499	90.05

*Table 3: Flame speeds as a function of transmittance for methane-air seeded with SiC at*  $\varphi = 1.0$ 



*Figure 23: Flame speeds of seeded and non-seeded methane-air flames at*  $\varphi = 1.0$ 

As inert particles are added to methane-air flames, the concentration of particles increases and consequently transmittance decreases.

There does not seem to be a significant difference in the flame speed due to the seeding of inert particles. This is a strange result since it is expected that as inert particles are introduced, the thermal diffusivity of the mixture will decrease leading to a lower temperature and thus a lower reaction rate as described by the Arrhenius law; The flame speed should decrease as the concentration of silicon carbide particles is increased.

Thus, there must be another effect that accounts for the speeding up of the flame. If the flame speeds are normalized by the surface area of the flame front, a more reasonable relationship is established as can be seen in Figure 24.



Figure 24: Normalized flame speeds of seeded and non-seeded methane-air flames at  $\varphi = 1.0$ After normalizing, it becomes evident that as the concentration of inert particles increases, the normalized flame speed decreases due to the lowering of temperature as predicted by the Arrhenius law.

Thus, as the concentration of inert particles increases, the onset of thermo-diffusive instabilities leads to an acceleration of the flame at the convex regions, counteracting the deceleration resulting from the decrease in thermal diffusivity. Therefore, it can be concluded that the addition of solid inert particles should have a small if not negligible effect on the flame speed of gas flames.

3.2 Determination of number and average size of cells

A cell-tracking MATLAB code was developed by Luis Aranda from the university of Texas at El Paso during his stay at the Alternative Fuels Lab at McGill. This code is used to determine the number and average size of cellular structures that are formed as the flame propagates through the cell. An illustration of the cell-tracking can be seen in Figure 25.



Figure 25: Cell-tracking algorithm

The code goes through every frame of the recorded video, finds the brightness that represents the flame boundary most accurately, and then attempts to adequately capture all the cells along the boundary. It does so by going from point to point along the front to identify cusps in the flame. At every point, a square is formed around the point to check what percentage of the square is on the side of the reactants and what percentage is on the side of the products. If the flame front is free of wrinkles, the area of the square on the side of the reactants is equal to the area on the side of the products, thus there is no cell. As the proportion deviates from this standard, there is a chance that the point is a cusp which can lead to the identification of a cell. A cut-off threshold is used for

categorizing points as cusps. The code eliminates cusps which are too close together since they might lead to erroneous cell detection. Once cells have been identified, circles are used to approximate the cells, where the radius of the circle determines the size of the cell. Finally, the size is converted from pixels to millimetres for practical purposes.

### 3.2.1 Methane-air flames seeded with silicon carbide

The results of the cell-tracking algorithm are shown for stoichiometric methane-air flames at T = 1.0 in Figure 26, where no silicon carbide is present. The unseeded flame is then compared to flames seeded with silicon carbide at T = 0.7499 and T = 0.3998 in Figures 27 and 28. The results for the remaining values of transmittance are given in Appendix A6.



*Figure 26: Number of cells and average size for* T = 1.0 (*no particles*)



*Figure 28: Number of cells and average size for* T = 0.3998

It is clear from observing Figures 26-28 that as the number of cells increases, the average size of the cells decreases. This is because as the flames become more unstable, the cells that form split

more readily into smaller cells. Hence, the higher the number of cells formed the lower their average size will be. As more cells are formed, the average size should converge down to the minimum value which numerically identifies a portion of the flame as a cell.

By comparing Figure 26, with no inert particles, to Figures 27 and 28, there is a noticeable increase in the number of cells as inert particles are added to the mixture. Most notably, at a much higher concentration of silicon carbide, there is a significant increase in the number of cells from 5-6 cells on average at T = 1.0 up to 20 cells at T = 0.3998.

On the other hand, contrary to what is expected, the average radius of the cells does not seem to decrease significantly as the concentration of inert particles is increased. This is most likely due to numerical issues where the algorithm cannot accurately identify cells of a size smaller than some minimum value leading to a non-negligible loss of information. Attempts at increasing the resolution of the cell detection have led to erroneous identification of cells where there are none in addition to exceeding system memory due to poor code optimization. The results which were obtained required a significant decrease in the amount of computations which was accomplished by reducing the number of frames investigated, among other adjustments which decreased the accuracy of the cell-detection.

Thus, there are inherent limitations in the cell-tracking code when attempting to capture small cells formed due to thermo-diffusive instabilities. Exceeding system memory usually indicates storing and processing of too much data at the same time, possibly from extremely large arrays resulting from hundreds of video frames, leading to inefficient memory usage throughout the computation. Therefore, this might necessitate a complete re-development of the cell-tracking algorithm with a controllable memory approach in mind, potentially requiring foundational changes in the code. Alternatively, a brute force method can be implemented by accessing virtual

machines with much higher memory.

Although the code cannot accurately identify all cells of interest when studying thermodiffusive instabilities, there are high hopes for its utility in studying hydrodynamic instabilities which are of a relatively larger scale.

# **Chapter 4**

# Conclusions

Experiments in a Hele-Shaw cell were conducted on methane-air flames, propane-air flames, and methane-air flames seeded with inert solid silicon carbide particles at various equivalence ratios to study the effects of adding inert particles on the thermo-diffusive stability and average flame speed of the flames. MATLAB codes were developed in-house and used to track the flame front and the formation of cells yielding results on the average flame speed of the flame front, the number of cells and the average size of such cells.

Studies on the average flame speed showed a consistent existence of a linear portion in plots of the position of the leading point of the flame front as a function of time leading to constant flame speed propagation. According to the results obtained in these experiments, the normalized average flame speed decreases as the concentration of inert particles increases by the Arrhenius law due to a lower thermal diffusivity leading to a lower temperature of reaction. However, due to an increase in thermo-diffusive instability, the flame surface area increases with increasing concentration of inert particles leading to high temperature convex regions which increase the average flame speed of the flame. These two effects counter each other and lead to an overall negligible change in the average flame speed.

Moreover, as the concentration of inert particles increases, there is a substantial increase in the number of cells formed throughout the flame's propagation, as was initially expected. However, due to numerical issues, there is no numerical evidence of the expected decrease in average cell size with increases in the concentration of inert particles. There were a variety of issues which proved problematic throughout the research process. Methane flames at rich equivalence ratios did not yield adequate results of average flame speeds when compared to known methane laminar burning velocities. However, after normalizing with respect to the flame surface area, the normalized average flame speed resulted in a plot consistent with plots of laminar burning velocities thus proving the importance of area change due to instabilities.

Furthermore, the cell-tracking algorithm, although accurate for bigger cells, proved insufficient in detecting smaller cells formed throughout the propagation of the flame front. Difficulty in tracking very small cells proved inconvenient and would provide a reason for the lack of an observable decrease in average cell size for increasing concentrations of inert particles. Moreover, issues in code optimization leading to system memory exceedance proved problematic when modifying the code in an effort to more accurately capture all cells of interest.

Other sources of errors include a progressive dirtying of the cell which may have had longterm effects on the transmittance of light through the glass. Although the cell was cleaned after every run in an effort to reduce this effect, there was no way to avoid dirtying of the glass during the experiments themselves. Hence, the light emanating from the laser was partially absorbed by both the solid particles in the flow and by the particles which remained stuck on the glass. This resulted in an unavoidable error which overestimates the concentration of particles in the flow. Furthermore, the perimeter of the flame was determined by calculating the distance between individual points comprising the flame boundary, which induces an error in the calculation of the surface area. This is not an ideal method but was implemented after spline interpolation methods failed because the boundary points did not possess unique x and y values. A more accurate method of area calculation should be used in the future.

Additionally, the calibration setup was unsuccessful and did not yield adequate information

for a Beer-Lambert calibration for particle concentration, see Appendix A4.

Thus, work on a more effective particle capture calibration system and on more accurate and more optimized cell-tracking codes would prove useful in the future.

Further research can be done on thermo-diffusive instabilities by testing other types of inert particles such as aluminum oxide to compare with results from silicon carbide. Likewise, different sizes of particles can be used for future testing. Moreover, a variety of oxidizing mixtures can be used in the future which are different from air<sup>10</sup> to study the effects of oxygen concentration and type of gaseous inert on the stability of the flame. For example, a mixture of 23% Oxygen in Argon can be used for testing.

Furthermore, the temperature distribution in the flames could be evaluated through infrared thermography by using a high-speed thermographic camera. Density measurements could also be made on the products and the reactants across the flame to study the hydrodynamic instability through the thermal expansion effect. Studies can also be done on thermoacoustic instabilities by installing a microphone to measure pressure variations in the cell.

Finally, in the future, research can be done on chemically reactive particles such as aluminum and iron to study instabilities in metal flames or in hybrid flames involving metals.

<sup>&</sup>lt;sup>10</sup> Air is composed of approximately 21% Oxygen and 79% Nitrogen

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# Appendix

# A1 Additional tests

Aside from methane-air and propane-air flames, a variety of other flames were tested which were later rejected due to incorrect calibration of the equivalence ratio among other reasons.

# A1.1 Ethane-air flames

Figure 29 shows the propagation of ethane-air flames.



Figure 29: Ethane-air flames, increasing in fuel-richness as the erroneous equivalence ratio increases.

The values at the bottom of the flames give a vague indication of which flames are richer in fuel albeit the values themselves being incorrect measurements of equivalence ratio due to erroneous flowmeter calibration. The numbers were kept in the figures for ease of presentation. Although the actual equivalence ratios are unknown, at its most lean configuration the flame is hydrodynamically and thermo-diffusively stable. As the flame becomes more fuel rich, hydrodynamic instabilities begin to dominate resulting in flame wrinkling. Finally, as the flame becomes even richer in fuel, thermo-diffusive instabilities promote further wrinkling of the flame leading to the onset of cellular instabilities as is expected.

At first, excited CH radicals result in a blue flame. As the flame becomes richer in fuel,  $C_2$  radicals are excited resulting in teal flames first and then primarily green flames at higher richness.

## A1.2 Propane-21% Oxygen/Argon flames





Figure 30: Propane-21% Oxygen/Argon flames with erroneous equivalence ratios.

Once again, the equivalence ratios given are incorrect as the flowmeters were not calibrated for the Oxygen/Argon mixture.

Moreover, hydrodynamic instability dominates at much leaner mixtures. As the fuel becomes richer, the wrinkling of the flame is more pronounced due to an increase in the hydrodynamic instability. Finally, thermo-diffusive instabilities take over at much higher fuel richness and lead to the formation of cellular structures comprised of many small-sized cells.

Furthermore, it is evident that there is a transition from excited CH radicals to excited  $C_2$  radicals resulting in a change in luminescence from blue to green. However, at much higher fuel richness red-orange tails form at the flame front, probably due to the incandescence of gases.

A1.3 Propane-21% Oxygen/Helium flames

Propane flames at 21% Oxygen and 79% Helium were briefly considered. The flames recovered can be seen in Figure 31.



Figure 31: Propane-21% Oxygen/Helium flames

Once more, the numbers below the flames in the figure are not the actual equivalence ratios since the flowmeters were not calibrated for the Oxygen/Helium mixture.

Little work was done using an oxidizer mixture of 21% Oxygen in Helium as the experiments proved too dangerous to pursue. The significantly lower molar mass of Helium<sup>11</sup> led to extremely fast flame propagation speeds which resulted in fire balls emanating from the top of the cell. After witnessing these fireballs, which threatened to ignite the gas lines above the cell, the work was quickly abandoned in favor of safer alternatives.

 $<sup>^{11}</sup>$  The molar mass of Helium is about 7 times lower than that of Nitrogen (N2) molecules.

### A2 Alternate flame-tracking attempt

Edges are defined as curves in an image that follow a path of rapid change in image intensity. There is a MATLAB function called *edge* which returns a binary image containing 1s where the function identifies an edge and 0s elsewhere [44]. This function implements a variety of edge-detecting methods depending on what the user requires. First however, the frames needed to be converted into grayscale for the function to be used. After attempting all the available methods, only three were deemed potentially useful.

The LoG method first filters the image with a Laplacian of Gaussian filter (LoG) and then determines edges by identifying zero-crossings in the image.

The Zerocross method exploits the fact that edges occur where the Laplacian changes sign by finding where the value of the Laplacian of the image passes through zero.

Finally, the Canny method looks at local maxima of the gradient of the image to locate an edge. First it calculates the derivative of a Gaussian filter to determine the gradient and then uses two thresholds to identify strong and weak edges in the output to reduce the effect of noise when detecting edges.

All three methods were attempted at different thresholds, but the approximations proved inefficient in approximating the boundary at a satisfactory level of accuracy free of noise. Therefore, this approach was abandoned in favor of the flame-tracking algorithm developed by Jan Palecka at the Alternative Fuels Lab.

Figures 32-34 only show a sample of the resulting approximations. The most promising results either minimized the noise, or accurately captured the flame boundary. However, no image was obtained where both metrics were satisfied. In reality, the threshold chosen greatly affects both metrics and leads to a trade-off between local noise and accurate flame front identification.



Figure 32: LoG method at threshold T=9e-4



Figure 33: Zerocross method at Threshold T = 1.3978e-04



Figure 34: Canny method at the default threshold

# A3 Plots of leading point as a function of frame number



## A3.1 Methane-air flames

*Figure 36: Position of leading point for Methane*  $\varphi = 0.7$ 



*Figure 38: Position of leading point for Methane*  $\varphi = 1.0$ 



*Figure 40: Position of leading point for Methane*  $\varphi = 1.2$ 



*Figure 42: Position of leading point for Methane*  $\varphi = 1.4$ 



*Figure 44: Position of leading point for Propane*  $\varphi = 0.7$ 



*Figure 46: Position of leading point for Propane*  $\varphi = 1.0$ 



*Figure 48: Position of leading point for Propane*  $\varphi = 1.2$ 



*Figure 50: Position of leading point for Propane*  $\varphi = 1.4$ 



*Figure 52: Position of leading point for Propane*  $\varphi = 1.6$


*Figure 53: Position of leading point for Propane*  $\varphi = 1.7$ 





*Figure 54: Position of leading point for methane-air*  $\varphi = 1.0$ , T = 0.3382



*Figure 56: Position of leading point for methane-air*  $\varphi = 1.0$ , T = 0.4177



*Figure 58: Position of leading point for methane-air*  $\varphi = 1.0$ , T = 0.6874



*Figure 59: Position of leading point for methane-air*  $\varphi = 1.0$ , T = 0.7388

## A4 Calibration curves

To determine the concentration of inert particles in the flow, an application of Beer-Lambert's law must be implemented. The Beer-Lambert law states that there is a linear relationship between absorbance and concentration of absorbing species. Absorption can be determined in terms of transmittance, which can be defined as

$$T = I/I_o \tag{11}$$

where I is the light intensity after passing through the cell and  $I_o$  is the light intensity emitted from the laser. Absorption is then described as:

$$A = -\log T = -\log(I/I_o) \tag{12}$$

To acquire calibration curves which would convert transmittance into particle concentration in SI units, powder dispersion runs were done where powder was dispersed in the cell and then captured above the exhaust using a vacuum cleaner and a filtering system. The mass of the captured particles was then determined, and calibration curves were obtained. Unfortunately, this method of capturing particles proved ineffective as the vacuum cleaner heavily influenced the flow within the cell by recirculating the air near the exhaust leading to inaccurate voltage readings as can be seen in Figure 60. The blue curve represents the readings from the oscilloscope while the red curve represents the portion of the curve where the vacuum was collecting particles.



Figure 60: Calibration curves

Thus, an alternative method of collecting particles needs to be developed to determine what the actual concentration of the inert particles is. The current avenue of interest for a potential solution to this problem includes the design of an attachment to the exhaust which would insulate the flow in the cell from disturbances outside the cell. Another idea would be to develop two one-way filters which would capture the particles as they attempt to exit the cell.

## A5 Information on MATLAB codes.

The Matlab codes which were developed for this honours thesis have been omitted from this report due to their length. Scripts which were written include: a script for calculating flame speeds and a script for calculating the surface area of the flame front. These scripts utilized a flame-tracking algorithm written by Jan Palecka from McGill University as the foundation for the analysis. The flame-tracking algorithm provided the pixel locations of points comprising the flame front by identifying sections of the flame above a certain threshold of luminosity. Converting these pixel locations to centimeters permitted calculations of average flame speeds and approximations of the flame area using distances between individual points. A separate code developed by Luis Aranda from the University of Texas at El Paso during his stay at McGill also utilized the flame-tracking algorithm developed by Jan Palecka to identify cellular structures which developed in the flame throughout its propagation. This code provided information on the number of cells formed and the average size of these cells.

## A6 Results of cell-tracking algorithm

The number and average size of cells for methane-air flames seeded with silicon carbide for transmittance values of T = 0.7388, T = 0.6874, and T = 0.3961 are given in Figures 61-63.



*Figure 61: Number of cells and average size for* T = 0.7388



*Figure 63: Number of cells and average size for* T = 0.3961