Controlled Cooling of Permanent Mold Castings of Aluminum Alloys

by

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Abstract

The permanent mold casting process is a relatively popular and effective casting technology that can produce near-net-shape aluminum components with integrity, particularly for the automotive and aerospace industries. It is well recognized by the casting industry that it is essential to control the cooling of permanent mold castings in order to improve the quality of the castings, so there is a considerable incentive to develop a more effective method of mold cooling to control the temperature distribution of the mold and the casting.

The current technologies for controlled cooling are air or water cooling passages and chill inserts. Each of these cooling methods presents certain disadvantages, and none offer optimum cooling control.

Based on these considerations, a novel, effective and controllable water-based heat pipe has been successfully developed to be used as a new method of permanent mold cooling where high heat fluxes are normally encountered. Heat pipes featuring this design have been incorporated in an experimental permanent mold made of H13 tool steel that contains three symmetric steps. Computer modeling for the permanent mold casting process has been accomplished to predict the effect and potential of heat pipe cooling for permanent mold casting. Castings of A356 alloy have been produced by this permanent mold. The effects of heat pipe cooling on permanent mold castings have been evaluated by analyzing the temperature distribution of the mold and the casting, as well as by measuring the dendrite arm spacing and shrinkage distribution of the castings. The effect of heat pipe cooling on the mold solidification time of castings of A356 alloy with different coating types was also studied.

Industrial trials have been carried out to evaluate this new cooling technology on an industrial scale casting machine. Because the space around the mold installed on a low pressure die casting machine is very limited, it is often very difficult to install the heat pipe in the specific desired location in the mold. A new version flexible heat pipe cooling system has been developed for the industrial casting process. Preliminary and industrial tests of the heat pipe cooling system have been performed. The effects of heat pipe cooling, as well as the effects of using traditional water and air cooling on the low pressure die casting were studied.

Data on the cooling rates obtained by heat pipes, as well as some microstructures and measurements of the dendrite arm spacing are presented in this thesis.

Modeling and experimental results have shown that the water based heat pipe can provide high cooling rates in casting processes. The dendrite arm spacing (DAS) of A356 alloy is refined considerably by the heat pipes, and changes in the shrinkage pattern are provided by the dramatic changes in the heat flow patterns.

Résumé

Le moulage en coquille est une technique de coulée relativement populaire et efficace pour produire des pièces en aluminium intègres et proches de leur forme finale pour les industries automobile et aérospatiale. Dans l'industrie de la fonderie, il est bien reconnu qu'il est essentiel d'avoir un bon refroidissement des pièces moulées pour en améliorer leur qualité. Aussi existe-t-il un grand intérêt à développer une méthode de refroidissement plus efficace pour contrôler la distribution de la température dans le moule et dans la pièce coulée.

Les technologies actuelles pour un refroidissement contrôlé sont des passages d'air ou d'eau et des inserts refroidisseurs. Chacune de ces méthodes de refroidissement présente des inconvénients, et aucune n'offre un contrôle optimal du refroidissement.

En se basant sur ces considérations, un caloduc innovateur à base d'eau, efficace et contrôlable a été développé avec succès pour être utilisé comme une nouvelle méthode de refroidissement des moules où des flux de chaleur élevés sont observés. Des caloducs de ce type ont été fixés sur un moule permanent en acier H13 comprenant trois marches symétriques. La modélisation du procédé de coulée en coquille a été faite pour prédire l'effet et le potentiel du refroidissement par caloduc pour des pièces moulées. Des pièces en alliage d'aluminium A356 ont été produites dans ce moule. Les effets du refroidissement par caloduc sur ces dernières ont été évalués en analysant la distribution en température dans le moule et dans la pièce ainsi qu'en mesurant l'espace interdentritique et la distribution de la retassure. L'influence du refroidissement par caloduc sur les temps de solidification des pièces en A356 coulées avec différents revêtements sur le moule a été aussi étudiée.

Des essais industriels ont été effectués pour évaluer cette nouvelle technologie de refroidissement sur une machine de coulée utilisée en production. Étant donné le peu d'espace disponible autour du moule monté sur la machine de coulée à basse pression, il est très difficile d'installer les caloducs dans les positions spécifiquement désirées. Une nouvelle version du système de refroidissement utilisant des caloducs flexibles a été développée pour le procédé de coulée industriel. L'évaluation de ce nouveau système a été faite dans un premier temps en laboratoire puis assemblé sur le moule de la machine industrielle. Les effets du refroidissement par caloduc ainsi que ceux des systèmes de refroidissement par eau et par air sur les pièces coulées en basse pression ont été étudiés.

Les données sur les vitesses de refroidissement obtenues par caloducs ainsi que des microstructures et des mesures d'espace indentritique sont présentées dans cette thèse.

Les résultats de modélisation et expérimentaux ont démontré que le caloduc à base d'eau peut fournir des vitesses de refroidissement élevées pour les procédés de coulée. L'espace interdendritique de l'alliage A356 a été considérablement réduit par l'utilisation des caloducs. De plus, des changements dans la retassure ont été obtenus résultant des changements dramatiques observés dans la distribution du flux de chaleur.

Acknowledgements

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In memory of my dear aunt, Mrs. Shufang Zhang, to whom I am indebted for her motherlike care and concern, I am sure that she would have been proud to have a Ph.D. in the family.

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Nomenclature

Symbol	Meaning	Units
A	regression coefficients for chemical compound	
C_1	constant, 0.0012 $m^{1/4}/s^{1/2}$	
C_2	constant, 0.0016 $m^{1/4}/s^{1/2}$	
C_p	specific heat	J/kg·K
d	pipe inner diameter	m
D	internal diameter of the passage = 0.028 m	m
g	acceleration due to gravity	m/s^2
H	180 deg twist pitch	m
$\bar{h}$	average heat transfer coefficient = 20,000 W/m^2K	W/m^2K
H_{fg}	latent heat of evaporation	J/kg
k	thermal conductivity	W/m·K
K	a constant (which may change with temperature gradient)	
$\dot{m}$	mass flow rate of water	kg/min
n	exponent (0.3 to 0.4)	
n_1	regression coefficients for chemical compound	
$\overline{Nu_D}$	the average Nusselt number based on the pipe diameter, D	
Pr	Prandtl number of the fluid	
q	interfacial heat flux	$W/m^2 \cdot K$
$q''_{CHF,vert}$	critical heat flux for vertical surfaces	W/m^2
$q''_{CHF,hor}$	critical heat flux for horizontal surfaces	W/m^2
q/A	heat flux through the heating surface	W/m^2
R	solidification time	s
Re_D	Reynolds number of the fluid	

Re_{sw}	Reynolds number based on swirl velocity	
S_w	swirl parameter	
T	temperature	K
Tc	casting surface temperature	K
T_{Cont}	regression coefficients for chemical compound	
Tm	mold surface temperature	K
ΔT	the differential between the temperature of the heating surface T_w and that of working fluid T at one atmosphere	K
v	average velocity of the water flow	m/s

Greek Characters

δ	thickness of flow modifier	m
λ	average secondary dendrite arm spacing	μm
μ	viscosity of water 555.1x10-6 Ns/m^2	Ns/m^2
ρ	density	kg/m^3
ρ_G	density of vapor	kg/m^3
ρ_L	density of liquid	kg/m^3
σ	surface tension	N/m

Subscripts

c	casting
m	mold

Chapter 1 Introduction

1.1 Controlled Cooling of Permanent Molds for Aluminum Castings-an Overview

Aluminum alloys are now widely used, particularly in the automotive and aerospace industries due to their excellent properties and their low densities. The permanent mold casting process is a relatively popular and effective technique, which can produce near-net-shape aluminum components with high integrity.

In the process of permanent mold casting of aluminum alloys, molds experience a series of complicated changes during casting cycles. The temperature distribution of molds is a key factor which affects solidification during casting, and produces thermal stresses and thermal fatigue in the mold which shorten mold life. The casting surface quality is closely related to the temperature distribution on die cavity surfaces in permanent mold casting. Defects such as shrinkage, die soldering and cold shuts are also related to poor surface temperature distributions. In addition, it is well known that grain size and dendrite arm spacing are important considerations in cast aluminum alloy microstructures. The rate at which the metal solidifies is reflected in several features of microstructures. With increasing solidification rate, the size of the grains, dendrite cells, and their spacing decrease and the number of second-phase particles is reduced. The removal of heat during the solidification process is as an obvious requirement.

Therefore, in the production of permanent mold castings, it is necessary to keep the mold temperature within a certain specified range for the following basic reasons.

- Ensure that the casting solidifies progressively towards feeders and running systems, in order to reduce porosity or other defects
- Reduce hot spots between thin and thick sections of the casting and make the mold more isothermal

- Modify the grain size and microstructure to improve mechanical properties
- Lengthen service life of the permanent mold

The current technologies for controlling heat transfer in permanent mold casting are 1) internal cooling of the mold and 2) coating of the inner mold cavity. For cooling, air, water and chill inserts present certain problems. Each of the coolants has some disadvantages. Air is not a very effective coolant so its use provides little influence on microstructure and mechanical properties of castings, and compressed air is expensive. Water is a better coolant, but there are definite safety and infrastructure issues. The channels and equipment for water cooling are very complicated. Many foundries are trying to avoid water in the vicinity of castings. In addition, the cooling passages for water may become clogged with scale from minerals in the water. Water demineralizing and passage cleaning are expensive. Chills are only effective for controlling solidification within a very thin layer of the casting from the interface between the casting and the chill. In addition to direct cooling, the application of mold coatings on the cavity surfaces is also common practice for modifying the heat transfer between the casting and the mold. However, their influence is limited in this area. Their primary use typically is to prevent the casting from sticking to the mold.

A new effective method of mold cooling that is not yet available commercially, but which shows great promise and is the subject of this dissertation involves the use of heat pipes.

Heat pipes are effective cooling devices with extremely high thermal conductivities. These thermal superconductors can provide much more effective cooling of permanent molds than air and can approach the cooling of water jets. By using a heat pipe system, it should be possible to spot cool castings, to provide cooling at specified times in the aluminum casting process.

In the past years, some work has been done which relates heat pipe cooling of molds in metal casting with computer modeling and laboratory experiments. Some of these studies evaluated the effect of heat pipes on solidification behavior. The cooling with heat pipes was not as effective as what was expected or hoped for. There are two main reasons. One is that a contact thermal resistance exists between a heat pipe and the mold; the other is that the heat pipes didn't work very effectively because of characteristic heat transfer limitations.

Current commercial softwares can simulate the casting process on a computer. Most of the softwares can predict solidification patterns, temperature distribution, gradients, and solidification times. Some of the more advanced softwares include filling simulation and property prediction. With these models one can predict the operating status and find optimum operating parameters for the designed mold in advance. With this knowledge, the specified locations which need to be chilled in order to eliminate defects can be determined.

1.2 Objectives

With the development of the aluminum industry and the demand for high quality castings, especially for automotive components, permanent mold casting of aluminum alloys has been considered to be one of the most effective production methods. This project aims to solve existing mold cooling problems by development of heat extraction devices, based on heat pipe technology, to the point that they will be effective in cooling selected regions of molds. Overall the objectives of the current research project consist of:

- Development of more effective water-based heat pipes
  - Design, build and demonstrate a controllable, high heat flux heat pipe
  - Test this new heat pipe under simulated high heat flux operating conditions
- Experiments and analyses of the controlled cooling of a permanent mold in the casting of aluminum
  - Laboratory experiments at McGill
    - Permanent mold design

    - Computer modeling of the casting process to determine the specified regions for cooling and optimum technology parameters
    - Manufacture of the mold and installation of heat pipes for mold cooling
    - Experiments of permanent mold casting of aluminum alloys
  - Industrial trials at Grenville Castings Ltd.
    - Structure design of a new flexible heat pipe for low pressure die casting
    - Preliminary tests of the flexible heat pipe system in the laboratory
    - Manufacture and installation of the heat pipe in a commercial mold operating on a low pressure die casting machine
    - Industrial tests of the heat pipe cooling system on a commercial low pressure die casting machine
- Characterization of aluminum castings to evaluate the cooling effects of heat pipes
    - Refinement of the DAS of aluminum alloys
    - Distribution of shrinkage in the casting of aluminum alloys
- Comparison of the cooling effects using air, water and heat pipe cooling on the actual low pressure die castings.

Chapter 2 Literature Survey

2.1. Heat Pipe Technology

2.1.1. Basic Concept of a Heat Pipe

A heat pipe is a closed heat transfer device with very high thermal conductivity. It can quickly transmit heat from one location to another over almost no temperature gradient. As shown in Fig. 2.1, a heat pipe consists of two basic sections, an evaporator and a condenser. A small quantity of working fluid, for example water, is placed in a pipe. Then, all air inside the pipe must be evacuated completely and the pipe is sealed to create a vacuum environment inside the chamber. The evaporator section absorbs heat from heat sources causing the liquid to vaporize, and the vapor moves to the condenser section, where it condenses on the pipe wall and releases its latent heat of vaporization. The heat is extracted by cooling air or other coolant. The condensate is returned to the evaporator by gravity or capillary forces. Because the latent heat of vaporization is very large, considerable quantities of heat energy can be transported from the evaporator to the condenser. Thus the system has a very high effective thermal conductance. As a result, a heat pipe is sometimes referred to as a superconductor in the heat transfer field.

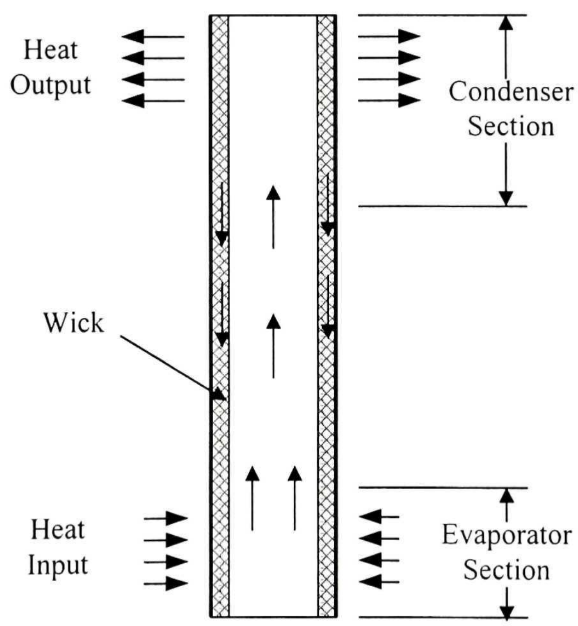


Figure 2.1 Schematic diagram of operating principles of a heat pipe

This continuous cycle is extremely efficient and able to move large heat loads with very low thermal impedance. The heat pipe, a passive device, does not need any external power, being driven only by the heat that it transfers. This results in high reliability and long life. Details and equations to quantify the working mechanisms of the heat pipe are described in several books on heat pipe technology (1, 2, 3, 4).

The heat transfer characteristics of a heat pipe can be measured with a setup such as shown in Fig. 2.2 (1). Tests have shown that a heat pipe can be as effective in transporting energy as 1,000 times the equivalent quantity of copper under similar heat transfer conditions. The heat pipe can be effectively used as a thermal conductor to link heat sources and sinks at different heat fluxes. Heat can be input at a high heat flux rate to a heat pipe over a small surface area and extracted over a larger surface area at a lower heat flux, because the ratios of condenser/evaporator can be very large, as much as 25 or more.

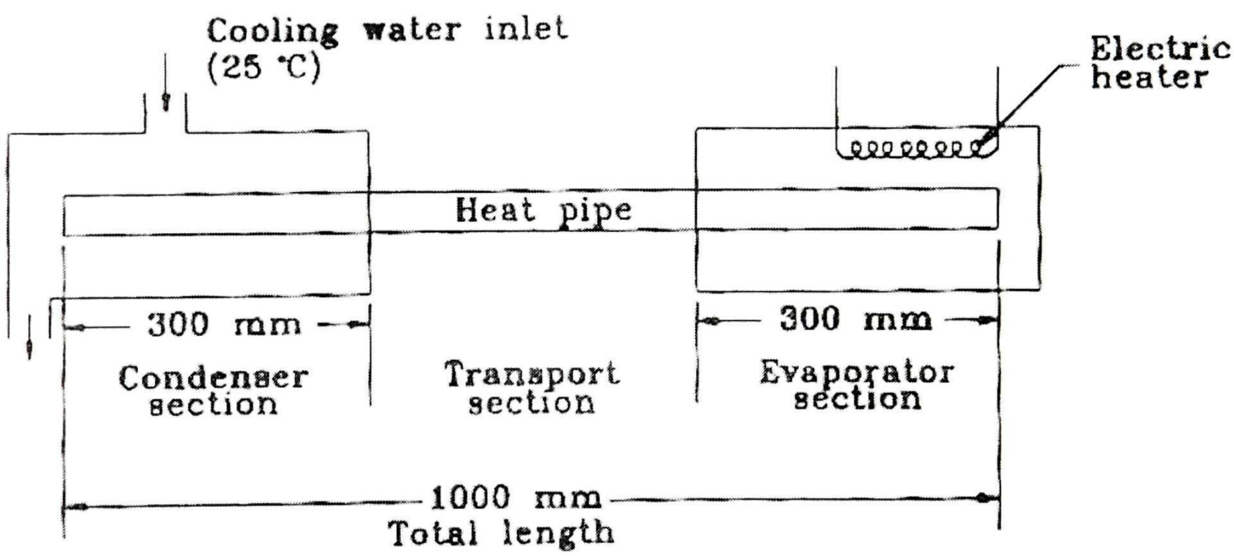


Figure 2.2 Testing configuration (1)

By actively controlling the cooling conditions at the condenser, a heat pipe can be used to keep a nearly constant temperature at the evaporator even though the rate of heat input to the evaporator may change frequently.

2.1.2 Development and Applications of Heat Pipe Technology

Heat transfer enhancement in heat exchangers is a challenge for those actively involved in the fundamental research of heat and mass transfer as well as those who design new heat exchangers. A heat pipe is one of the most efficient heat exchangers in existence today. Initially, the concept of the heat pipe came from an invention by Gaugler (5) of General Motors in 1944, however, it was not until the early 1960s when an independent invention was done by Grover (6) that the remarkable potential of heat pipes started to be appreciated, and research and development were expanded. In recent years, heat pipe technology has been rapidly developing. Numerous investigations and studies focusing on heat pipes have been performed in order to better understand the operating mechanisms, and to develop more extensive applications for the technology. Literally thousands of technical papers and articles on heat pipes have been published in journals and conference proceedings (4). The papers published cover basic processes and fundamentals, theoretical and experimental studies of heat pipes and thermosyphons, materials problems and heat pipe technology, and include commercial, scientific and space applications.

Heat pipes operate at temperature ranges referred to as "Cryogenic" (0 to 150 K), "Low Temperature" (150 to 750 K) and "High Temperature" (750 to 3000 K), based on different working substances contained in the heat pipes, as shown in Figure 2.3. Working fluids are usually elemental or simple organic gases in the cryogenic range. Polar molecules such as water or other hydrocarbons in the low temperature range, liquid metals, for example alkali metals are used in the high temperature range. Sodium and potassium are the major working fluids for high temperature heat pipes operating from 400-1200 ^{o}C, with boiling points of 882.8 ^{o}C and 760 ^{o}C, respectively (7). The high temperature alkali metal based heat pipes have shown great potential and success in high temperature applications. Mucciardi and his research team are concentrating their efforts on developing high temperature applications of heat pipe technology (8, 9, 10, 11). The sodium based heat pipe cooled lances have been developed in cooperation with several industrial corporations for steel making in such units as the BOF, the electric arc furnace and RH degassing. A United States Patent (12) was granted for the heat pipe lance in 1994. The research team with Noranda has worked extensively to developed a twin roll caster based on a sodium heat pipe. In 1997, a unique method for conducting thermal analysis of melts and in particular aluminum alloys based on a heat pipe was developed by Mafoud, Gruzleski and Mucciardi (13, 14).

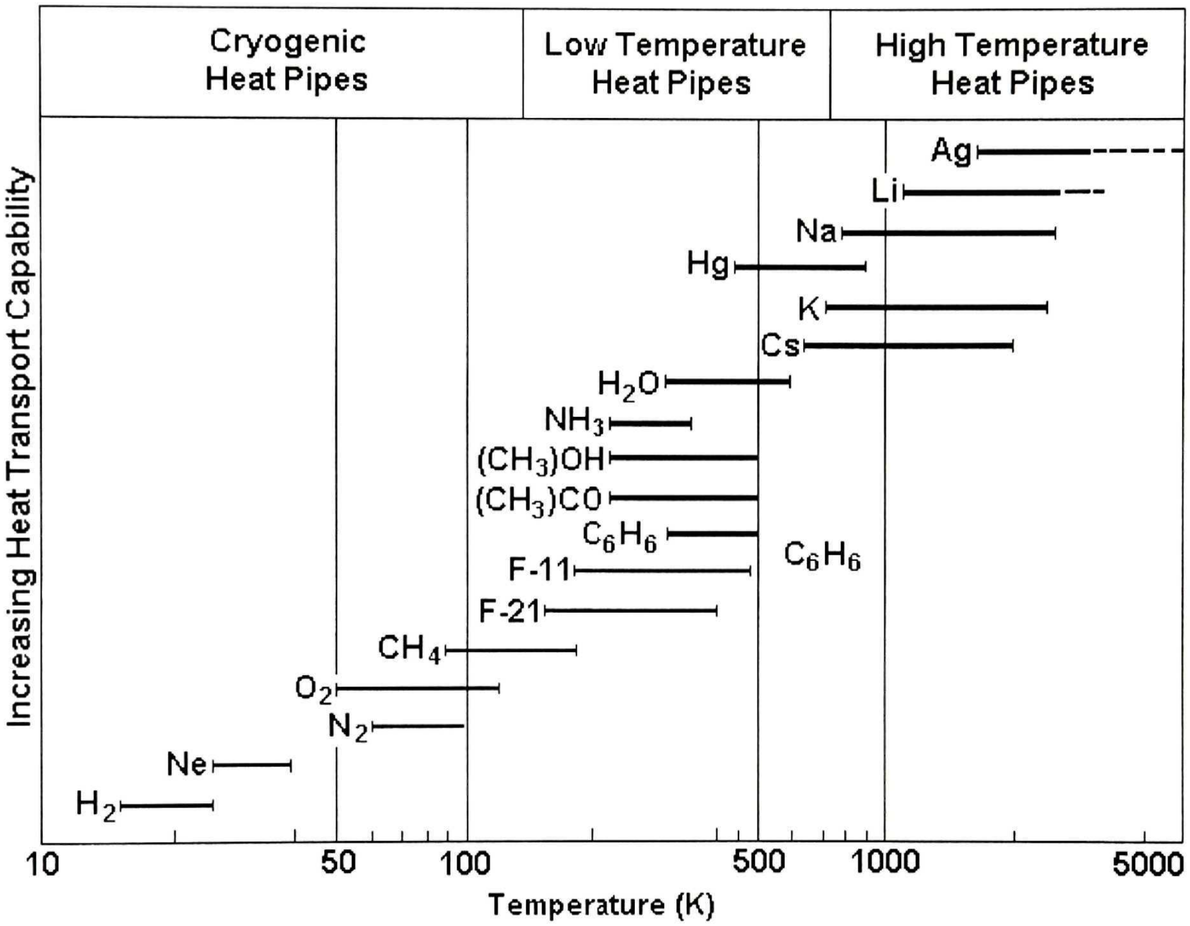


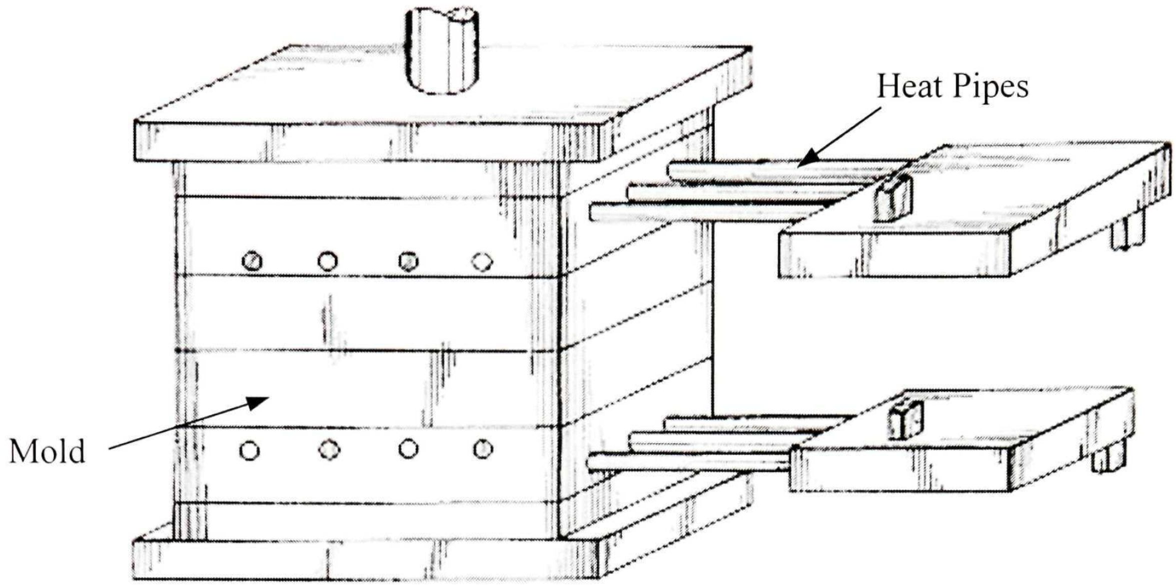
Figure 2.3 Typical operating ranges for heat pipe working fluids (4)

Besides the applications of high temperature heat pipes in metallurgical engineering, heat pipes are also used in other industrial applications, including aerospace, electronic devices, telecommunication, snow melting and numerous cooling/heating devices.

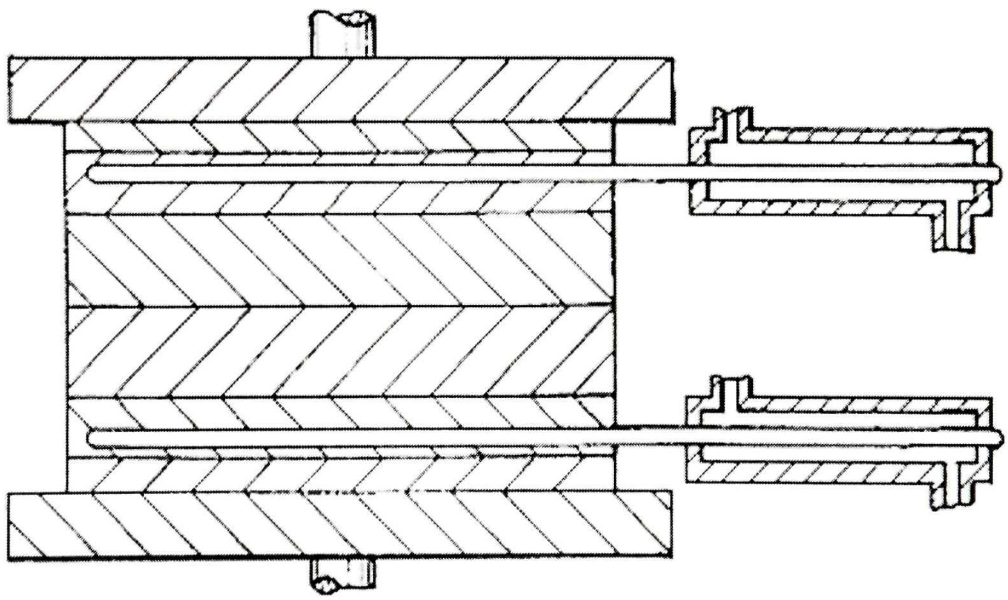
Heat pipe technology has received widespread attention in plastics technology. Plastics are processed to a final shape by injection molding in which it is necessary to control the cooling of the mold to get a uniform temperature distribution in order to avoid local contraction. On Feb. 18, 1997, Rioch Company of Japan was granted a US patent (15) that describes a plurality of heat pipes arranged in an injection mold to provide uniform and rapid controllable cooling of the mold as shown in Figure. 2.4.

The main applications of heat pipes deal with the problems of thermal management, environmental protection and energy and fuel savings. The heat pipe is rapidly becoming a main stream thermal management tool, particularly in the electronic and computer industry. Heat generated in modern electronic devices, from microprocessors to high-end power converters, must be extracted in order to ensure their successful and reliable operation. Many efforts have been made to apply the cooling technology for thermal control in the electronic industry (16, 17). Several of the more common examples of the use of heat pipes in electronics cooling were presented in the paper (17). These include cooling of processors of notebook computers and high power electronics, such as Silicon Controlled Rectifiers (SCR's), Insulated Gate Bipolar Transistors (IGBT's) and Thyristors.

Currently, one of the highest volume applications for heat pipes is cooling processors in notebook computers. Due to the limited space and power available in laptop and desktop computers, heat pipes are ideally suited for cooling the high power chips. The first time a heat pipe was used in a notebook computer was in 1994 (18, 19). The introduction of heat pipes in notebooks was thought of as a radical evolution in thermal management (20). Heat pipes were first used to take the heat from the heat source, i.e., CPU and transfer it to another location inside the notebook, i.e., a remote heat sink as shown in Figure 2.5. Almost every current notebook computer uses a heat pipe in its thermal management design. The use of heat pipes for the thermal management of desktop computers is also an accepted and applied technology. The reliability and flexibility of the heat pipe has proven to be a valuable attribute that provides the system designer with increased layout possibilities and typically improved thermal performance (21).



(a) Injection mold with heat pipe cooling



(b) Cross-section of the mold

Figure 2.4 Ricoh Co. Mold for plastic molded production (15)

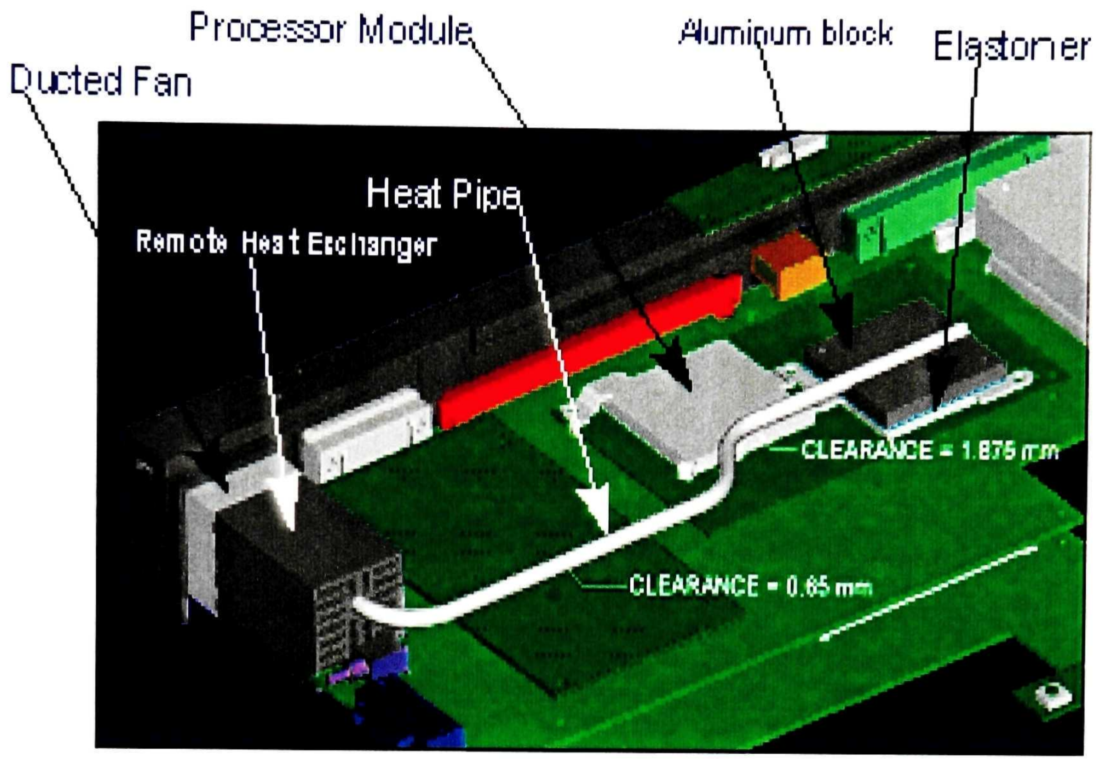


Figure 2.5 Contemporary Thermal Solution for a Pentium ® II Based Notebook Computer (18)

2.1.3 Characteristics of a Heat Pipe

1) Very high effective thermal conductance

The most important feature of a heat pipe is the ability to transfer considerable quantities of heat over a relatively long distance with low or no thermal gradient between the heat source and the heat sink. The high thermal conductivity of heat pipes minimizes spreading thermal resistance and makes the heat sink far more efficient by more effectively moving the heat to the extremities of the sink. This reduction of spreading thermal resistance is particularly beneficial in high heat flux applications.

2) An isothermal surface of low thermal impedance

An extraordinarily low thermal resistance in the heat pipe allows it to transfer the heat from the evaporator to the condenser almost without temperature drop, so the heat pipe can generate an isothermal surface anywhere inside the pipe.

3) Quick thermal response

The thermal response time of heat pipes is considerably shorter than other types of heat transfer devices (22), solid conductors for example, because heat pipes operate in closed two-phase cycles. The thermal response time is not a function of length.

4) Heat Flux transformation

The heat pipe is able to accommodate different heat fluxes at the evaporator and condenser by presenting different surface areas at these two locations.

5) Energy efficient

A heat pipe allows the developer to acquire additional surface area for heat rejection by natural convection, thus eliminating the need for a fan. If a natural convection cooling solution is needed, a heat pipe related to a miniature fan or heat sink might be more economical than other cooling solutions.

6) High reliability and long longevity

The heat pipe shows minimal or no degradation with time. Heat pipes, when properly designed and manufactured, have been shown to be highly reliable due to the fact that they contain no moving parts. They must, however, operate under acceptable pressure inside the chamber (23), and choice of materials must be made to eliminate the possibility of corrosion and/or physical degradation of the pipe.

7) Cost effective

Heat pipes are competitively priced with alternate cooling technologies. A heat pipe thermal solution has no moving parts to fail; consequently product maintenance requirements are eliminated or reduced.

8) Environment friendly

The heat pipe provides a thermal path to a sealed enclosure. There is no contamination release. Because a heat pipe is a passive device with no moving parts, it will result in no noise or noise reduction compared to a large system fan.

9) Flexible design

Heat pipes can be used to passively transfer heat from a source to a sink. They generally work in any orientation and can be bonded to the component to be cooled. With this arrangement, the heat sink may also be remotely located from the component. In some applications, the height over the embedded module does not provide sufficient space to provide direct cooling at this location. Heat pipes offer much design flexibility due to the ability of the heat pipe to transfer heat efficiently. While traditional heat sinks must be located on the heat source, heat pipes transfer heat away to areas where dissipation is more convenient or airflow is greater. Heat pipes can be bent and formed into a variety of configurations while maintaining their heat transfer properties.

2.1.4 Problems with Current Heat Pipe Technology

Although heat pipes are currently being used as thermal management tools in different areas, the commercial cooling applications are not at a large scale, and are limited to cooling with low heat fluxes. Water-based heat pipes in particular are expected to be capable of handling high heat fluxes. So far, most electronic cooling applications use a water-copper heat pipe operating at low heat flux. The trends of high power in a small package are pushing chip heat fluxes into the range of 50 to 100W/cm ^{2}. This requirement is very difficult for water-based heat pipe due to the problem of film boiling in this heat transfer regime. High heat flux causes film boiling resulting in heat pipe dryout and large thermal resistances.

As shown in Figure 2.6 (24), the heat flux through the heating surface q/A varies with the differential ΔT between the temperature of the heating surface T_w and that of working fluid T at one atmosphere. In the first region AB, at the low temperature, the mechanism is that of heat transfer to a liquid in natural convection. As the radial heat flux increases, the rate of bubble formation increases and very high heat transfer rates may be achieved. The heat transfer coefficient becomes greater in this region. This segment, BC, at temperatures below the critical temperature drop, Point C, is called the nucleate boiling regime, as shown in Figure 2.7 (a) (the isolated bubble region) and Figure 2.7 (b) (the slugs and columns region). If the heat flux continues to increase beyond the maximum heat flux, the bubble population becomes so high that portions of the heating surface are covered by a layer of insulating vapor. The segment CD is known as the partial film boiling region. When the layer of vapor becomes stable, the boiling action in this region DE is called stable film boiling shown as Figure 2.7 (c), which is undesirable in the operation of high heat flux heat pipes. The quiescent vapor film becomes the bulk of the resistance to heat transfer. At this point, the heat is only transferred by conduction and radiation. As ΔT increases, the heat flux rises. When the heating surface superheat ΔT reaches a certain value (Point E), melting point of the heating material, the physical surface is destroyed.

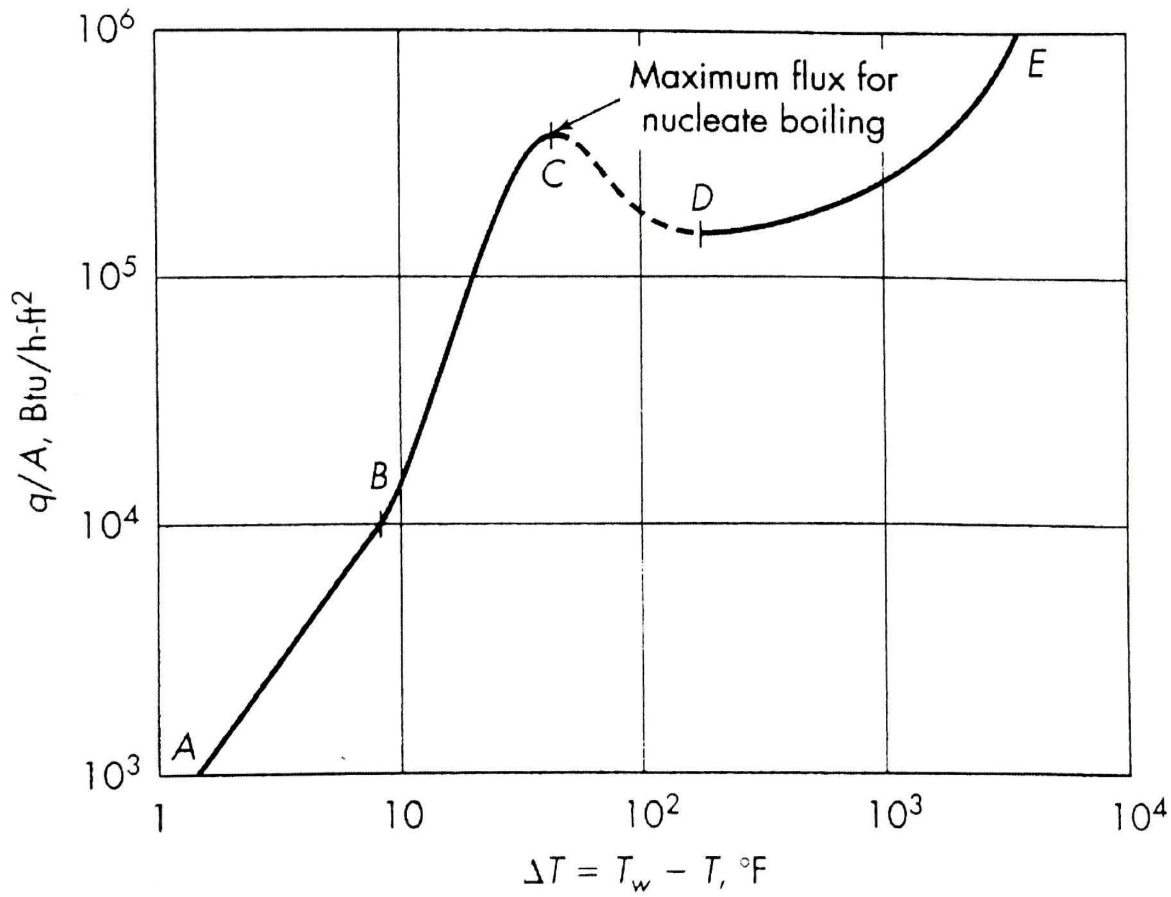


Figure 2.6 Pool boiling regimes-Heat Flux versus temperature drop ΔT, boiling of water at 1 atm (24)

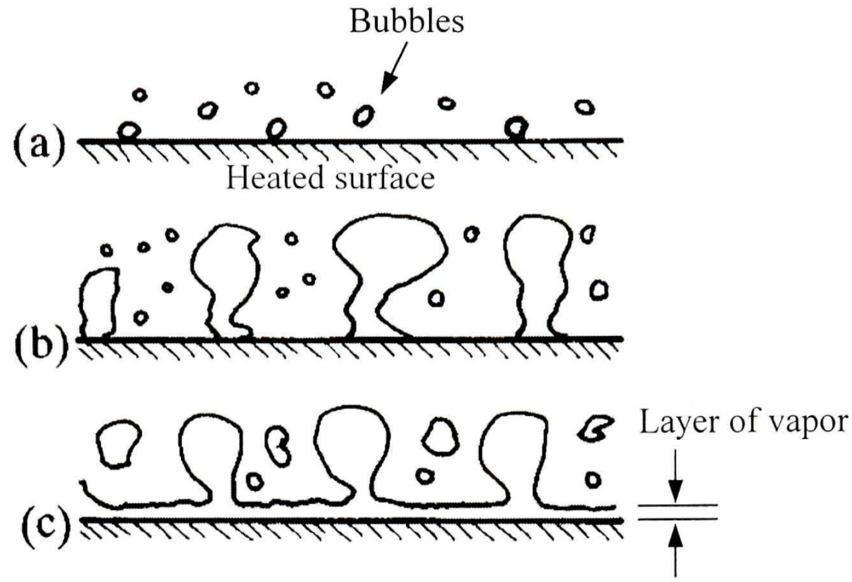


Figure 2.7 Visualization results in nucleate and film boiling (25): (a) Nucleate boiling – the isolated bubble region; (b) Nucleate boiling – the slugs and columns region; (c) Film boiling

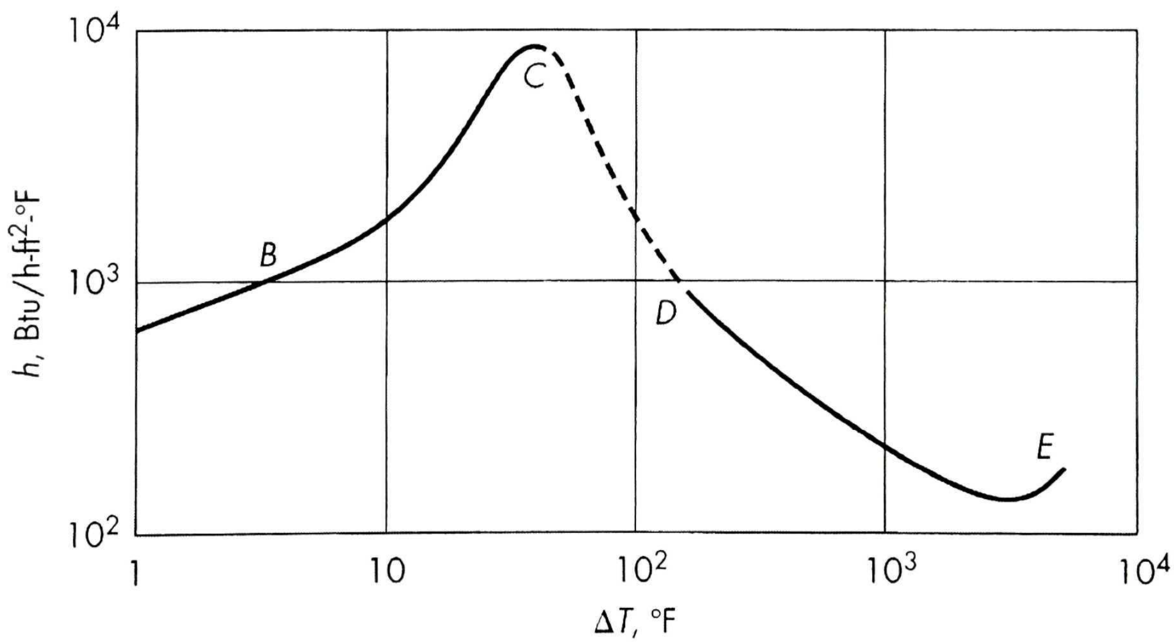


Figure 2.8 Heat transfer coefficients versus ΔT, boiling of water at 1 atm (24)

A heat transfer coefficient, h, represents the proportionality constant between the heat flux and the average temperature difference as defined in Newton's law of cooling. The maximum and minimum coefficients of boiling heat transfer are evident in Figure. 2.8.

Nowadays, researchers are making many efforts to investigate and develop high heat flux heat pipes, as a critical tool of thermal management (26).

2.2 Cooling Control of Permanent Molds in Aluminum Casting

2.2.1 Permanent Mold Casting of Aluminum

The permanent mold casting process utilizes metal molds into which molten aluminum is poured by using gravity, low pressure, vacuum or centrifugal pressure. A metal mold is made up of two or more parts (27). This casting process is repeatedly used for long production operations of identical castings. The process is optimal for high volume production of castings with fairly uniform wall thickness and limited complexity with respect to undercuts or intricate coring (28).

Permanent mold casting of aluminum alloys is the main casting method used in the production of high-quality automotive parts or other components. In order to obtain sound cast parts, several measures must be taken to make parts defect-free with good mechanical properties. Casting defects due to shrinkage, shown as Figure 2.9, may only be reduced by controlling the temperature distribution in the mold with an adequate cooling system. Generally speaking, solidification should start from the thinnest region in the cavity and advance toward the riser heads. The production of high quality castings requires an understanding of the temperature distribution in both the mold and the casting. Thermal management is an essential feature of a controlled casting process. It is one of the main objectives of this thesis to study the use of heat pipes for providing thermal management of this casting process.

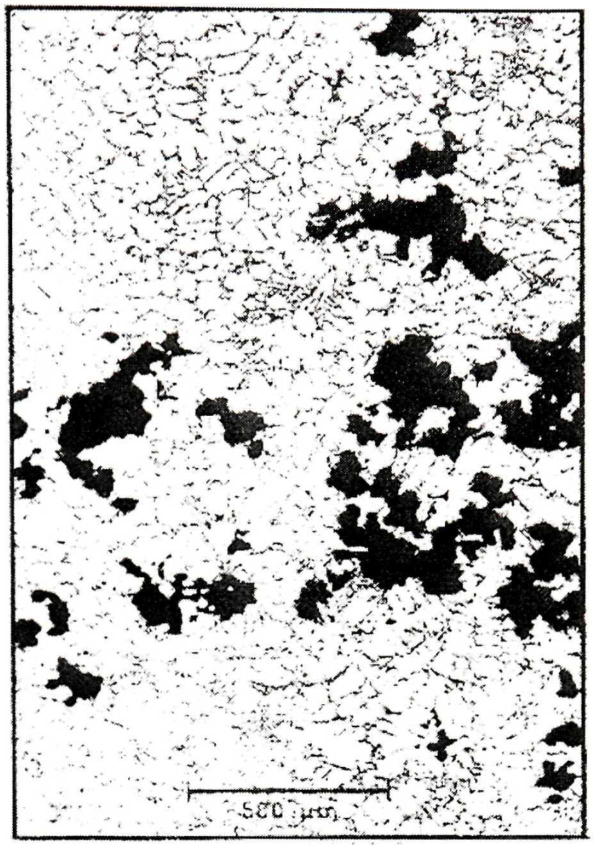


Figure 2.9 Aluminum casting microstructure with shrinkage pores (**29**)

2.2.2 Heat Transfer Behaviors in Permanent Mold Casting

The heat transfer conditions during solidification in permanent mold casting are complex, since the boundary conditions between a casting and its mold change with time. It is well known that the heat transfer between the solidifying casting and the permanent mold is very important to casting quality. The rate of heat transfer is controlled by a number of resistances described by Flemings (30). The resistances, shown in Figure 2.10, to heat flow from the interior of the casting are (31):

- The liquid
- The solidified metal
- The metal-mold interface
- The mold

- The surroundings of the mold

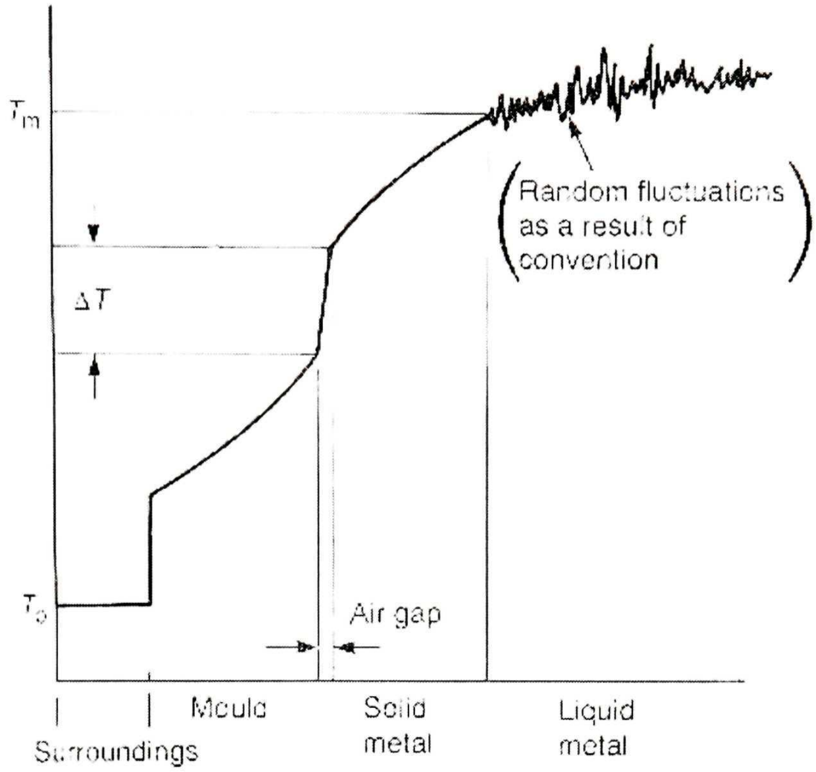


Figure 2.10 Temperature profile across a casting freezing in a mold, showing the effect of the addition of thermal resistances which control the rate of heat transfer (31).

1) Casting-Mold Interfacial Heat Transfer

On an interface between two different materials, there is always resistance to heat flow. In the permanent mold casting process, the interface is usually represented by a small air gap formed between the casting and the mold cavity surface due to the casting contraction and the mold expansion. A coating is often applied on the mold cavity surface, and this also contributes to the heat flow resistance.

The analysis of heat transfer problems pivots on the accurate knowledge of the heat transfer coefficient, h. The heat transfer coefficient is affected by many parameters which have been defined differently by various investigators (32). The heat transfer at the casting-mold interface is controlled by the interfacial heat transfer coefficient, h, which is defined as:

$$h = q/(T_c - T_m) \qquad (1\text{-}1)$$

where: q- interfacial heat flux, W/m^2

T_c- casting surface temperature, K and

T_m- mold surface temperature, K.

The heat transfer coefficient at the mold-metal interface is controlled by many factors, and can be expressed as a function of several parameters as shown in Figure 2.11.

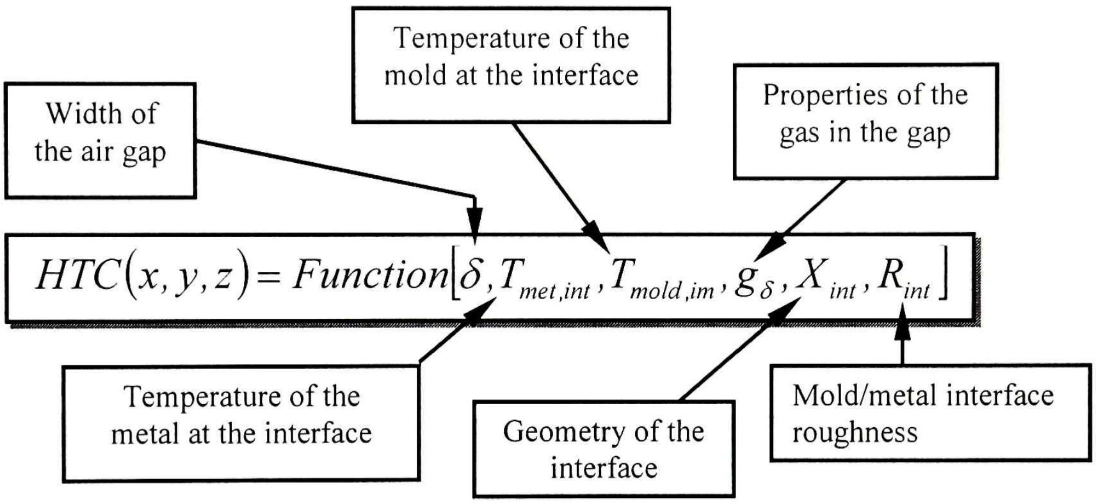


Figure 2.11 General form of the heat transfer coefficient correlation (33)

The interfacial heat transfer coefficient varies from one casting to another. In order to obtain an accurate value, the best way is to apply inverse calculations to the experimental temperature data from the permanent casting process.

Figure 2.12 illustrates the typical variation of the gap width and the interfacial heat transfer coefficient (HTC) with time. The HTCs were derived by inverse calculations using the software package 3-MOS (34). The interfacial gap widths were measured in different parts of an experimental stepped cylindrical mold. H13 tool steel and beryllium copper (BeCu) were used in the same mold (so-called composite mold) in order to investigate the effect of different material properties of the mold on the interfacial heat transfer between the mold and the casting.

2) Heat Flow in the casting and the mold

The heat transfer analysis for the casting and mold is based on the energy equation. The governing equation is

$$\rho C_p \left(\partial T/\partial t\right) = \nabla \cdot k\nabla T \tag{1-2}$$

where: ρ, -density, kg/m^3, C_p -specific heat, J/kg·K, and k -thermal conductivity, W/m·K are equal to: ρ_m, C_{pm}, and k_m in the mold and ρ_c, C_{pc} and k_c in the casting.

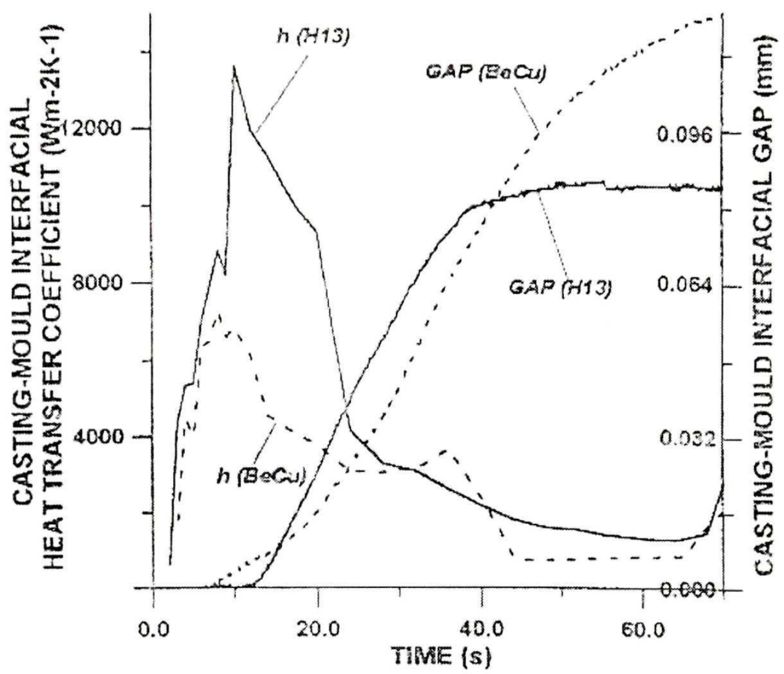
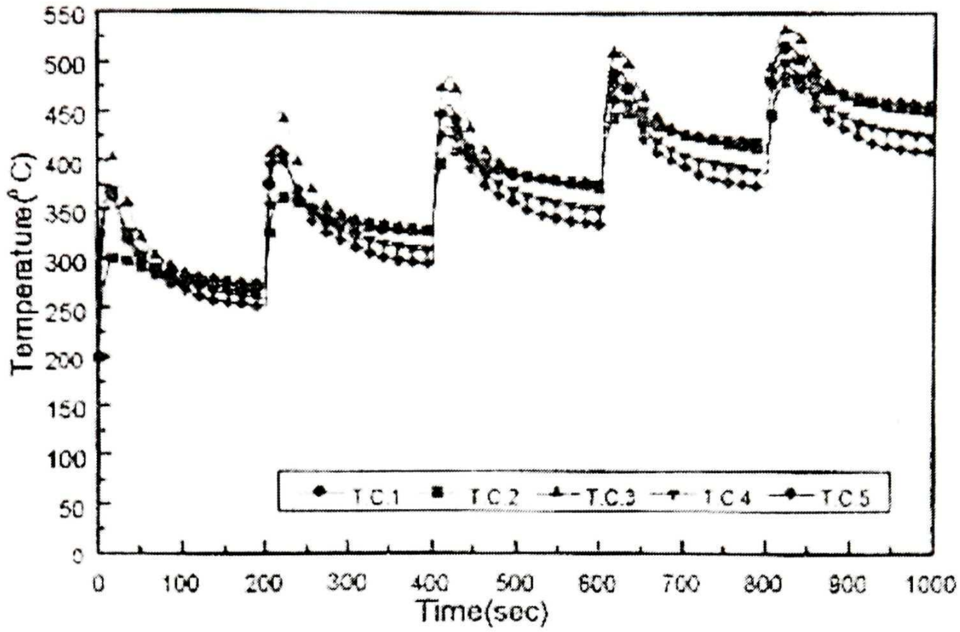


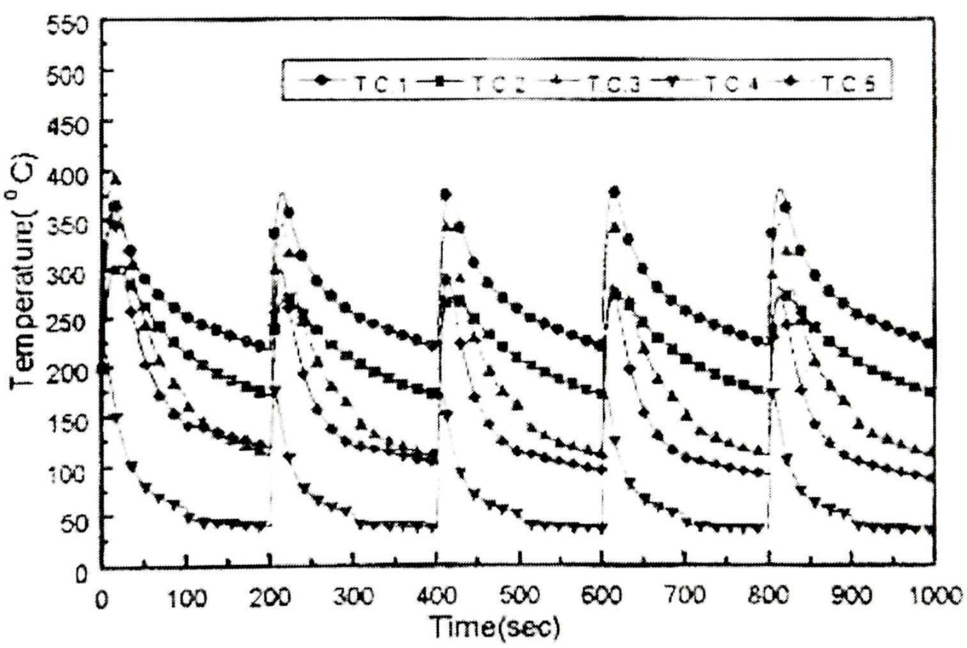
Figure 2.12 Measured interfacial gap width and calculated heat transfer coefficient (**34**)

One of the roles of the mold is to dissipate heat generated by the solidifying metal. This is very important in permanent mold casting. Thermal behaviors of the mold and casting during the operation of permanent mold casting will determine important production parameters such as equilibrium mold temperature, number of castings produced per unit time, and so on (35).

Permanent mold casting involves a cyclic process. In every casting cycle the mold is closed during melt pouring and solidification, and is opened to remove the casting. The mold will reach a pseudo steady-state when the temperature at any position in the mold oscillates in a regular manner (36). Many experiments on the thermal conditions in permanent mold casting have been carried out in the past years (37, 38, 39, 40). Figure 2.13 shows temperature history at various locations for a cyclic analysis (41) in mold cooled by water flowing through channels in the mold, and in mold not cooled.



(a)



(b)

Figure 2.13 Temperature history at various locations for cyclic analysis (**41**): (a) without cooling; (b) with water cooling

It is clear that the temperature profiles are very different between applying cooling (Figure 2.13a) and no cooling (Figure 2.13b). During the casting cycles, the temperature of the mold continuously increases without cooling, while in the case with water cooling it is easy to keep the heat balance in the mold. While steady state will eventually be attained without cooling, it is fairly obvious that there is a high probability that the mold will run hot. Cooling offers the possibility of using a smaller mold whose temperature distribution can be controlled.

2.2.3 Thermal Modeling of Permanent Mold Casting of Aluminum Alloys

Recently, developments in computer modeling techniques in the process of metal castings have been achieved (42, 43, 44, 45, 46). One of the main benefits of this technique is to optimize the casting design by simulating the mold filling, solidification and thermal stress behavior to predict the formation of casting defects. By properly optimized casting design based on numerical simulation, the extra trials and errors can be greatly reduced, resulting in improvement of the casting quality with lower cost and higher productivity.

Numerical simulation for mold filling and solidification processes in permanent mold castings, based on solving coupled Navier-Stokes equations for Newtonian flow, and energy equations for heat transfer, has been well developed, and simulated results are widely verified and recognized.

Normally, the modeling software includes pre-processor, calculation module and post-processor. In the pre-processor, the solid model, meshing model, materials properties and boundary conditions are built up and input. The simulation for casting processes is run in the calculation module. In the post-processor module, the simulation results are analyzed and visualized on the screen.

2.2.4 Thermal Management of the Permanent Mold Casting of Aluminum Alloys

As mentioned in the introduction, it is necessary to control the cooling of permanent mold castings. Of particular interest in cooling control is to speed up solidification and control the solidification pattern in low pressure and gravity permanent mold castings. For many years, thermal management of the permanent mold process has been a significant challenge (47). Foundrymen realize that thermal control during permanent mold casting is essential to ensure casting quality by establishing the desirable temperature gradients within the mold and the casting. In addition, with a uniform temperature distribution within the mold, thermal shock and molten metal erosion of the mold can be reduced or eliminated, leading to longer mold life (48).

There are two major classical methods to control the thermal behavior during permanent mold casting: coating and cooling. Coatings applied to the mold's inner surfaces improve casting quality by providing the appropriate thermal resistance at the metal/mold interface, as well as by promoting directional solidification (49, 50, 51). The application of coatings is very hard to control, and the options of coating parameters are limited.

Air, water and chill inserts are often used in permanent mold casting. With air cooling the physical arrangement is simpler, but the effect on casting microstructure is small. For water cooling, channels are cut inside the wall of molds, and equipment for recycling the cooling water is needed. Safety problems must be addressed in foundries that use water. For chill inserts, thermally conductive metal, such as copper, is used in the mold system to influence casting solidification. However, the chills become ineffective for heat removal once they reach equilibrium (52)

There are a number of instances in production processes where heat transfer considerations which govern the cycle time of the permanent mold casting process are controlled with heat pipes. The heat pipe can be likened to a practically perfect thermal conductor, which can make it possible to solve certain very complex thermal problems in the foundry and in particular to improve and simplify the cooling circuits. An example of a virtual application in which the use of heat pipes led to an improvement in casting quality, with a rapid cycle time, is described below.

Figure 2.14 shows the concept of cooling several points with a single cooling circuit and heat pipes in parallel. The heat pipes are used for moving heat from hot spots to cold spots within a die block. Die designers will no doubt quickly take advantage of this feature, since it offers for the first time a simple way of reducing thermal gradients within the mass of a die, to contribute to longer service life (53).

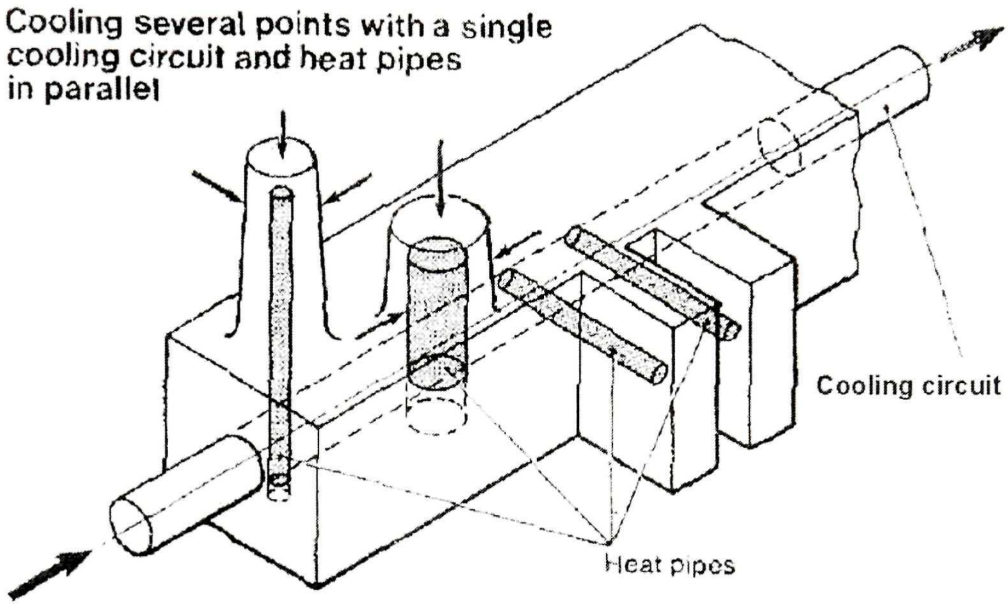
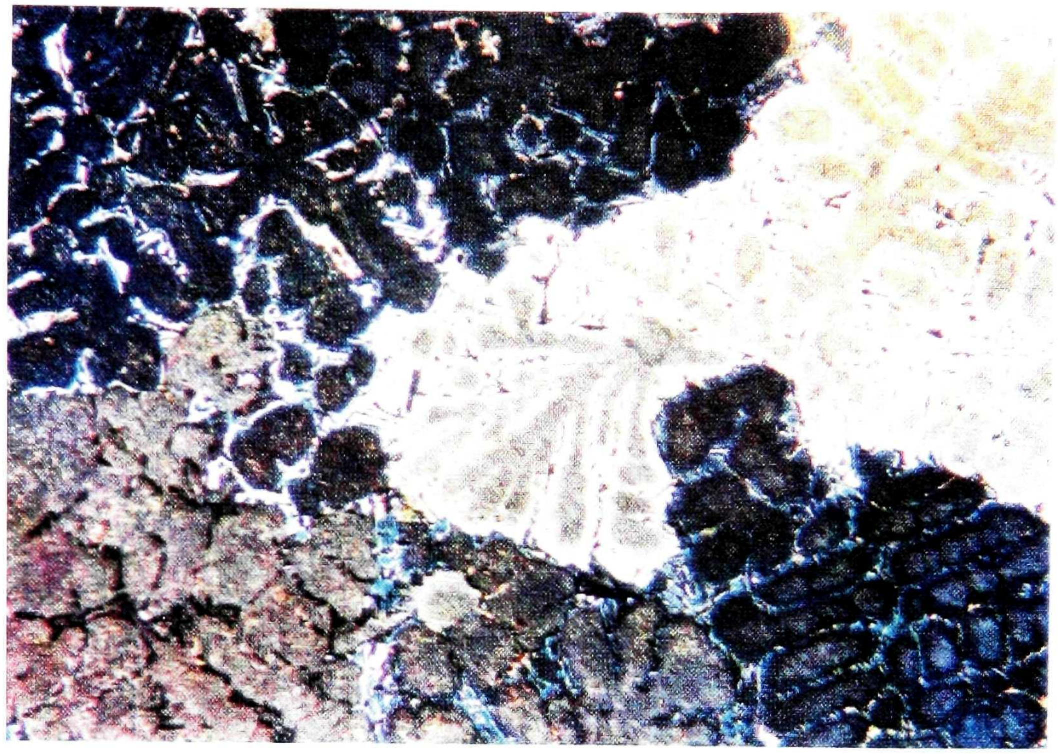


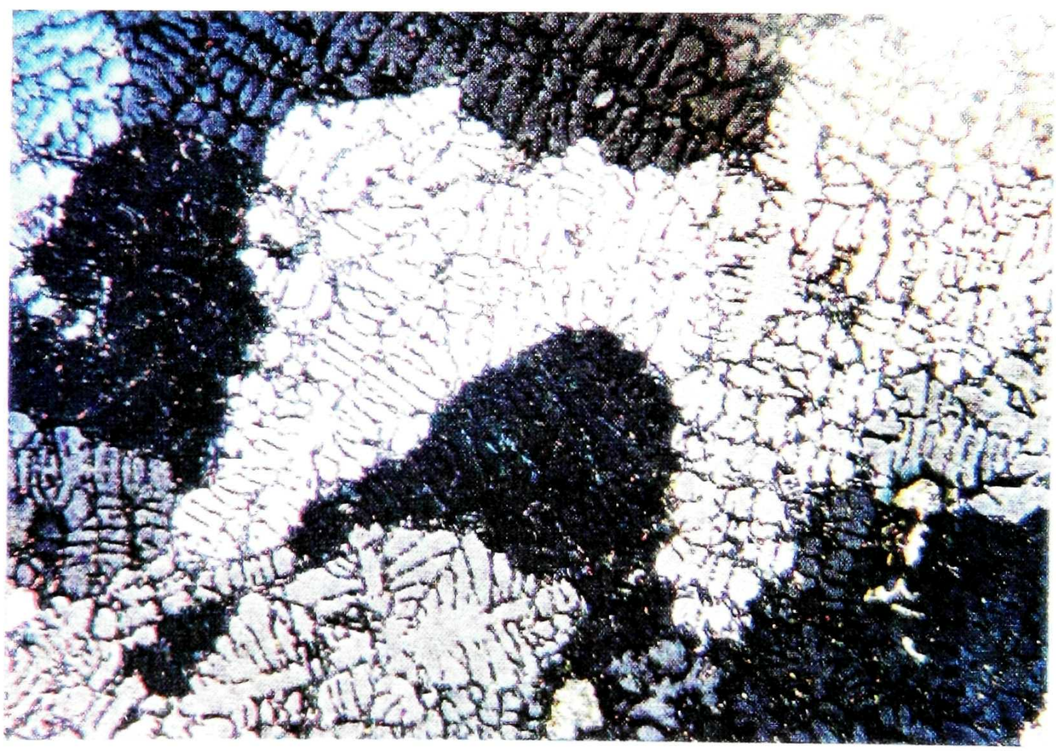
Figure 2.14 Cooling several points with a single cooling circuit and heat pipes in parallel (53)

2.3 The Relationship of Microstructures and Mechanical Properties vs. Cooling Rate

Aluminum alloys have widespread application, especially in the automotive industry due to their excellent properties. Increasing demands for such materials have resulted in increasing research and development for high-strength and high-formability aluminum alloys. To improve the mechanical properties of these materials, a common practice is to refine the microstructure of the casting, because the finer the dendrite cell size and grain size, the higher the strength, all other features being equal (27).



(a)



(b)

Figure 2.15 Grains and dendrites of alloy A357.2 under the different cooling rates: (a) Cooled at a rate of 0.3 °C/s; (b) Cooled at a rate of 4 °C/s (54)

Cooling rate plays an important role in determining the microstructure of the casting. Higher cooling rates reduce solidification time and grain size of the casting. Hence, grain density increases with cooling rate (55). The size of the dendrite cells (cross sections of the dendrite arms or branches) and their spacing decreases and the size of second-phase particles is reduced with the increment of cooling rates. The grains and dendrites under two different cooling rates are shown in Figure 2.15. The improvements in mechanical properties obtained by the change in dendrite formation controlled by solidification rate are shown in Figure 2.16 (56)

Correlations have been established between measurements of average secondary dendrite arm spacing and solidification rate indicating a relationship of exponential form (27):

$$\lambda = KR^{-n} \qquad (1\text{-}3)$$

where:

λ = average secondary dendrite arm spacing, μm

R = solidification time, s

K = a constant (which may change with temperature gradient), and

n = exponent (0.3 to 0.4)

From experimental observation, the average pore size decreases with increased cooling rate. There are a number of explanations for this phenomenon. For a higher cooling rate, the dendrite arm spacing (DAS) decreases as do the intergranular regions. Pore growth is thus limited. Another explanation is that with decreased solidification time, there is less time for hydrogen to diffuse from the solidifying dendrites to the liquid. Hence, gas pore growth rate is inhibited, as shown in Figure 2.17.

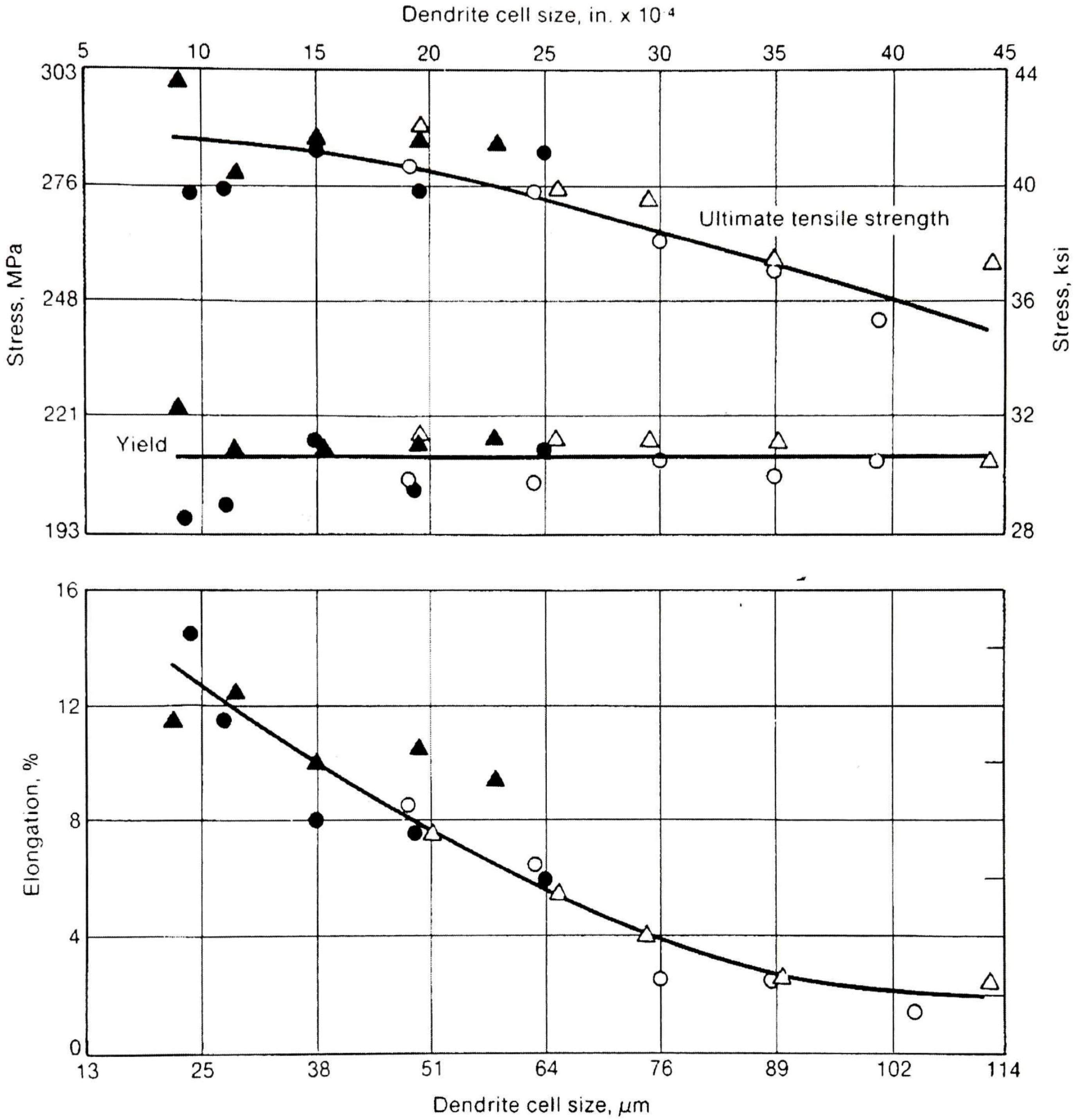


Figure 2.16 Tensile properties versus DAS for the castings of aluminum alloy A356 (**56**)

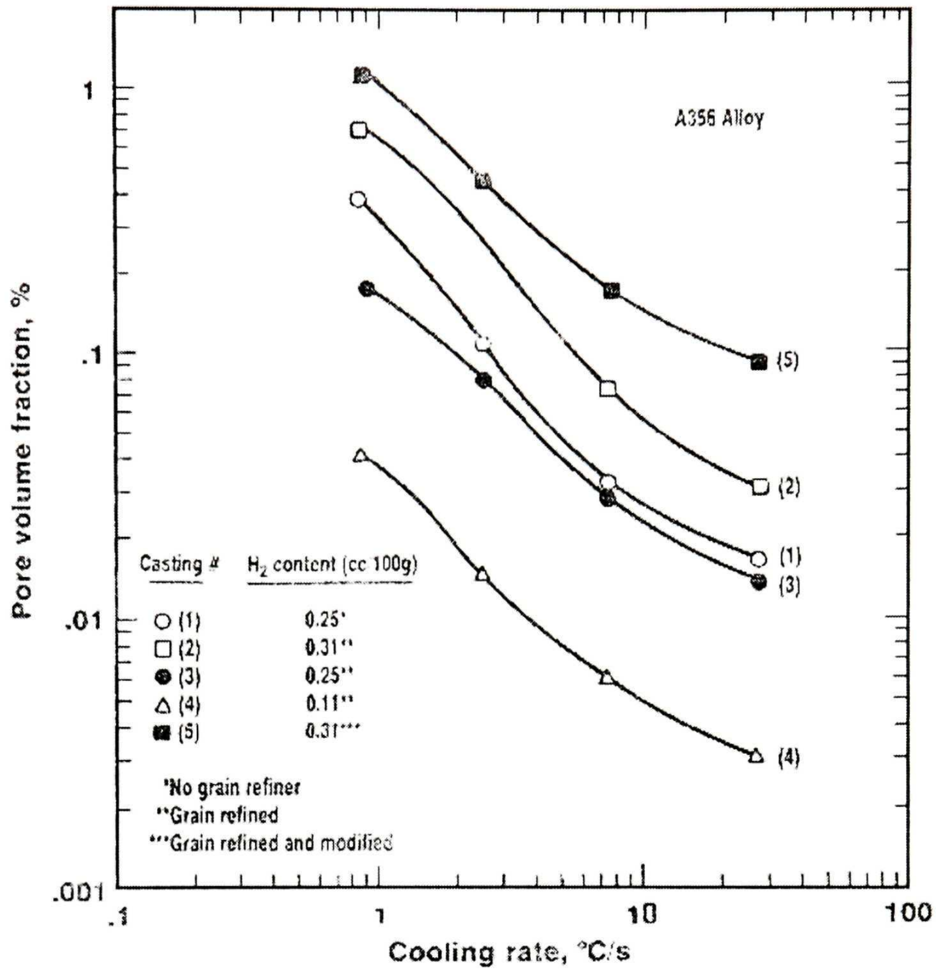


Figure 2.17 Pore volume fraction as a function of cooling rate for A356 Alloy casting (55)

2.4 Problems of Current Thermal Management for Permanent Mold Castings of Aluminum Alloys

As higher quality products and tighter process control become critical, so does the demand for high quality permanent mold castings of aluminum alloys. Effective, efficient reliable and inexpensive cooling technologies are required for the thermal management in permanent mold casting process.

All of the current cooling methods present certain problems as described previously. Over many years, foundrymen have suffered the disadvantages of the currently used cooling systems to gain benefits for the permanent mold casting process (57). The following two examples (48) of water-cooled permanent molds show some of these disadvantages. In Figure 2.18, a permanent mold with water-cooling is shown. In this mold the cooling jacket is affixed to the casting machine. The drawback of the method is the air gap that often occurs between the mold and cooling jacket. This leads to slower and less aggressive cooling. A second example is shown in Figure 2.19. The cooling is applied to the permanent mold by drilling cooling passages in the mold. The openings of the cooling path are often sealed by threaded plugs. Thermal expansion between different materials, and defects, for example porosity, in the mold materials may result in leaks. Moreover, this cooling method is unable to provide uniform cooling and to avoid hot and cold spots in the mold because the temperature distribution along the cooling passages is non-uniform, resulting from the temperature differential between water input and output within the mold for certain flow rates of water.

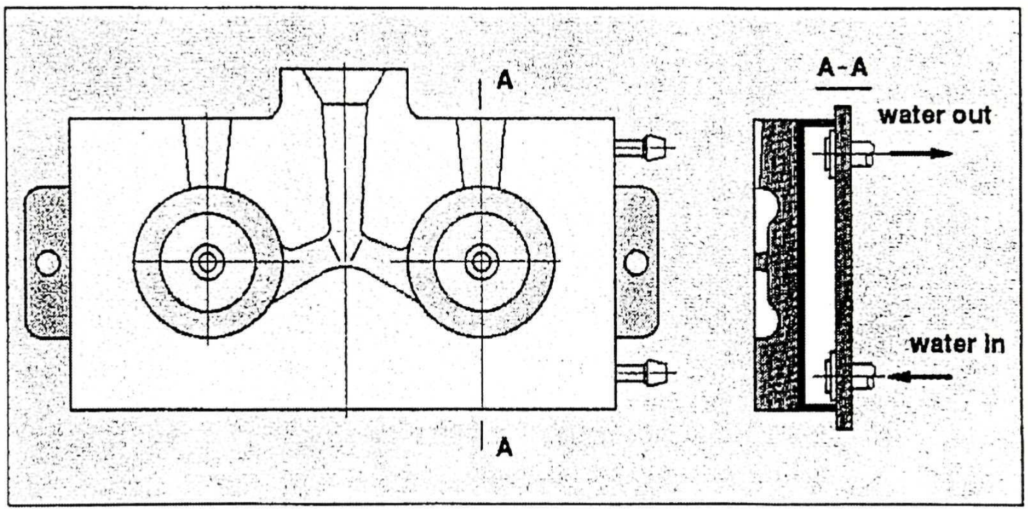


Figure 2.18 Water-cooled permanent mold by cooling jacket affixed to casting machine (48)

Several investigations on the use of heat pipe cooling in metal casting have been done (58, 59, 60, 61). These studies have shown potential applications of heat pipe cooling in metal casting, however, the optimum cooling capability of the heat pipes was not obtained in these studies. The main reasons for the poor behavior were the thermal contact resistance between the mold and the heat pipes, and the film boiling regime of heat pipe operation. It is the aim of the project described in this thesis to develop a highly efficient heat pipe for aluminum casting, and to demonstrate its effectiveness both in the laboratory and in the plant.

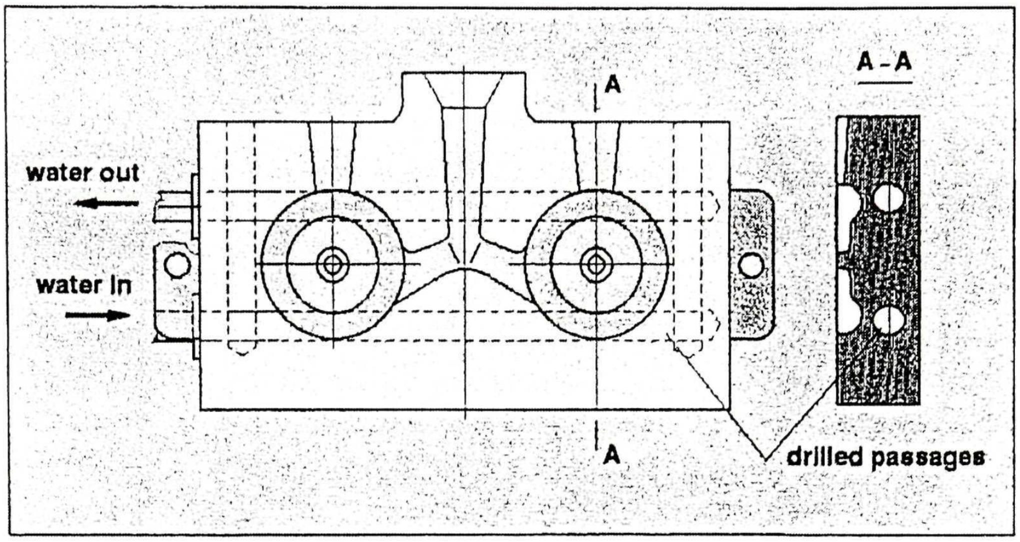


Figure 2.19 Water-cooled permanent mold with drilled cooling passages in the mold (48)

Chapter 3 Development of a novel water based heat pipe

3.1 Design of the Novel Water-Based Heat Pipe

3.1.1 Background

One of the main objectives of this research is to develop a heat pipe to be used for controlled cooling of permanent mold castings of aluminum alloys, as mentioned in Chapter 1. With the use of the new heat pipe cooling system, the problems associated with the current technologies for mold cooling can be overcome. Moreover, the heat pipe must be highly efficient to provide high cooling rates which are comparable or better than those of current water cooling systems being used in casting processes. The approach should make it possible to cool a casting according to a predetermined cycle, provide more cooling at specified times in the casting process, and less cooling at other times. The conventional heat pipe cannot offer the feasibility of controllable, manageable and high cooling rates for permanent mold castings because of the problems discussed in Chapter 2. With these considerations in mind, a novel and effective heat pipe was to be designed and developed. This heat pipe must be acceptable to industry and it should provide sufficient heat extraction in the cooling of permanent molds in aluminum casting.

3.1.2 Considerations of the Heat Pipe Design

3.1.2.1 Required Criteria of a Heat Pipe for Mold Cooling

The optimum heat pipe to be employed for the controlled cooling of permanent mold castings in a commercial foundry should meet a number of basic criteria. These include:

- Be reliable and safe;
- Can be turned on/off at specific times;

- Can achieve cooling rates as high as water cooling without using water;
- Provide uniform cooling;
- Meet the required performance criteria;
- Should respond immediately when being turned on;
- Based on air cooling;
- Simplify the cooling circuits and infrastructure;
- Can be used to redistribute heat from high temperature regions to low temperature regions;
- Have a long operating life and no degradation of performance;
- Be free of maintenance requirements;
- Be environment friendly;
- Be of competitive cost to other cooling techniques that are capable of dissipating similar heat fluxes.

The performance of a heat pipe depends on its structure, shape, dimension, orientation and other parameters. To obtain the features required above for the new heat pipe was a challenge and a major objective of the present research project.

The most important heat pipe design consideration is the amount of thermal energy that the heat pipe is able to transfer, the so called heat flux capability of a heat pipe. The maximum heat transport capability of the heat pipe is subject to several limiting parameters which will be discussed in subsequent sections.

3.1.2.2 Heat Pipe Heat Transfer Limitations

The operation of a heat pipe involves: phase change, vapor flow, liquid flow and interaction of the two phases. It is the thermal fluid phenomena that lead to the limitations of the maximum heat transfer rates of the heat pipe. Limitations to heat transfer capacity of a heat pipe have been well investigated and discussed in several books on heat pipes (1, 2, 3, 4). Generally, there are five primary limitations. They include: the viscous, sonic, capillary, entrainment or flooding, and boiling limitatons. The possible limits to maximum axial heat transfer capability as a function of operating temperature of the heat pipe are shown schematically in Figure 3.1 (3).

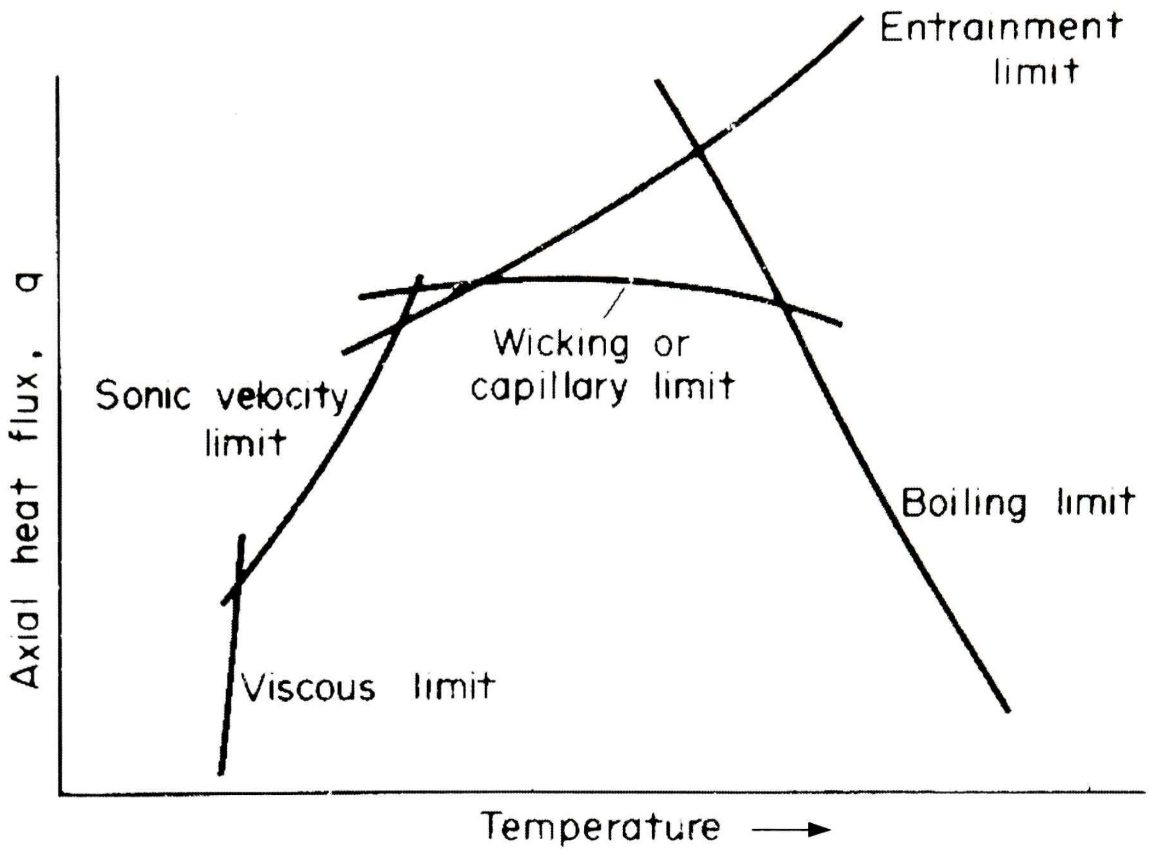


Figure 3.1 Primary limitations to the heat transport capability of a heat pipe (3)

1) Viscous limit

If the vapor pressure gradient is very small between the evaporator and the condenser of a low temperature heat pipe, and this is actually smaller than viscous forces, the viscous forces then prevent vapor flow in the heat pipe. In other words, a given flow will require the existence of a minimum pressure gradient to sustain the flow. If the heat pipe pressures are too low, it may not be possible to produce the required pressure gradient to overcome viscous effects. Under such an operating condition, the heat pipe reaches a heat transfer rate that is referred to as the viscous limit. Moderate temperature heat pipes seldom achieve this limit.

2) Sonic limit

The sonic heat transport limit of a heat pipe happens at the evaporator exit of the heat pipe for a certain vapor temperature when the vapor velocity approaches sonic velocity. A critical or choked flow condition exists. The sonic limitation imposes a ceiling on the maximum heat transfer rate for the heat pipe and it leads to a high axial temperature gradient because of the choked flow.

3) Entrainment limit

The entrainment limit results from the shear force existing at the liquid-vapor interface because of the countercurrent flow condition between the vapor and the liquid, especially when the vapor velocity is sufficiently high. This phenomenon prevents the condensate from returning to the evaporator and eventually makes the evaporator dryout by entraining the condensate into the vapor flow stream.

4) Capillary limit

For a heat pipe to return working fluid through the capillary structure, there is, for a given capillary structure, a limited pumping ability to move the liquid from the condenser to the evaporator. This limit is referred to as the capillary limit, which depends on the wick material and structure, working substance, evaporator heat flux and the operating temperature.

5) Boiling limit

There is a heat flux limit for the evaporator of a heat pipe which is termed the boiling limit. It arises as a direct consequence of the boiling action on the evaporator walls. For the case of heat pipes, the boiling heat transfer regime that is desired is nucleate boiling (see Figure 2.6). As discussed in Chaper 2, there are two broad modes of boiling: 1) nucleate (free, pool) boiling and 2) film boiling. Nucleate boiling is the preferred mode. Film boiling on the other hand is normally avoided because it can lead to failure. However, when the radial heat flux or the heat pipe wall temperature becomes excessively high, the critical heat fluxes may be reached. At that point, the boiling heat transfer regime becomes dominated by film boiling. This leads to a sudden drop in the heat transfer coefficient, and to heat pipe dryout and to a large thermal resistance at the interface. This phenomenon is also called the boiling crisis. For a high heat flux water based heat pipe, the boiling crisis is a critical issue. One of the targets of this research was to see if a solution could be found whereby it would be possible to have a high heat flux water heat pipe work efficiently in the nucleate boiling regime and not be subject to film boiling.

The theories of boiling heat transfer have been very well investigated. In 1962, Chang derived a general equation for critical heat flux (CHF) of pool boiling (62). By simplification, he obtained the critical heat flux for vertical surfaces as:

$$q''_{CHF,vert} = C_1(\rho_G)^{1/2} H_{fg}\left[\sigma g(\rho_L - \rho_G)\right]^{1/4} \quad (3\text{-}1)$$

where:

$q''_{CHF,vert}$ — critical heat flux for vertical surfaces, W/m^2

ρ_G — density of vapor, kg/m^3

H_{fg} — latent heat of evaporation, J/kg

σ — surface tension, N/m

g — acceleration due to gravity, m/s^2

ρ_L — density of liquid, kg/m^3

C_1 — constant, 0.0012 $m^{1/4}/s^{1/2}$

and for boiling from horizontal surfaces,

$$q''_{CHF,hor} = C_2(\rho_G)^{1/2} H_{fg}\left[\sigma g(\rho_L - \rho_G)\right]^{1/4} \quad (3\text{-}2)$$

Where:

$q''_{CHF,hor}$ — critical heat flux for horizontal surfaces, W/m^2

C_2 — constant, 0.0016 $m^{1/4}/s^{1/2}$

Besides surface tension, density and latent heat of the liquid shown in the theoretical equations above, there are a number of other experimental parameters that influence the CHF in boiling heat transfer. They include: conductivity, wettability, bubble formation and density, heated surface condition, dimension and orientation of heater, agitation, acceleration, and subcooling.

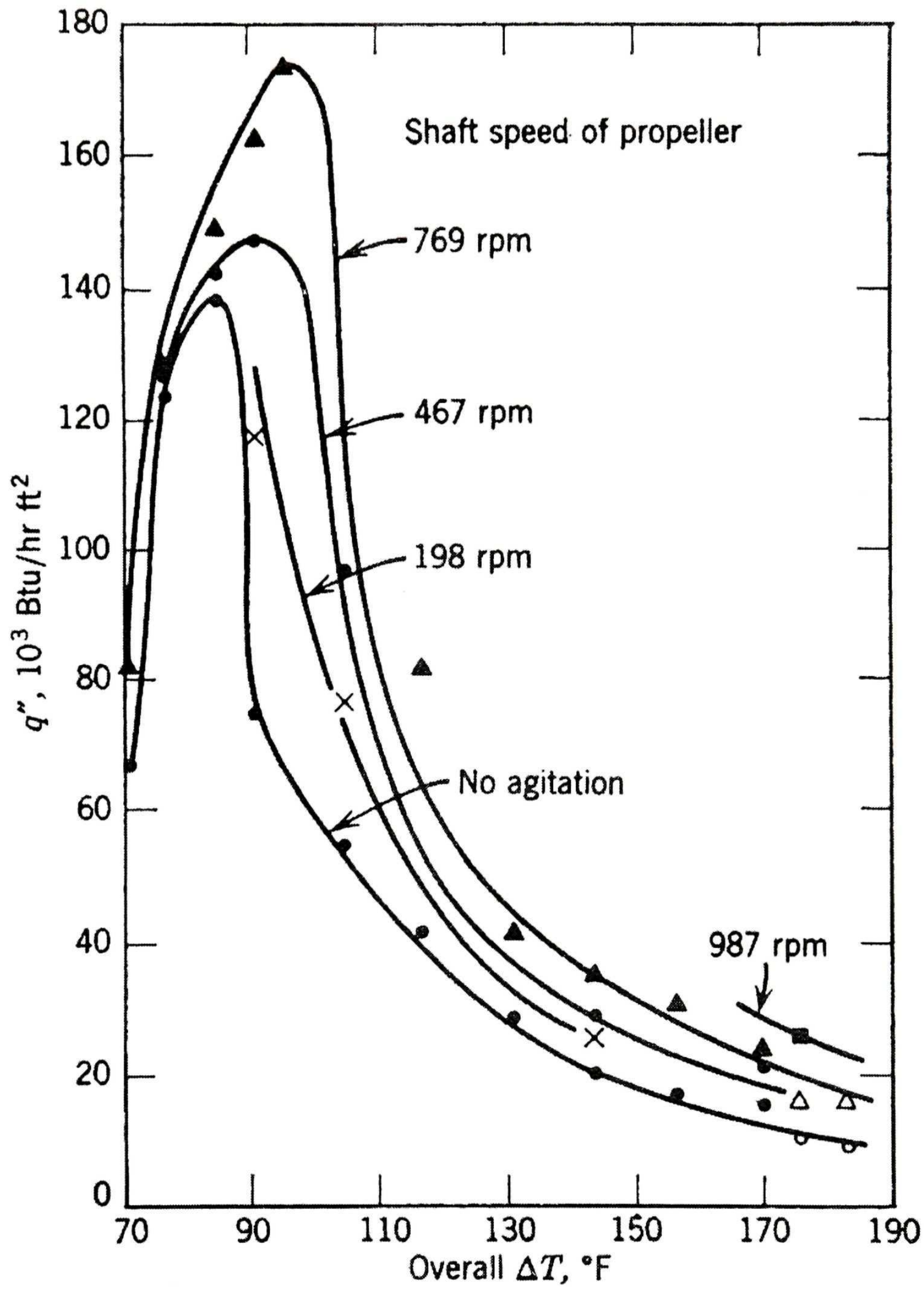


Figure 3.2 Effect of agitation in methanol boiling at 1 atm (63)

Among the parameters, the factor of agitation should be mentioned here, which is one of the key concepts for the design of the novel heat pipe. In 1956, Pramuk and Westwater did some experiments with boiling methanol at 1 atm (62, 63). They found that the CHF of boiling heat transfer could be increased considerably by introducing agitation. Their results are shown in Figure 3.2.

3.1.2.3 Practical Design Considerations

1) The heat flux capability of the designed heat pipe

The heat pipe will be used for the thermal management of a permanent mold during the casting process. Control of the solidification of the casting and the mold temperature should be largely achieved by the new cooling system in order to replace current mold cooling methods, such as water cooling. To ensure the quality of the cast component, it will be necessary to reduce hot and cold spots and to accelerate the solidification process. In addition, the mean temperature variation around the mold cavity must be controlled within a narrow temperature range. This means that the heat pipe must extract and dissipate the heat from the casting during solidification in the selected locations of the mold within the cycle time. Based on the experience with water cooling passages by the industries producing permanent mold castings, and Davey's experimental and theoretical results on the cooling channels of the pressure die casting process (64), a high heat flux heat pipe will be required to handle the heat load generated during the permanent mold casting process. If the applied heat flux is beyond the capacity of the heat pipe, however, the effective thermal conductivity of the heat pipe will be significantly reduced. Therefore, it is important to assure that the heat pipe is of such a design as to transfer the required heat load.

2) Working substance and vessel materials of the heat pipe

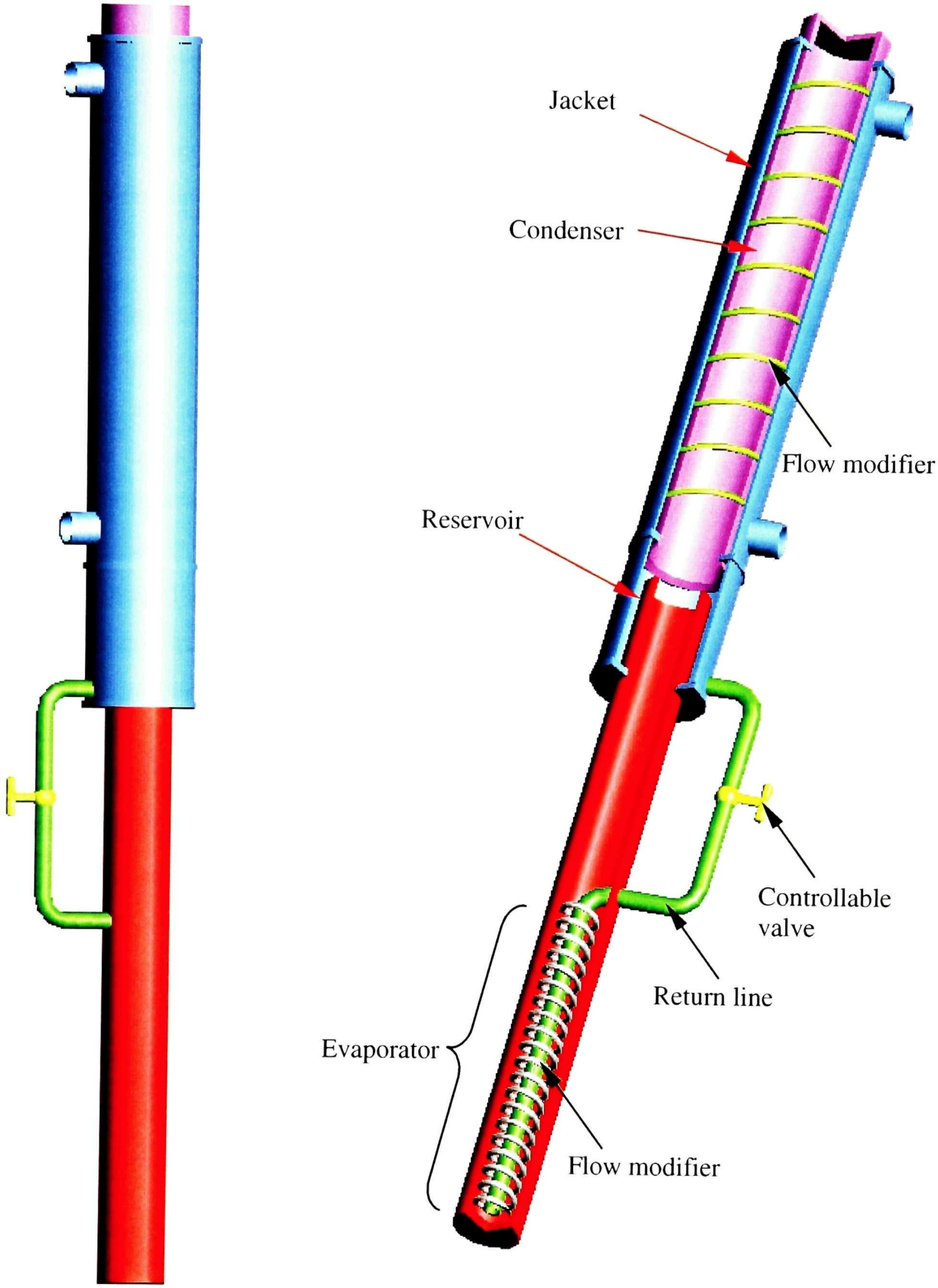
The selection of working fluid depends mainly on the heat flux and the operating temperature range of the heat pipe. The required characteristics of working fluids were well investigated by Dunn and Reay (3). As discussed in Chapter 2, heat pipe working fluids range from helium and nitrogen for cryogenic temperatures, to liquid metals like sodium and potassium for high temperature applications. The most common working substance is water for medium temperature heat pipes. Water is thermodynamically superior to other fluids under most conditions and becomes the fluid of choice when appropriate. The useful range for water is generally 50-200 °C, and it is thus suitable for mold cooling in aluminum casting. Water boils at 100 °C under atmospheric pressure. Inside a heat pipe, the working fluid (water) is not necessarily at atmospheric pressure. The internal pressure of the heat pipe is the saturation pressure of the fluid at the corresponding fluid temperature. As such, the fluid in a heat pipe may boil at any temperature above its freezing point. A liquid will appear to boil (i.e. create distinct vapor bubbles) if the heat loading inside the liquid is sufficiently large that not all the heat can flow to free surfaces where evaporation can take place. Under such a condition, vapor bubbles of a pressure that is comparable to the pressure of the gaseous environment surrounding the liquid will be formed. Thus, the formation of vapor bubbles occurs when the temperature of the liquid is such that its inherent vapor pressure is at least equal to the environment pressure, and the heat load is sufficiently large. By controlling the pressure of the environment, one can then control the boiling temperature of the liquid. Because of the high latent heat for the liquid/vapor phase change, water can transport large amounts of heat from the evaporator to the condenser.

The selection of the material for the heat pipe vessel is based on compatibility with the working fluid, as well as the criteria discussed in the literature (1, 2, 3) and McGill past experience with heat pipes. Incompatibility will result in corrosion, reaction between the materials involved, and generation of non-condensable gases. Stainless steel is an ideal and suitable material for a water based heat pipe vessel.

3.1.3 Preliminary Design of the Novel Heat Pipe

3.1.3.1 Configuration of the Heat Pipe

Based on the considerations and criteria of the heat pipe for permanent mold cooling discussed previously, a novel, water-based heat pipe has been developed which can



(a) Appearance of the heat pipe (b) Section view of the heat pipe

Figure 3.3 Basic configuration of the designed heat pipe provide sufficient heat extraction to cool permanent mold castings of aluminum alloys. The configuration of the novel heat pipe, known as the McGill Heat Pipe, is shown in Figure 3.3. This design was developed for preliminary investigation of controlled cooling of permanent mold castings (65). Among other things, the study assessed the thermal capability and operating performance of the heat pipe under actual casting conditions.

In the design of the McGill heat pipe (a gravity assisted heat pipe), the top section is the condenser which is a heat exchanger (heat sink). Various configurations of the condenser are possible depending on the actual application of the heat pipe. The condenser can have a single cooling circuit, multiple cooling circuits, a built-in chill — heat buffer and so on. In the design of the heat pipe for cooling permanent mold castings, the condenser is built to act as a chill. Thus its wall is relatively thick and its length is about 5 times that of the evaporator. The condenser, in effect, operates as an energy buffer. Thus, heat extraction from the evaporator is periodic while the dissipation of heat from the condenser (i.e. external chill of castings) is continuous throughout the casting process. The features of this condenser will be discussed in detail in a subsequent chapter. In the preliminary investigation, the focus was on the evaporator and the controllability of the heat pipe in order to resolve the problems of high heat flux heat pipe systems as outlined in the literature. Consequently, the condenser was designed simply as a single cooling circuit. The cooling jacket was built up around the condenser. The outer surface of the condenser was fitted with a spring to enhance the heat transfer by causing the cooling agent — air to swirl. This configuration enhances the turbulence and increases the heat transfer between the coolant and the condenser.

Below the condenser, is a reservoir which is used to collect the condensate from the condenser and excess liquid carried by the vapor from the evaporator. The reservoir is generated by the gap formed between the inner wall of Pipe A and outer wall of Pipe B, the extension of the connection section of the evaporator and the condenser, as shown in Figure 3.4.

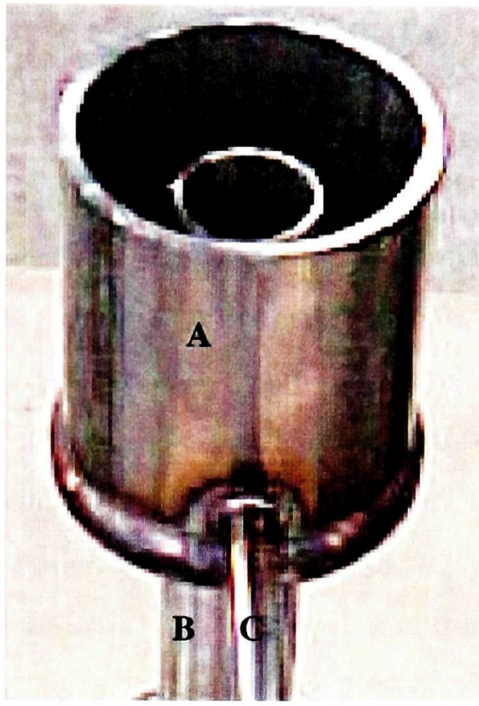


Figure 3.4 Configuration of the reservoir

A return line is positioned at the bottom of the liquid reservoir and extends to the end of the evaporator. This condensate returns to the bottom of the evaporator through the return line C. Since the collected liquid is brought to the bottom of the evaporator in a separate stream, the return line overcomes the problem of countercurrent flows of two phases (i.e. vapor and liquid) existing in the classical heat pipe, and instead, the McGill heat pipe operates in the co-current flow pattern of liquid and vapor. Thus the shear forces between the reverse flow streams are eliminated. Enough working substance is retained at the bottom of the evaporator by continuous flow through the return line so that the heat pipe never runs dry. Moreover, because of the presence of a liquid reservoir, the heat pipe can be charged with more liquid with the excess collected in the reservoir.

A valve is incorporated in the return line to control the return flow, and also to allow the heat pipe to be turned on or off anytime. When the heat pipe is turned on (i.e. the valve is opened), heat extraction is initiated. Conversely heat extraction can be stopped by turning off the heat pipe (i.e. closing the valve). This function is very important for a permanent mold as the mold is only required to be cooled during the actual solidification process. The mold does not need to be cooled, for example, when it is preheated.

In order to throw the working substance onto the wall of the evaporator to produce better heat transfer, a flow modifier is placed in the evaporator. The flow modifier can be a spring, a helical twisted tape, or a helical blade-shaped swirling insert. In the preliminary study, a spring and a swirl insert were applied as flow modifiers in the evaporator of the novel heat pipe. The swirl insert is shown in Figure 3.5. The flow modifier can push the flow from the evaporator to contact the inside wall by centrifugal forces and create a vortex motion in the flow. In this way, the vapor bubbles and films can be taken off the walls of the evaporator, and a uniform layer of working fluid is formed on the walls of the evaporator. The introduction of a flow modifier leads to a short response time and high heat-transport capability without film boiling. Heat transfer can be enhanced by an order of magnitude or more with this flow modification. This innovation has made it possible to produce a water-based heat pipe for high heat flux applications that were outside the realm of heat pipes.

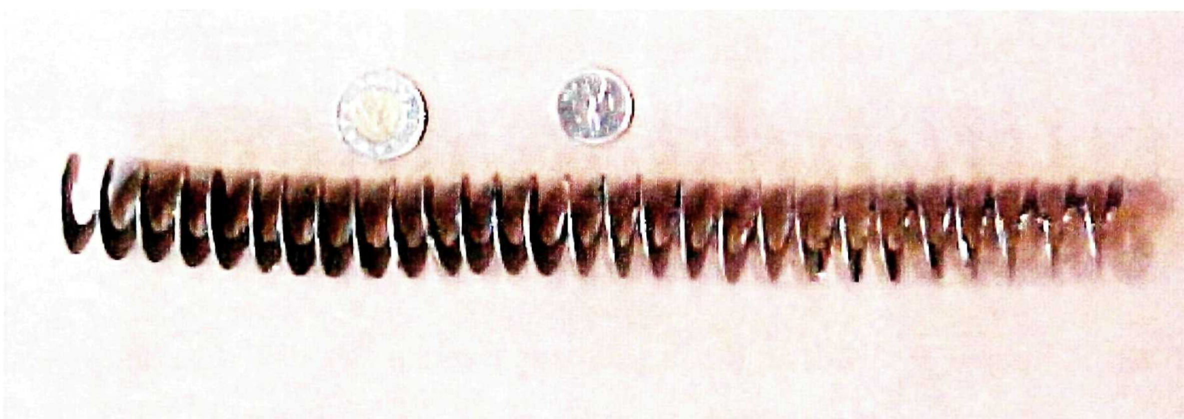


Figure 3.5 Shape of the swirl insert as a flow modifier inside the heat pipe

This heat pipe is capable of extracting very large heat fluxes which cannot be handled by a conventional heat pipe. To date they could only be handled with high velocity water flow passages. The McGill heat pipe has been designed to overcome the formation of a stable water vapor film on the evaporator walls. It operates in the nucleate boiling regime. Previous studies that attempted to use heat pipes in permanent molds were not successful for several reasons, the most important being that the heat pipes operated in the film boiling regime. Nucleate boiling can enhance heat transfer by an order of magnitude or more over film boiling. The presence of nucleate boiling is the main reason for the success of the McGill Heat Pipe.

The main features of the McGill Heat Pipe are summarized as follows:

- Can handle high heat flux loading, up to 1 MW/m^2.
- ON/OFF capability or controllability of heat extraction by introducing a valve on the return line.
- Operates in the nucleate boiling regime
- Both vapor and working liquid flow co-currently instead of countercurrent to each other
- Excess working fluid helps supply the evaporator and prevents the evaporator from drying
- For the heat buffer style condenser in the ON mode, the external chill absorbs virtually all of the heat generated by the casting during solidification; cooling air dissipates the heat stored in the chill during the OFF mode.

3.1.3.2 Mechanism of Boiling Heat Transfer Enhancement in the Pipe by Flow Modifiers

One of the highlights of the novel heat pipe design is the incorporation of the flow modifier, which greatly improves the heat transfer performance of the heat pipe. Heat transfer enhancement by generating swirl flow in high heat flux components has been explored, reported and investigated for a quite long time (66, 67, 68, 69, 70, 71). However, the introduction of swirling motion generated by the flow modifier in the heat pipe is a new idea.

The enhancement of heat transfer by the flow modifier in the heat pipe may be ascribed to the following effects:

- ✓ Centrifugal force promotes improved contact between the working liquid and the heat pipe walls, so that the good contact
  - removes vapor bubbles and films from the walls of the evaporator
  - promotes coverage of the heated surface of the evaporator with a uniform layer of working liquid
- ✓ A longer longitudinal flow path can be achieved because the fluid must follow the swirl path
- ✓ Higher flow velocities are induced because of the flow modifier, thus improving the heat transfer capability
- ✓ Higher heat transfer coefficients are obtained because of the nucleate boiling regime and the reduction of the hydraulic diameter
- ✓ The film boiling regime is suppressed by the swirl flow effect in the evaporator of the heat pipe when the flow modifier is present
- ✓ Swirling and mixing generated by the flow modifier also improves the convective coefficient
- ✓ The wetted perimeter is increased by the reduction of the flow cross-sectional area
- ✓ The critical heat flux is enhanced by the flow modifier

Heat transfer enhanced by twisted- tape inserts in isothermal tubes was studied by Manglik and Bergles (71, 72). The heat transfer behaviors in the presence of the twisted-tape insets are shown in Figure 3.6. Four flow regimes are described in terms of flow characteristics and heat transfer enhancement mechanisms. Higher values of Nusselt mean that the heat transfer is enhanced by the swirl flow motion.

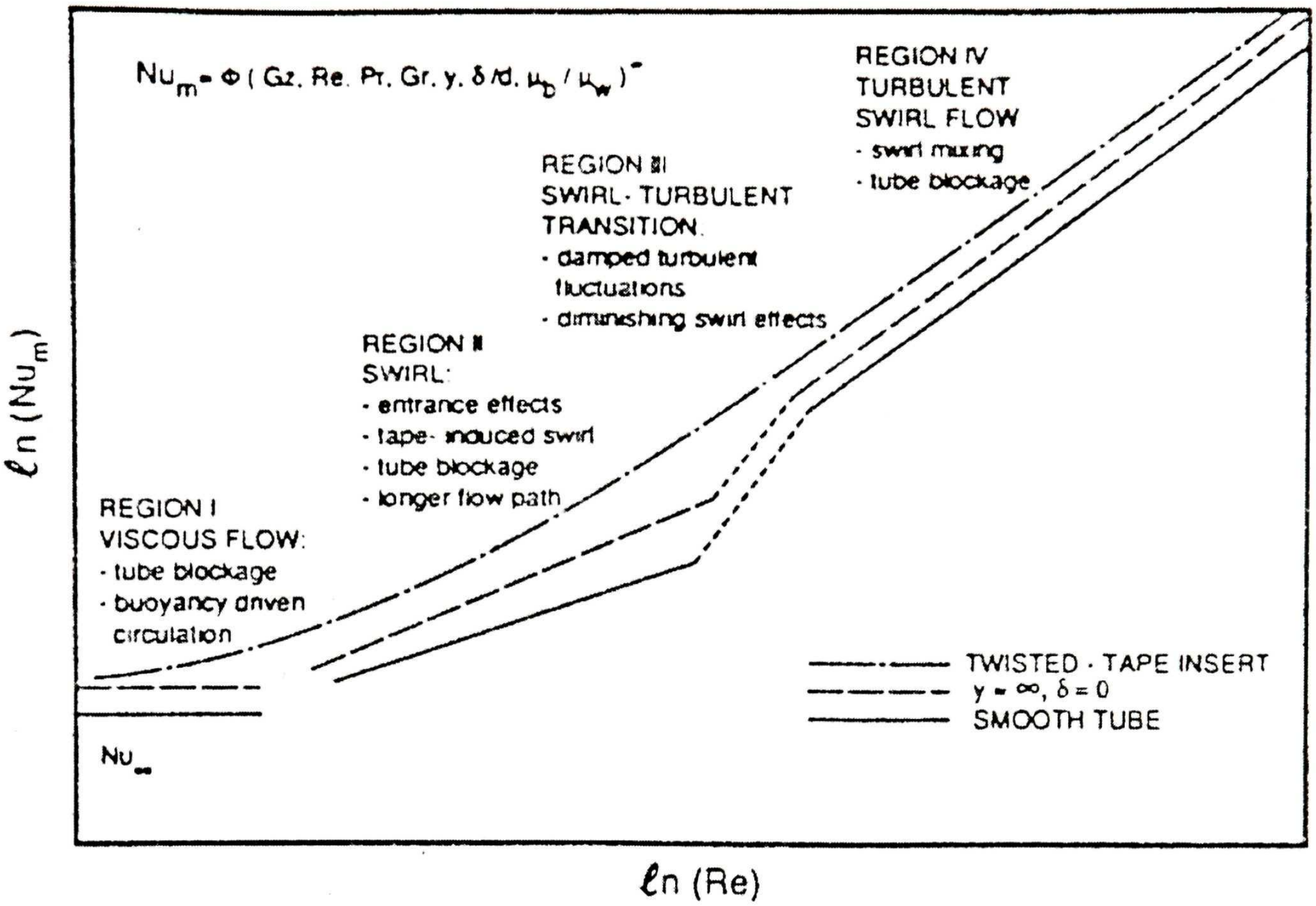


Figure 3.6 Influences of thermal behaviors by twisted tape inserts in pipe flows (71)

A swirl parameter S_w that describes the onset of swirl flow and the intensity of the flow modifier induced, secondary motion, can be defined as (71)

$$S_w = Re_{sw}/\sqrt{y} = \left(Re/\sqrt{y}\right)\left(\frac{\pi}{\pi - 4\delta/d}\right)\left(1+(\pi/2y)^2\right)^{1/2} \quad (3\text{-}3)$$

where:

Re_{sw} — Reynolds number based on swirl velocity

y — twist ratio, $Y=H/d$,

H — 180 deg twist pitch, m

δ — thickness of flow modifier, m

d — pipe inner diameter, m

The swirl parameter Sw defines the interaction between viscous, convective, inertia, and centrifugal forces during the swirl motion.

3.2 Experimental Investigation of the Novel Heat Pipe

3.2.1 Experimental Setup and Procedure

As described in the previous section, a high heat flux, water based heat pipe was conceived and developed in order to replace the conventional cooling methods for the permanent mold casting process. Before using the newly developed heat pipe in the permanent mold, preliminary experimental investigations were performed to make sure that the heat pipe satisfied the required performance for mold cooling. In order to create a similar boundary condition as encountered in permanent mold casting, and to achieve both uniform and large heat fluxes from the heat source, it was decided to use a bath of molten zinc to simulate the mold. The experimental set-up is shown in Figure 3.7. The tests were conducted by immersing varying lengths of the leading end of the evaporator into the molten zinc. For each immersion tested, the temperatures of the heat pipe, zinc melt and outlet cooling air from the cooling jacket for the condenser were recorded as a function of time by a data acquisition system. Also recorded was the flow rate of cooling air. The inlet temperature of the cooling air was relatively constant and only noted each day. All the immersion trials were conducted in a melt of about 25 kg of commercial purity zinc.

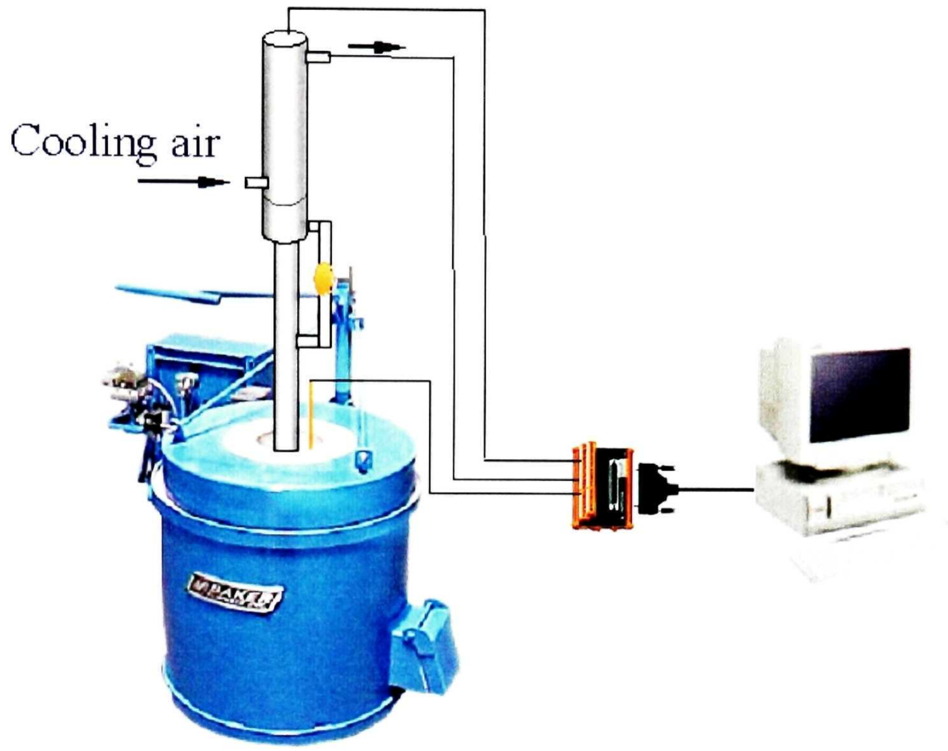


Figure 3.7 Experimental set-up for heat transfer capacity test of heat pipes in molten zinc

3.2.2 Experimental Results and Discussion

In the present section, some results of the tests, which were conducted by immersing varying lengths of the leading end of the evaporator into the molten zinc, will be presented and discussed.

3.2.2.1 Wickless Water Based Heat Pipe

As the conventional theories suggested, the McGill heat pipe of the original design was fitted with a wick structure within. The purposes of a heat pipe wick structure are to form flow passages for liquid returning from the condenser, to develop capillary pumping pressure, and to coat the evaporator walls with a layer of liquid. However, the application of a wick is, in some cases, undesirable. Such thinking is different from the prevalent thoughts of heat pipe experts. The following experimental results show the effect of a wick for the specific design of the McGill heat pipe.

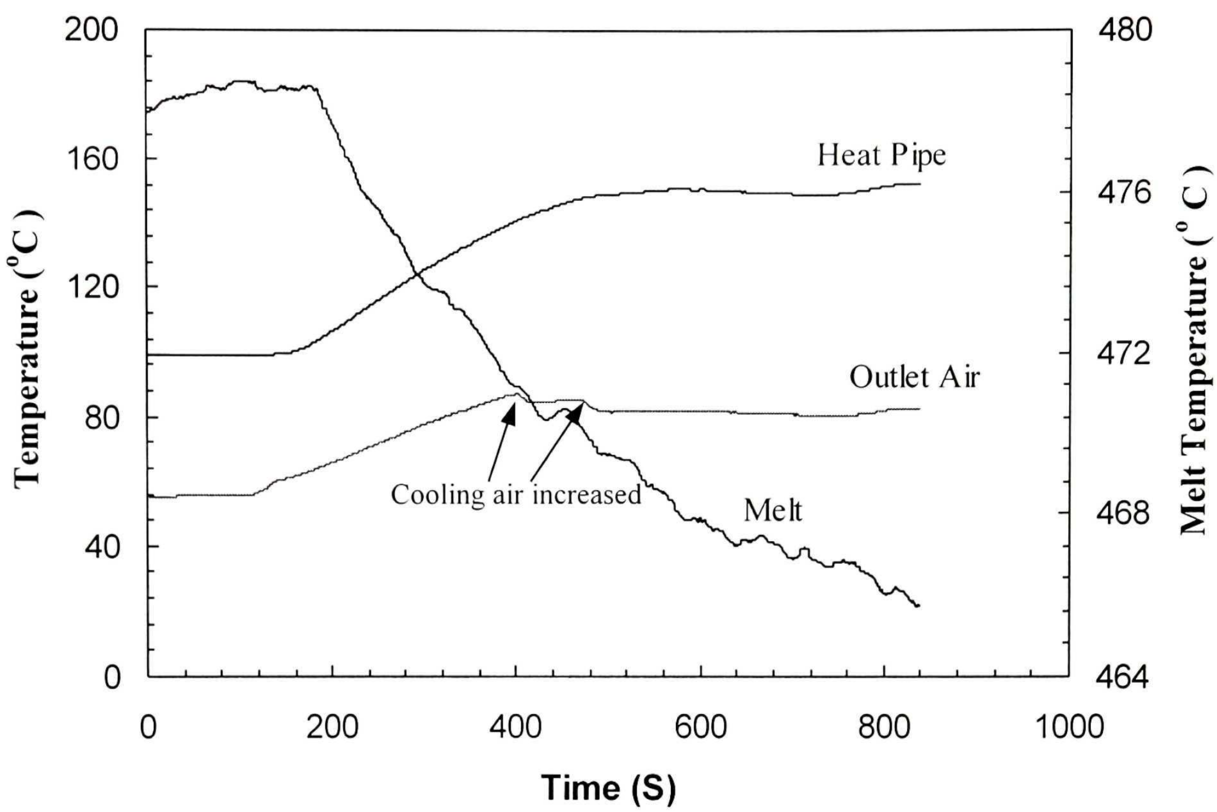


Figure 3.8 Results of the heat pipe with a spring flow modifier and wick from immersion into molten zinc: 2 cm immersed; flow rate of cooling air ≅ 22 Nl/S

A number of immersion tests in molten zinc were carried out to investigate the performance of the newly developed heat pipe. Figure 3.8 shows one of the typical experimental results. The heat pipe was immersed 2 cm into the zinc when the zinc was initially at about 480 °C. After the immersion of the heat pipe, there was a steady decline in the melt temperature because of the cooling by the heat pipe in the melt. The temperature of the heat pipe increased continuously. The flow rate of cooling air was adjusted to bring the heat pipe to steady state, at which point the heat extraction in the evaporator was equal to the heat dissipation in the condenser.

By immersing the evaporator of the heat pipe in molten zinc, one can impose a large heat flux on the evaporator. Under these circumstances, it is possible to cause the working substance (water) to undergo film boiling, a phenomenon that is undesirable in a heat pipe. When the bottom of the evaporator just touched the surface of the molten zinc, it is believed that film boiling did not happen in the heat pipe.

Table 3.1 Immersion tests in molten zinc of the heat pipe containing a wick and spring

Tests	Cooling air for the condenser			Heat Pipe		
	Flow rate (L/S)	Initial Temp. (°C)	Temp. at steady state (°C)	Immersed area of the evaporator (m^2)	Temp. at steady state (°C)	Heat extraction rate (W)
Case 1	22	20	55.2	1.385×10^{-3}	98.9	1009.3
Case 2	22	20	82.3	4.024×10^{-3}	152.6	1712.7

The calculated results of this test are shown in Table 3.1. The water based heat pipe contained three wraps of wick and a spring flow modifier inside. Comparing the experimental results in the two cases, one can see that the heat pipe extracted much more heat in case (2) (i.e. 2 cm immersion as shown in Figure 3.8) than in case (1) (i.e. only the bottom touches the surface of the molten zinc.), but the rate of heat extraction did not increase in proportion to the area immersed. The area immersed in case (2) is three times as that in case (1). This means that the heat flow rate at the bottom area of the pipe is much higher than at the sidewall under the same conditions. The reason underlying this phenomenon is that the side area was covered by a wick while the bottom had nothing. Thus there was a layer of vapor film trapped between the sidewall and wick under the centrifugal force from the vortex motion of the flow by the spring (Shown in Figure 3.9). This film is harder to remove than that on the bottom, with the result that the thermal resistance on the sidewall is much larger.

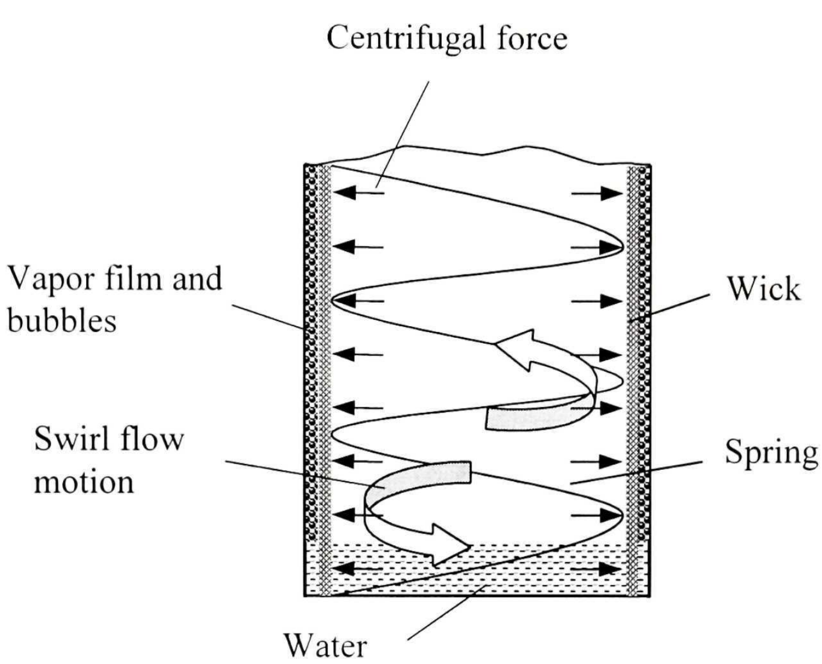


Figure 3.9 Heated Evaporator of the heat pipe containing a wick and spring — demonstrating the defect of the wick

In order to further demonstrate the issue of film boiling that may exist in the heat pipe, a series of tests were conducted whereby the heat pipe was frozen in the zinc after the power to the furnace was switched off. This proved to be a very effective way to determine if film boiling is the main reason for causing the thermal resistance on the sidewall of the evaporator.

The results are shown in Figure 3.10. It is noticed that the temperatures of both the heat pipe and cooling air of the outlet increased suddenly when the zinc cooled down to about 230 °C. This phenomenon indicates that film boiling predominated before this point. As the temperature of the zinc decreased, the vapor film trapped between the sidewall and wick became unstable and finally collapsed, at which time the heat flux into the heat pipe also increased sharply, as well as the cooling rate of the frozen zinc.

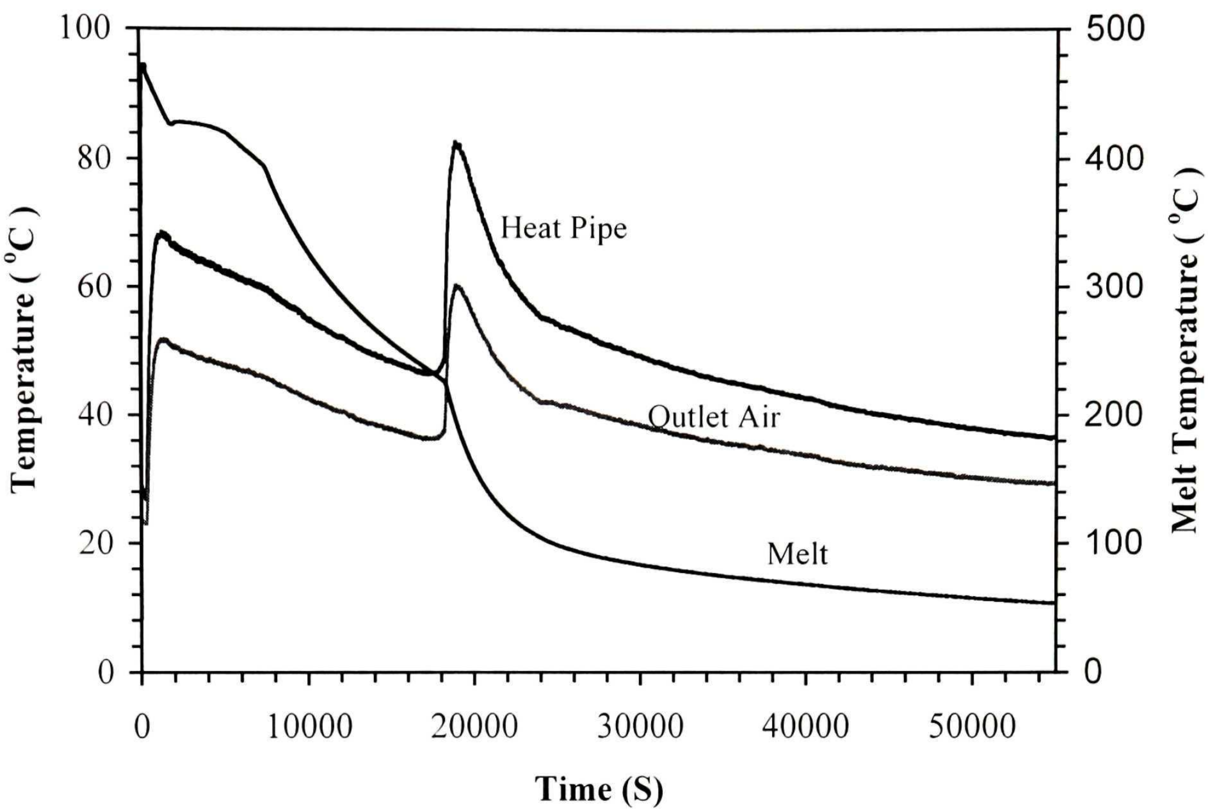


Figure 3.10 Results of the heat pipe freezing in the zinc: 3 cm immersed

3.2.2.2 Immersion Trials for Simulation of Permanent Mold Casting

As a result of these experiments wherein it became clear that the wick encouraged film boiling, the wick inside the heat pipe was removed, and a swirl insert was inserted in order to increase the centrifugal force of the flow stream motion. As shown in Figure 3.11, the immersion tests in zinc were done in several cycles by putting in and taking out the heat pipe to simulate the situation in permanent mold casting. From the curve of temperature-time, it is seen that the temperature of the heat pipe quickly increases once the pipe is immersed in the molten zinc. This means that there is no resistance inside the heat pipe. This heat pipe works much better than the former one since it overcomes film boiling heat transfer by removal of the wick and use of a swirler with high twist ratio and more total volume. The response time of the heat pipe is also much shorter, and from the temperature curve of the return line, we can see that the condensate flowed continuously through the return line to the bottom of the evaporator. There are three significant advantages of the design shown from these experiments:

1) The heat pipe unit is controllable
2) The bottom of the evaporator is flooded with excess working substance - water
3) The shear force from the reverse two-phase flow streams is eliminated

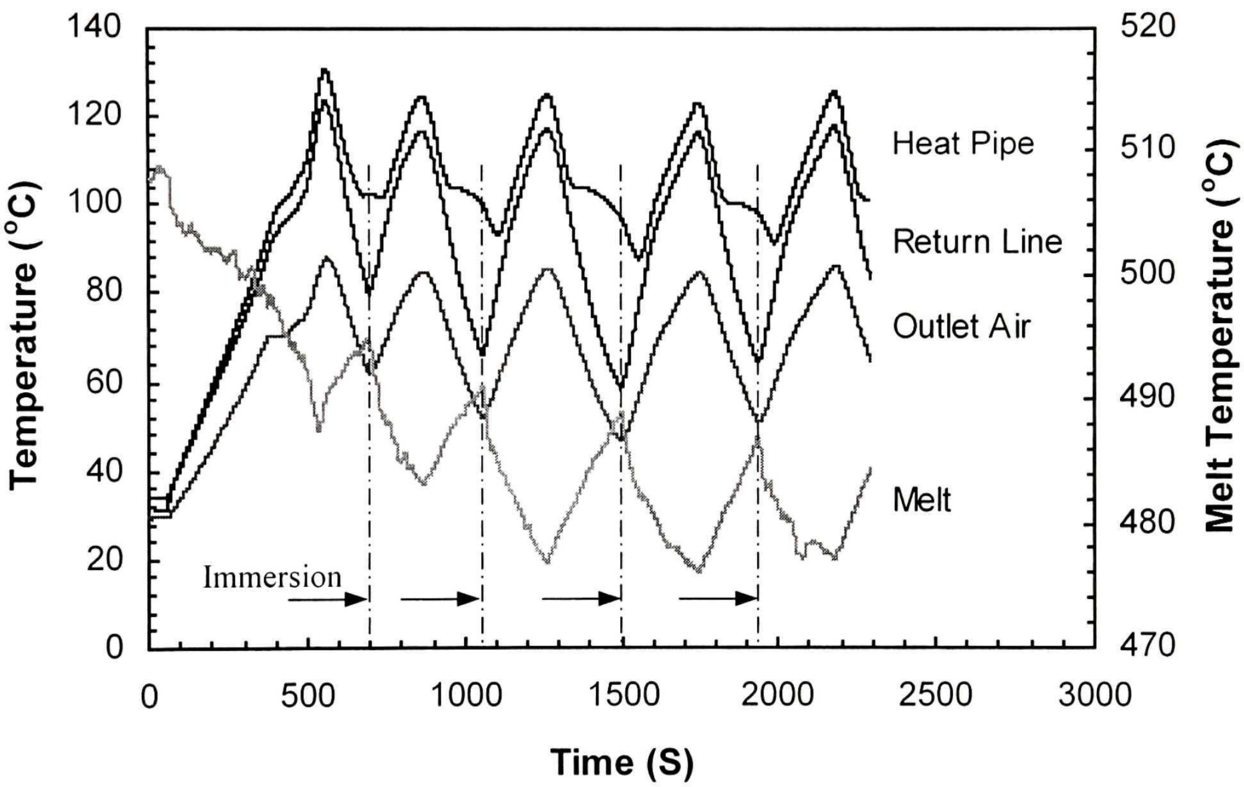


Figure 3.11 Results of immersion tests by putting in and taking out the wickless heat pipe with a swirl insert: 2 cm immersed; Flow rate of cooling air ≅ 22 Nl/S

For one cycle of the immersion tests, a photograph of the heat pipe after removal from the melt is shown in Figure 3.12. A layer of zinc had frozen on the pipe because of the very large heat extraction by the heat pipe. Apparent is the smooth contour of the frozen zinc layer, which indicates that heat extraction is uniform.

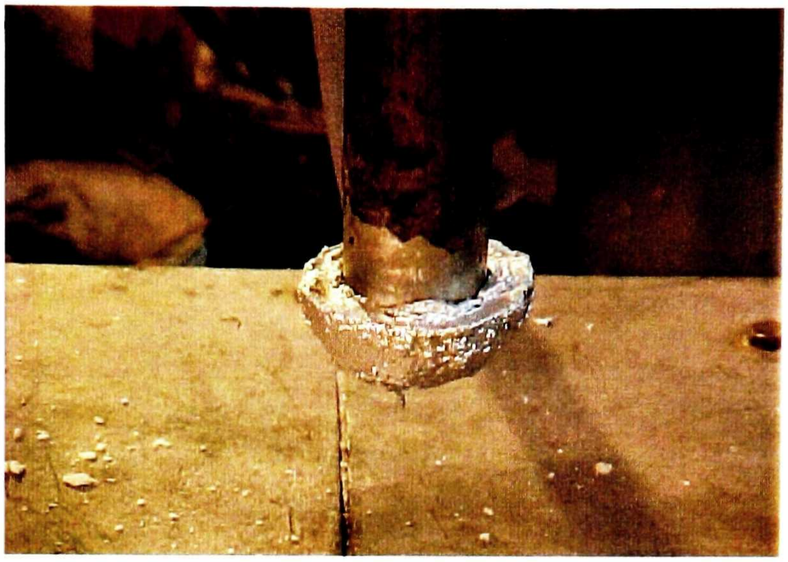


Figure 3.12 The novel heat pipe with frozen zinc accretion

In order to show the function of the return line and further simulate the situation of permanent mold casting of aluminum, cyclic immersion tests have been done by switching the valve of the return line instead of taking the heat pipe out of the zinc. The results shown in Figure 3.13 also indicate this type of heat pipe is suitable for controlled cooling of permanent molds in aluminum casting. The results show that heat extraction by the heat pipe increases very quickly with time when the return line is opened. It is to be noted that the temperature of the outlet cooling air is directly proportional to the rate of heat extraction. Obviously, the swirler had a profound effect on the rate of heat extraction without the wick attached. Thus the working substance (water) is able to absorb the high heat flux from the molten zinc. The new heat pipe with a flow modifier operates in the nucleate boiling regime, whereas the conventional pipe operates in the film boiling regime.

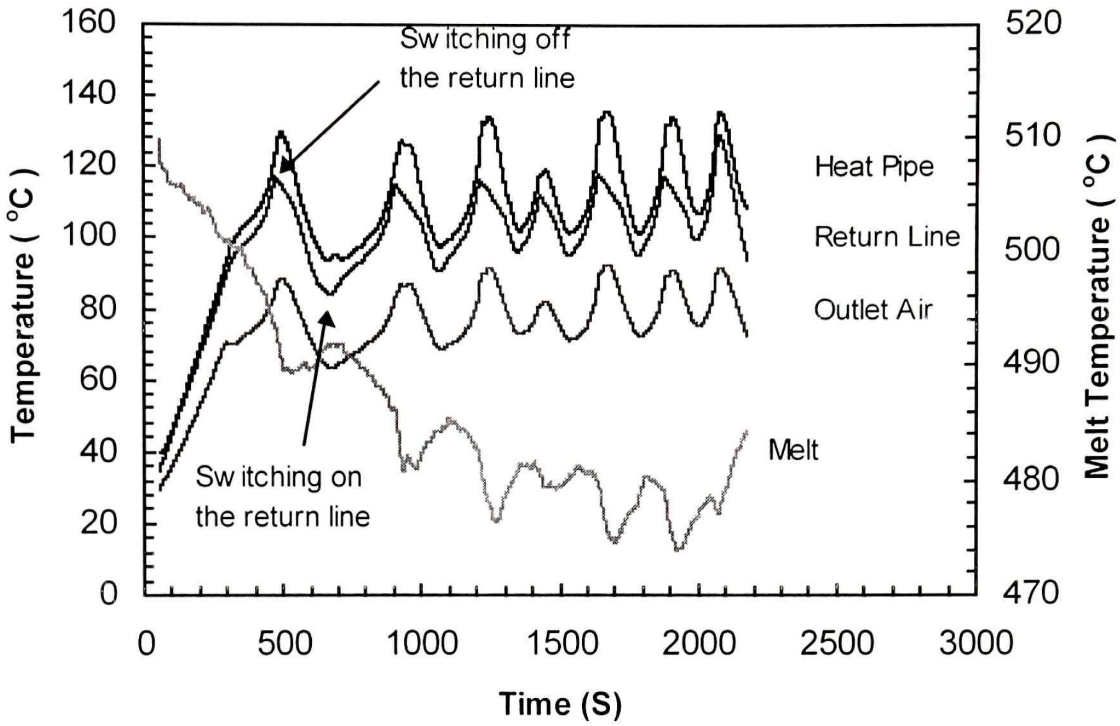


Figure 3.13 Results of immersion tests by closing the return line for the wickless heat pipe with a swirl insert: 4 cm immersed; Flow rate of cooling air ≅ 22 Nl/S

The experimental results also demonstrate that the functions of the return line and reservoir which are very important for permanent mold casting. The mold is only required to be cooled during the casting process. It should not be cooled when it is being preheated. The heat pipe can be controlled by switching on/off the return line as required during permanent mold operation.

For the case shown in Figure 3.13, the transient heat flux of the heat pipe has been calculated. The curve of heat flux vs. time is shown in Figure 3.14. The maximum heat flux is about 600 kW/m^2. If the flow rate of cooling air could be increased, it should be possible to achieve heat fluxes up to 1000 kW/m^2 through the heat pipe. This heat transfer capacity is enough for controlled cooling of permanent mold casting of aluminum alloys.

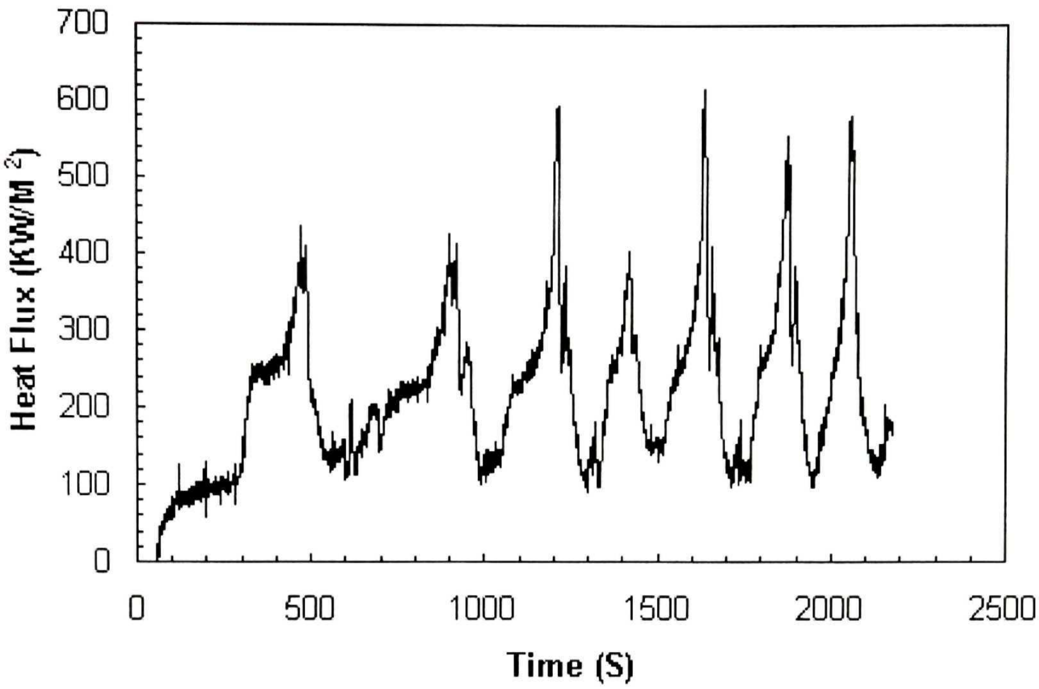


Figure 3.14 Transient heat flux of immersion test of the novel wickless heat pipe in the case of Figure 3.13

3.3 Modification of the Design of the McGill Heat Pipe for Mold Cooling

3.3.1 Reduction of the Effect of Surface Tension on Water Flow though the Return Line

The working substance in the McGill heat pipe for permanent mold cooling is water. A return line was built for the working liquid returning to the evaporator as shown in Figure 3.3. Because of the effect of surface tension on the flow behavior of water, the diameter of the return line cannot be too small, otherwise water cannot flow through the return line.

Surface tension is the property of a liquid that makes its surface area per unit volume as small as possible. It tends to make bubbles and drops spherical, and is strong enough to support light objects. Polar liquids have strong intermolecular interactions and thus high surface tension (water = 72.88 $N\times10^{-3}/m$ @ 20 °C) at room temperature. Water has the highest surface tension except for mercury among common liquids at room temperature. In other words, water has sticky and elastic properties, and tends to clump together in drops rather than spread out in a thin film. Thus it flows less readily than do non-polar liquids which have much lower values of surface tension.

Surface tension is a function of temperature. A modified Othmer relation is expressed as follows (73):

$$\sigma = A(1 - T / T_{Cont})^{n_1} \tag{3-4}$$

where

σ — surface tension, $N\times10^{-3}/m$

A, T_{Cont} and n_1 – regression coefficients for chemical compound

T — temperature, K

The surface tension of water is plotted as a function of temperature in Figure 3.15. With the increase of temperature, the surface tension of water decreases. As the temperature of water is changed from 0 °C to 100 °C, the decrease of surface tension is about 25%. In Figures 3.11 and 3.13, we see different slopes of the curves for the heat pipe temperature. The increase of the temperatures of the heat pipe and the return line accelerated around 100 °C. At this temperature, the surface tension of water became smaller and is no longer dominant for the water flow through the return line to the leading end of the evaporator. Thus the heat flow through the heat pipe increased because there is enough water to cover the heated surface of the evaporator.

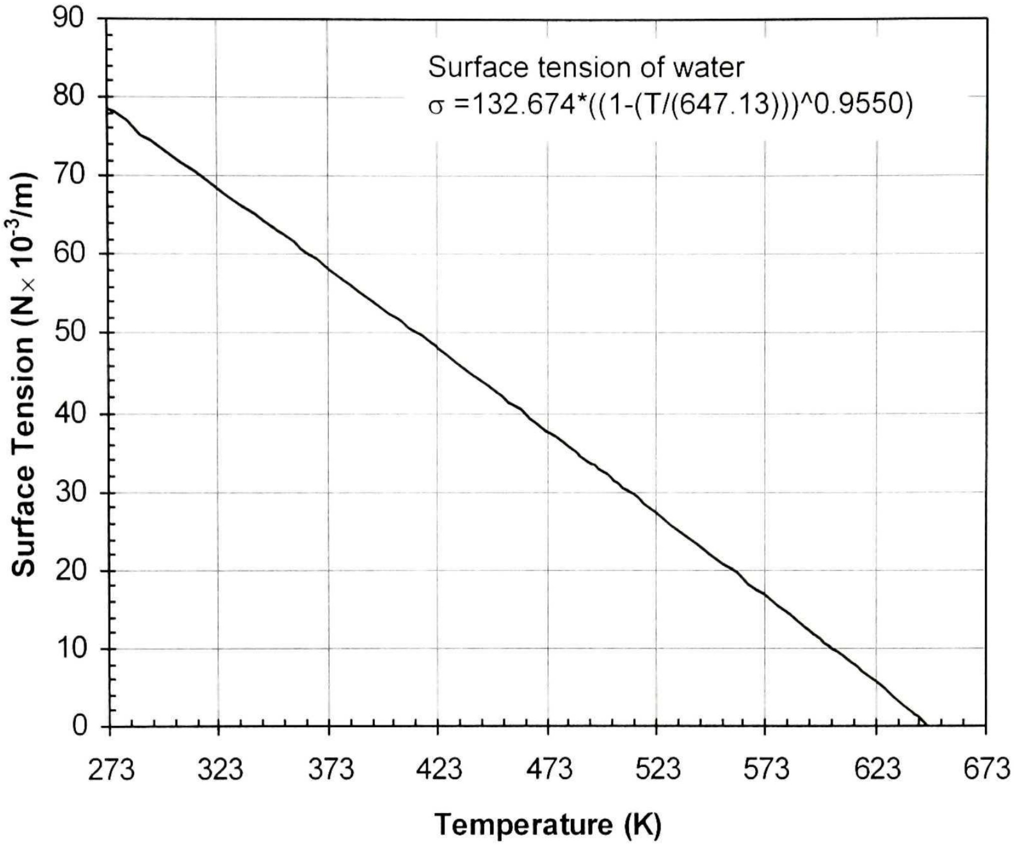


Figure 3.15 Surface tension of water as a function of temperature (73)

The effect of surface tension can be reduced by

1) Increasing the diameter of the return line: Based on the experiments on heat pipes at McGill, the diameter should be no less than 1 cm if the space of the heat pipe chamber permits
2) Adding surfactants, soap for example, that increase the adhesion force between two different materials. Molecules of the surfactant usually have a polar and a non-polar portion. When added, the wetting agent increases the wetting action of water with the non-polar material.

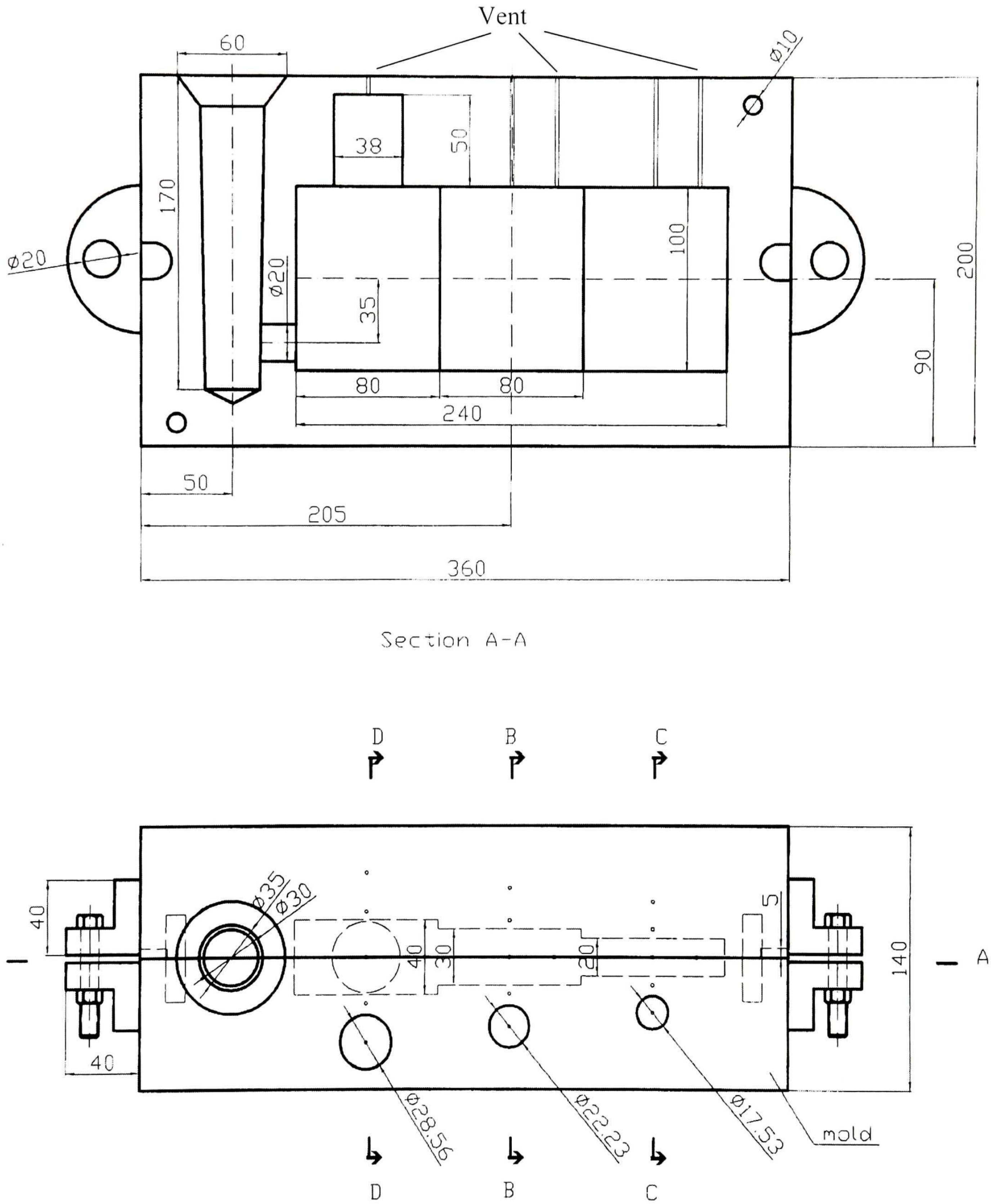
3.3.2 Necessity of a Vent Line for the Return Line

From the curves of the temperatures of the heat pipe and the return line shown in Figure 3.13, the response time of the heat pipe is somewhat delayed. When the return line was switched off, all water was collected in the reservoir. The return line together with evaporator was heated by the molten zinc since the heat pipe was kept in the zinc during the cycles of the tests. Once the return line is switched on, water will immediately boil when it tries to flow through the return line. As a result, counter current flow between liquid and vapor is generated in the return line, so that it can take a longer time for the water to reach the end of the heat pipe because the flow passage is blocked by the generated vapor. The same will happen in the cooling of a permanent mold. This problem was resolved by installing a vent line on the return line so that the first batch of vapor could escape, thus permitting the water to flow to the evaporator. The configuration of the vent line will be discussed further in the subsequent chapter.

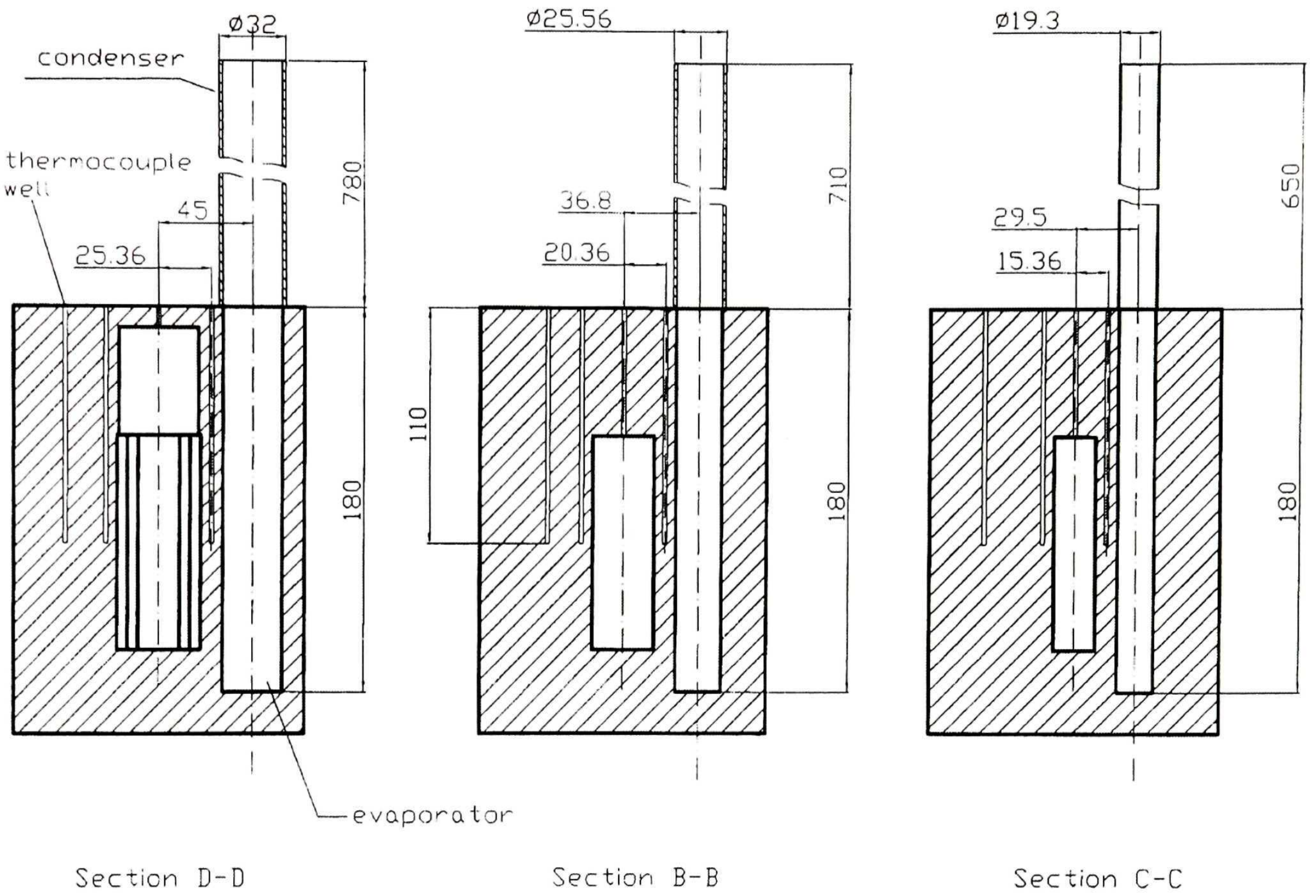
Chapter 4 Development of controlled cooling of permanent mold castings of aluminum alloys

4.1 Introduction

It is well recognized by the casting industry that it is essential to control the cooling of permanent mold castings to improve the quality of the castings. The problems associated with the current technologies for mold cooling have been described in Chapter 2. In order to demonstrate the thermal management of permanent mold castings of aluminum alloys by using heat pipes, and to replace the currently used cooling technologies in casting industries, experimental investigations of permanent mold castings were carried out in the laboratory at McGill. A simple experimental mold was constructed of the same materials as used in commercial molds (i.e. H13 tool steel). The mold was able to provide a variety of cooling rates during solidification as it was constructed in a step mold design. Controlled mold cooling of a casting requires that the cooling be confined to specific locations of the casting to ensure the desired microstructure and mechanical properties at those locations. The laboratory study concentrated on the influence of spot cooling on both casting microstructure as well as the temperature distribution in the parts of the mold which surround the heat pipe. Before the experimental study, thermal modeling was performed to predict the influence of heat pipe cooling on the temperature distribution in the mold and solidification behavior of the casting.


Vent
60
Ø10
38
50
170
Ø20
Ø20
100
200
35
90
80
80
240
50
205
360
Section A-A
D
B
C
Ø35
Ø30
40
40
30
20
5
140
A
40
Ø28.56
Ø22.23
Ø17.53
mold
D
B
C

(a)



(b)

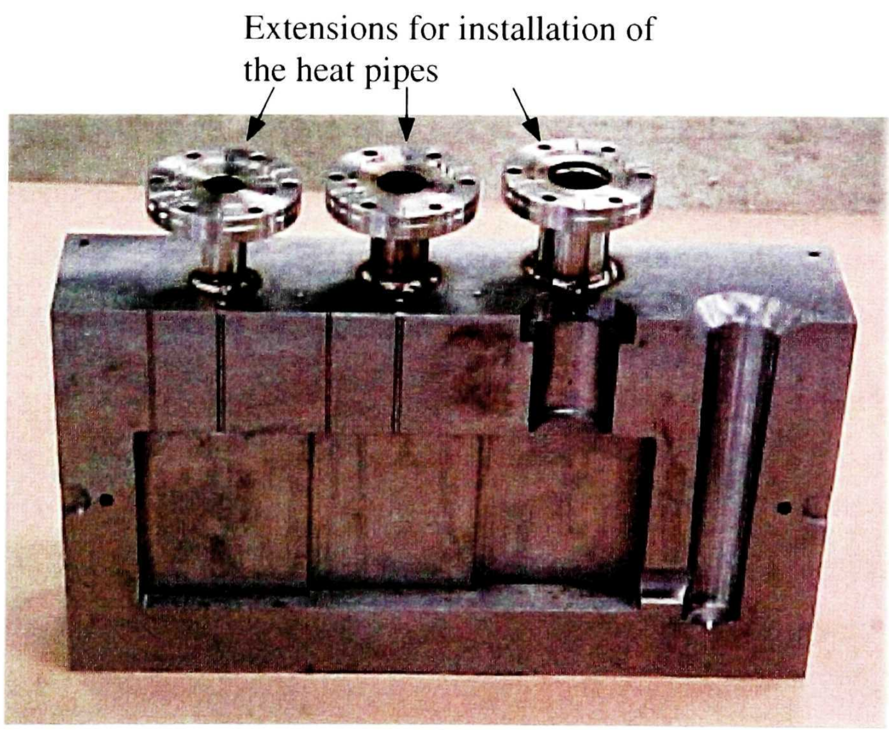
Figure 4.1 Design of the permanent mold cooled by three heat pipes (units: mm)

4.2 Design of the Laboratory Permanent Mold Cooled by Heat Pipes

4.2.1 The Permanent Mold

Several major factors that affect soundness of castings, such as gating, feeding and venting systems, must be considered in designing a permanent mold. Based on these considerations, a symmetric double step permanent mold made of H13 tool steel was designed for the experimental work. The design of the actual mold cooled by heat pipes that was used in this study is shown in Figure 4.1. A casting consisting of three sections of different thicknesses provided a variety of solidification rates. The mold is designed with a vertical parting plane, a side gating which is frequently used, particularly for aluminum castings, a vertical riser, and vents which allow all the air and gas in the mold cavity to escape.

(a)



(b)

Figure 4.2 Configuration of the step permanent mold (74)

The mold was symmetric about the parting plane as shown in Figure 4.2 (74). One half was cooled by three heat pipes, while the other half had only natural convective cooling. The design allowed for the evaluation of the effect of heat pipe cooling on the two halves of the mold and the casting. The weight of the mold was about 70 kg.

4.2.2 Design of the Heat Pipes Installed in the Permanent Mold

Based on the preliminary investigation for the novel heat pipe, the original design was modified for the controlled cooling of the permanent mold castings in order to further improve the operating performance of the heat pipe. The configurations of the three heat pipes are shown in Figure 4.3.

Besides the dimensions of the heat pipes, there are two differences from the preliminary design. One is the type of condenser. As mentioned in Chapter 3, there are three different condenser types for the McGill heat pipe. The type of condenser selected depends on the application of the heat pipe. Permanent mold casting is a cyclic process. Normally, cooling is required only during the solidification of a casting, when quite large amounts of heat should be extracted from the mold and the casting. The amount of heat which flows into the condenser should be dissipated promptly. If the condenser can function as an energy buffer to store heat temporarily during casting solidification, and the heat can be released and dissipated during the mold opening, the heat pipe cooling system will be very efficient and effective in the control of the solidification process. As a result the flow rate of cooling air can be greatly cut down. The built-in chill condenser type meets the required cooling performance.

The actual configurations of the condensers and the other components of the heat pipes are shown in Figure 4.4. During operation, heat is extracted and stored in the chill during the finite period of time that cooling is required. The heat stored in the chill is removed continuously by cooling air flowing through a cooling jacket. Thus, heat extraction is periodic while the dissipation of heat from the condenser (i.e. external chill of castings) was continuous throughout the casting sequence. The function of this type of condenser is similar to the internal chill used in casting processes. However, unlike the

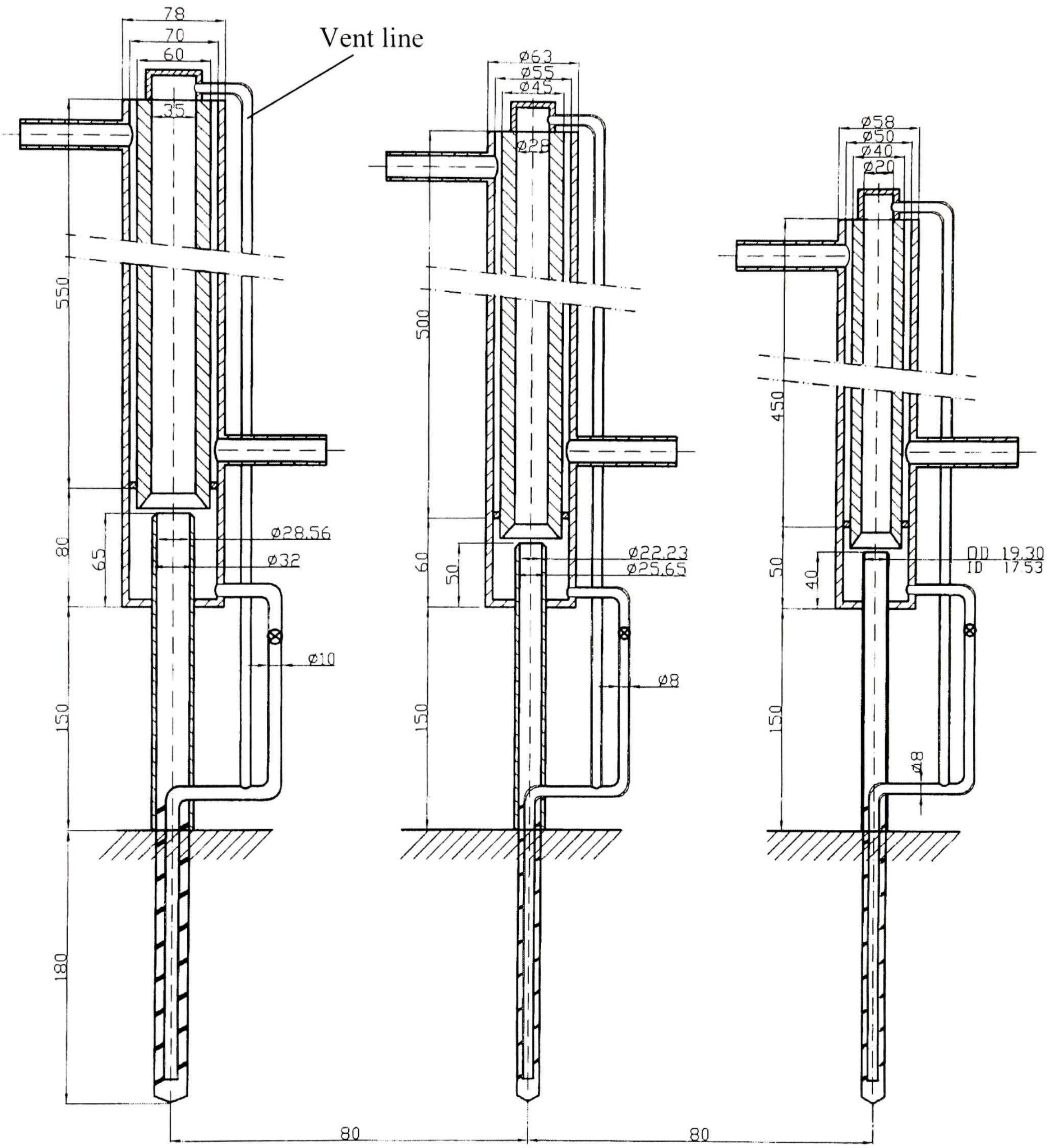
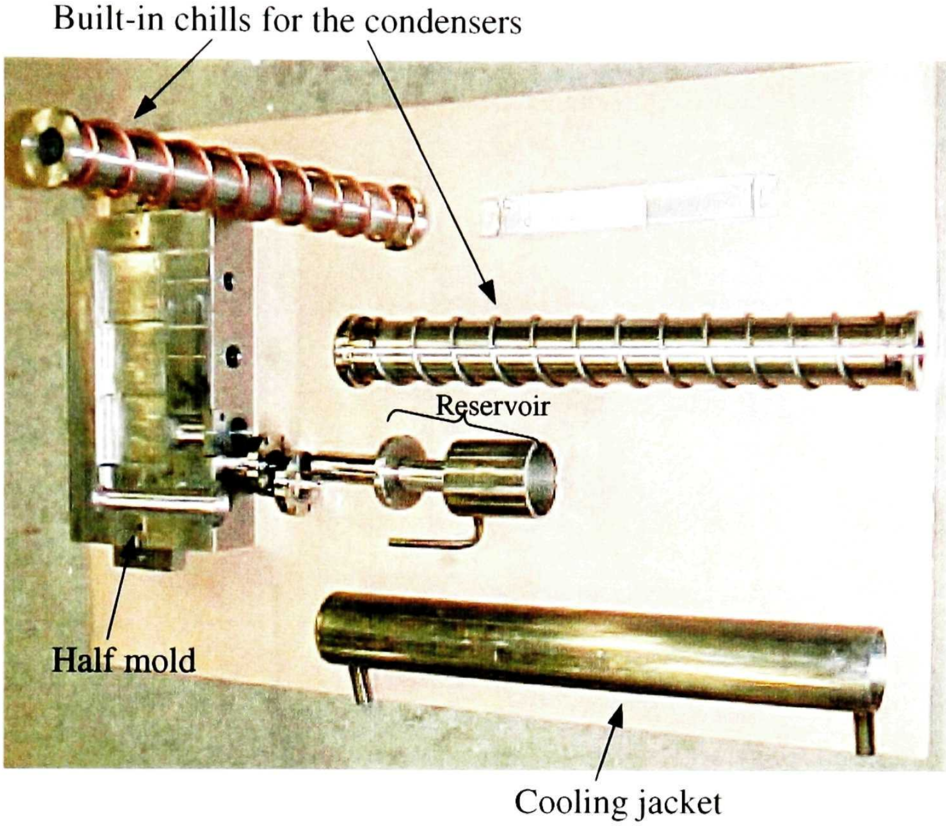


Figure 4.3 Design of the heat pipes for permanent mold cooling

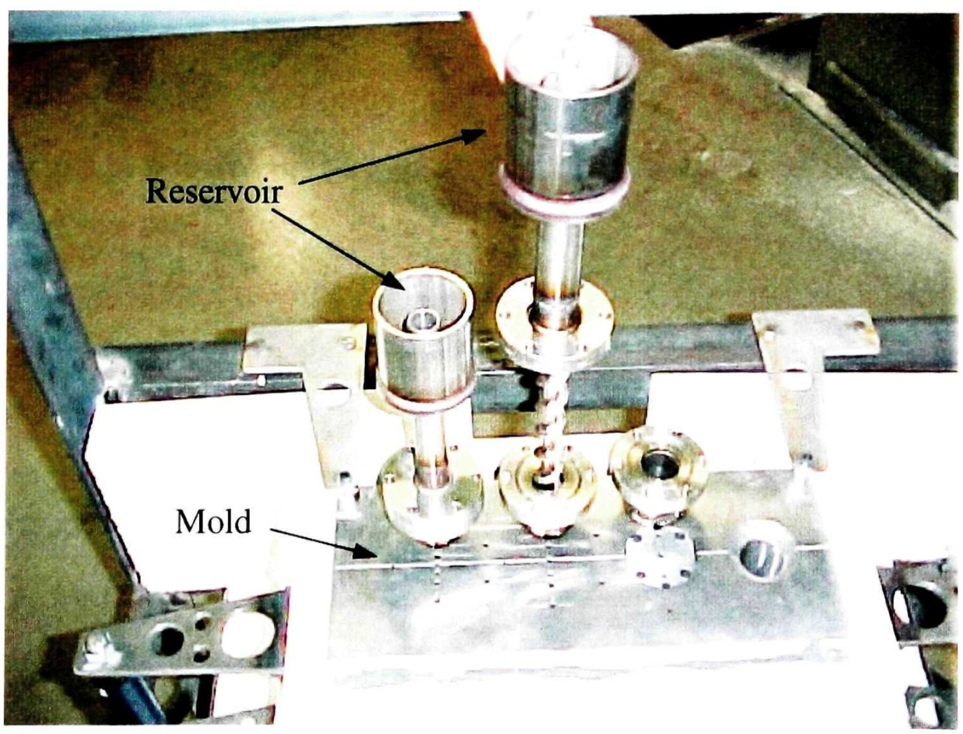
internal chill, the condenser never reaches equilibrium because of continuous cooling imparted by the cooling air. This is one of the main reasons that the McGill heat pipe can provide extremely effective enhanced cooling for permanent mold castings.

The second modification made was the installation of a vent line on the return line, and connected to the condenser as shown in Figure 4.3. The return line is heated by the mold when the cooling of the heat pipe is turned off, since the return line is in the evaporator which is inside the mold (See Figure 4.4). When the liquid (water) collected in the reservoir attempts to flow through the hot return line when the heat pipe is turned on, counter current flow between liquid and vapor will be generated in the return line. Upwards flow of vapor will be stopped when the vapor escapes from the vent line.

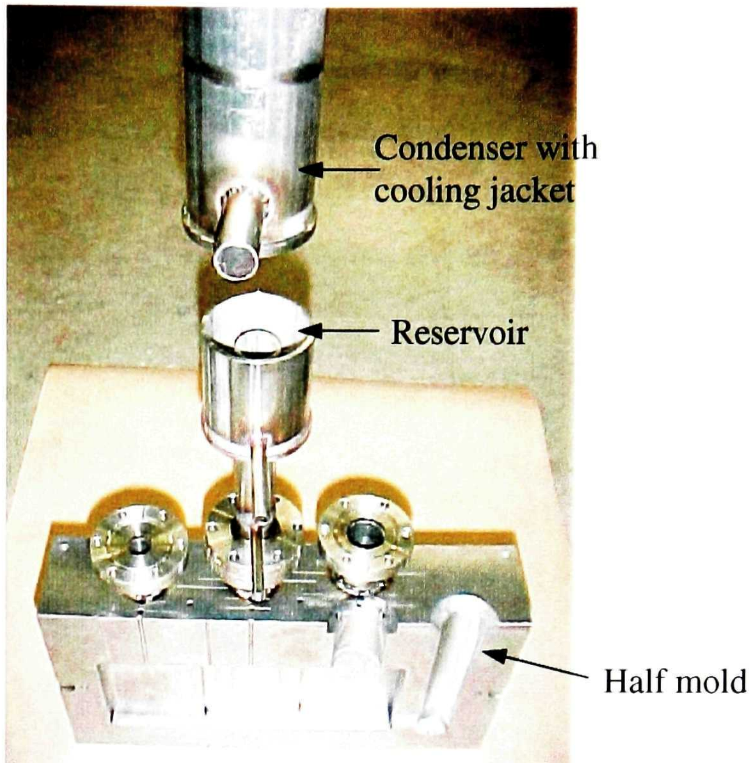
In order to avoid contact thermal resistance between the heat pipes and the mold wall, and to improve heat transfer between the heat pipes and the mold, the heat pipes were made as part of the mold. Three holes were drilled in the proper locations in one half of the mold wall, and extensions were attached to these holes such that the holes constituted the evaporators and the extensions were the condensers as shown in Figure 4.4.


Built-in chills for the condensers
Reservoir
Half mold
Cooling jacket

(a)


Reservoir
Mold

(b)



(c)

Figure 4.4 Components of the heat pipes for the permanent mold cooling

4.3 Solidification Modeling of Permanent Mold Casting of A356 Alloy

The next stage in the experimental program involved the casting of A356 alloy. The actual results are described in the following section. At this point some results from mathematical simulations are first presented. The solidification of the casting produced in the experimental mold was simulated by the commercial software package – SOLIDCast, a modeling program based on the finite difference method.

4.3.1 Creation of 3D Solid Model of the Casting

Basic geometric shapes (i.e. cylinders, spheres, rectangular blocks) that can be part of a casting model can be created by SOLIDCast. Some simple-shape castings may be entirely built with these basic shapes. In addition to basic geometric shapes, SOLIDCast allows the creation of three-dimensional shapes that are formed by revolving or extruding two-dimensional shapes (flat cross sections). These two-dimensional drawings may be contained in DXF files, or alternatively can be sketched on the screen, using the mouse. In order to simulate the process, a 3-D solid model of the step casting, gating, riser and heat pipes for mold cooling was built up by the software as shown in Figure 4.5 (74).

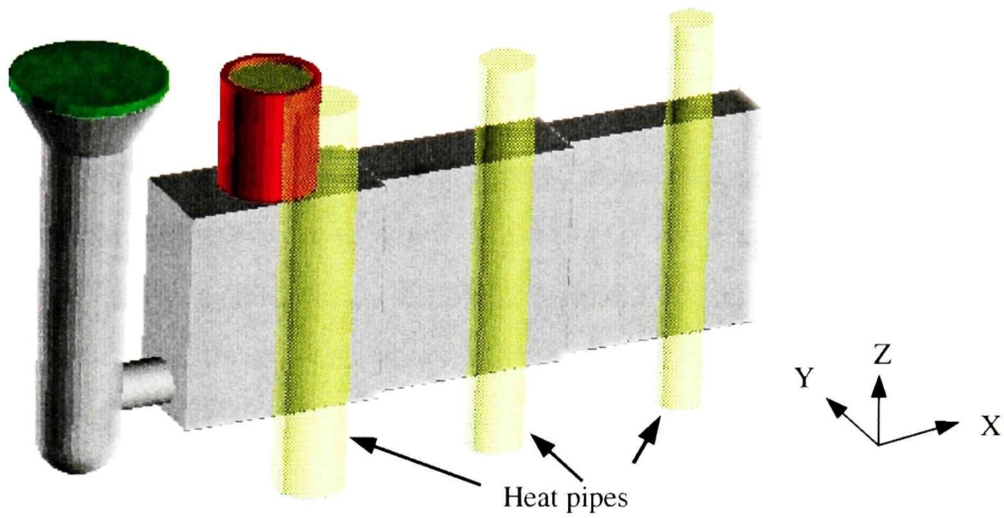


Figure 4.5 Solid model of the casting with three heat pipes

4.3.2 Determination of Boundary Conditions

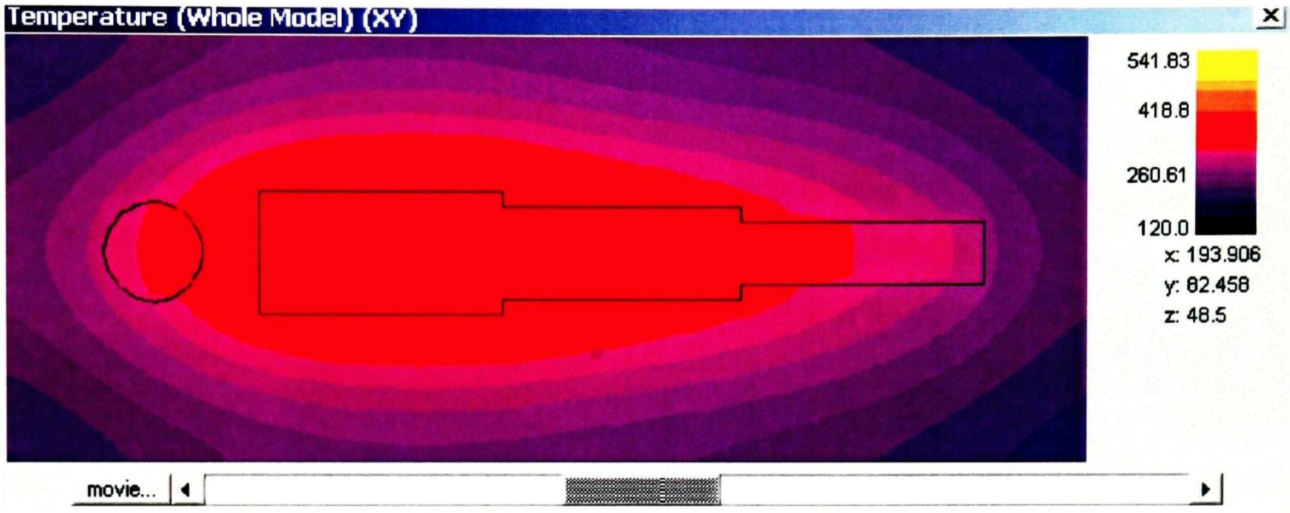
To simulate practical casting solidification processes, the proper physical and thermal properties of casting alloy and mold materials, as well as correct boundary conditions should be set up from the database of SOLIDCast. Then the solid mold is meshed into many small elements by SOLIDCast so that the thermal calculations can be performed on the casting, mold and cooling system. Boundary and initial conditions are one of the main factors influencing the computational precision. Improper boundary conditions could mislead the computational results far from the real casting process. Since the software package is not configured to take into account the incorporation of a heat pipe in the mold, it was necessary to represent the heat pipe with an alternative configuration. Given the limitations of the software, it was only possible to use a constant temperature boundary condition with an associated heat transfer coefficient. This type of boundary condition is normally associated with the use of relatively high velocity water cooled channels. The next section contains a comparison between the performance of water cooled passages and heat pipes.

Some results of several simulations will now be presented to illustrate how SOLIDCast was used to represent the heat pipes. The use of a constant surface temperature boundary condition required the specification of two parameters (the constant temperature and the heat transfer coefficient). Because these values cannot be arbitrarily chosen, it was necessary to carefully examine the experimental data and to reproduce relevant portions of the data. As the heat pipe typically operated between 30 and 100 ^{o}C, an average temperature of 65 ^{o}C was used as the value for the constant temperature boundary condition. The associated heat transfer coefficient was chosen by trial and error. A number of values were tested with the model and a value of 20,000 W/m^2K was ultimately chosen as the value that best fit the experimental data.

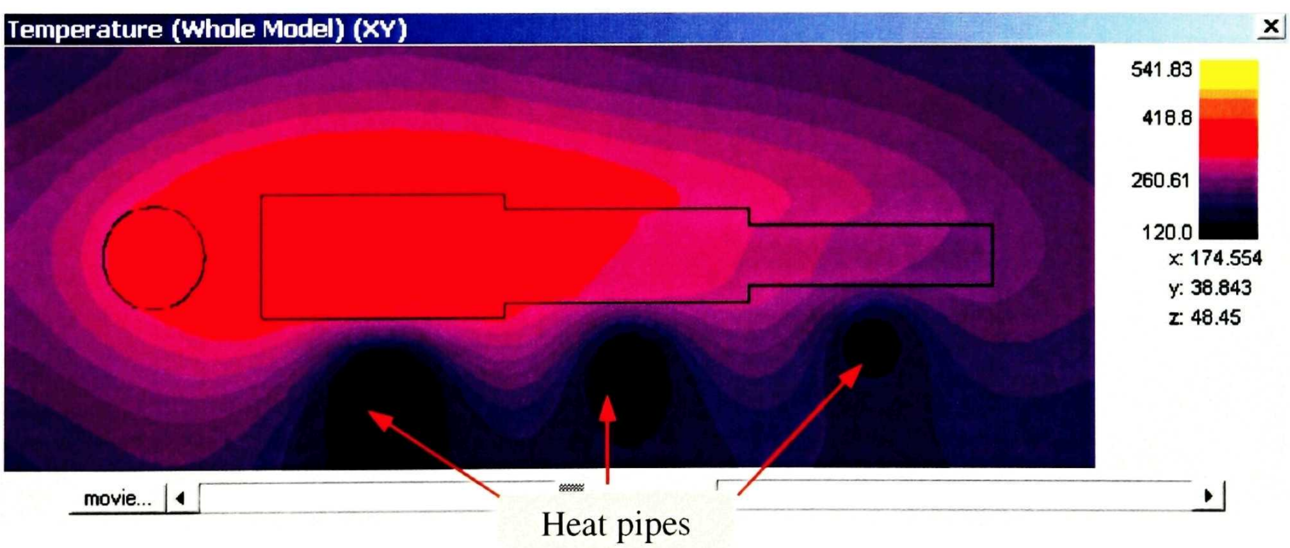
While it is acknowledged that the use of a constant surface temperature of 65 ^{o}C with a heat transfer coefficient of 20,000 W/m^2K for a cylindrical passage of 2.8 cm diameter (ID of Heat Pipe #1 shown in Figures 4.1and 4.8) is only an approximation of the actual heat pipe, it is nonetheless fairly realistic. It is important to note, however, that the simulations did not include the formation of an air gap during the solidification of the casting. As these are preliminary results, quantifying the size of the air gap will be performed at a later stage of the project. Nonetheless, the prominent role of the air gap in controlling heat transfer from the casting will become obvious when the experimental results that are presented in the following section are compared to the model results.

4.3.3 Modeling Results

Simulations of the casting, with and without cooling, were carried out. As shown in Figures 4.6 and 4.7, the simulated results of the temperature distribution indicate the influence of heat pipe cooling for the permanent mold casting of alloy A356. Also from the symmetric step casting, we can compare the two halves of the casting to check the effect of cooling by heat pipes.

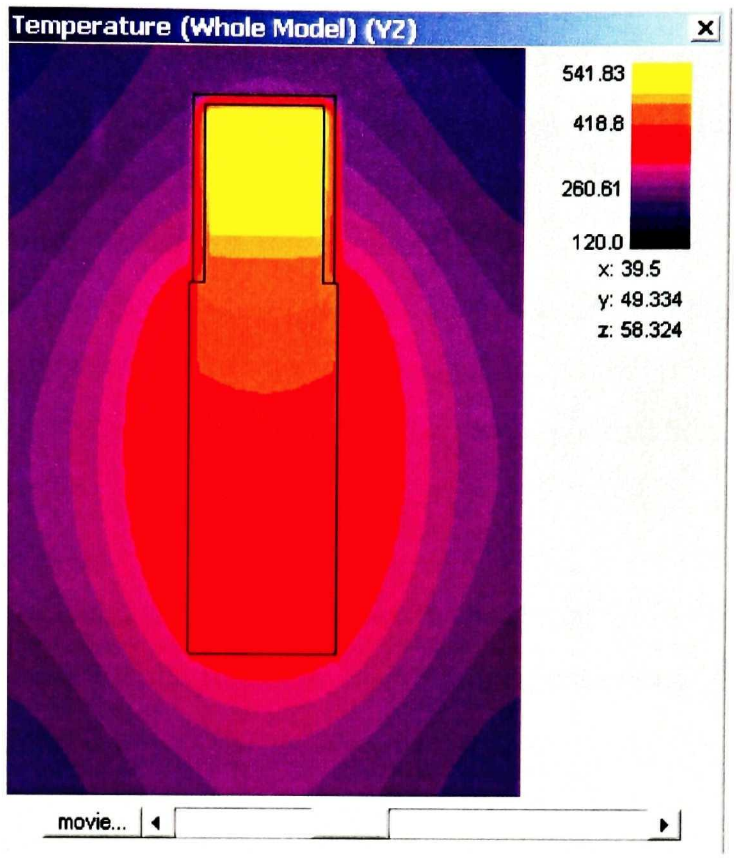


(a) Without any cooling

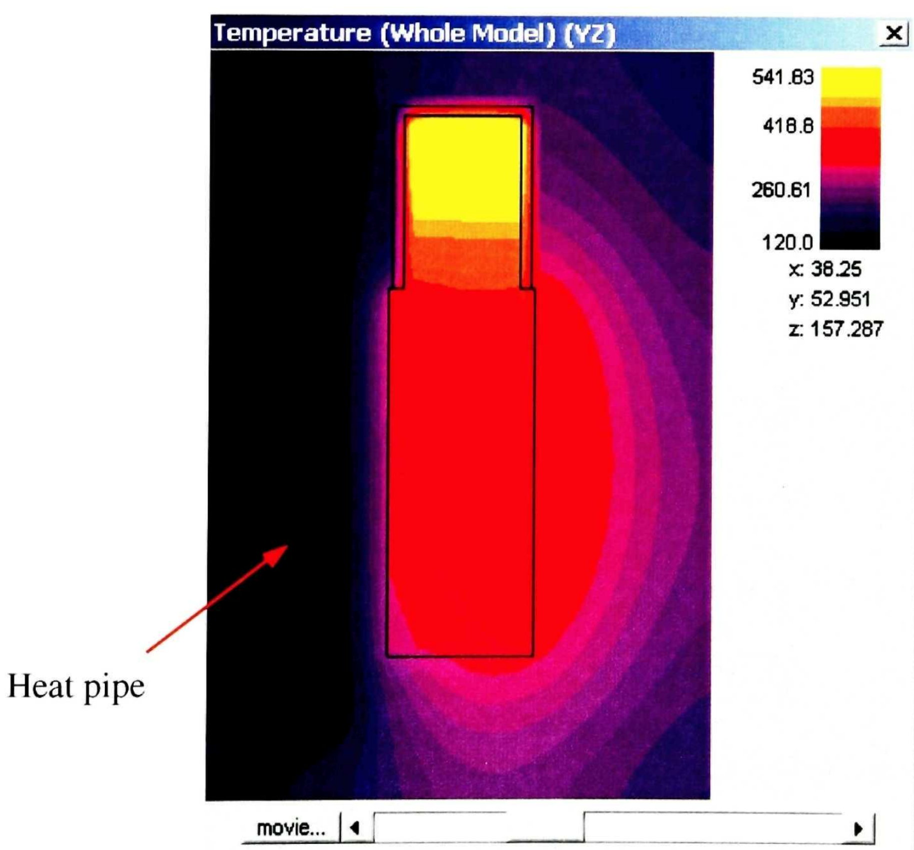


(b) With cooling by heat pipes

Figure 4.6 Temperature distribution of XY cross section of permanent mold casting



(a) Without any cooling



(b) With cooling by heat pipes

Figure 4.7 Temperature distribution of YZ cross section of permanent mold casting:

The results generated by the model for the temperature distributions with both the casting (A356) and the mold show the influence of the imposed cooling boundary condition very clearly. As has been stated, this imposed cooling condition is a fairly accurate representation of the cooling produced with a heat pipe. As expected, the half of the casting with cooling solidified more quickly. The symmetric casting allowed a comparison of the two halves of the casting to evaluate the effect of the heat pipe cooling. During the modeling process, the temperature of specific points in the casting and mold were recorded into a data file by setting up the thermocouple locations (TC1, TC2, TC3, etc. see Figure 4.8).

Results from the simulation for the case when the initial mold temperature was 200 °C are shown in Figure 4.9 while those for an initial temperature of 300 °C are shown in Figure 4.10. In both cases, the molten aluminum was poured into the mold when t = 0. During the casting solidification, only Heat Pipe #1 was activated. From the curves shown in Figures 4.9 and 4.10, the extent of the effect of heat pipe cooling is apparent by comparing the symmetric points (TC1 and TC3) of the mold about the parting plane. The temperature of the half of the mold without cooling (TC3) is substantially higher than that with heat pipe cooling (TC1).

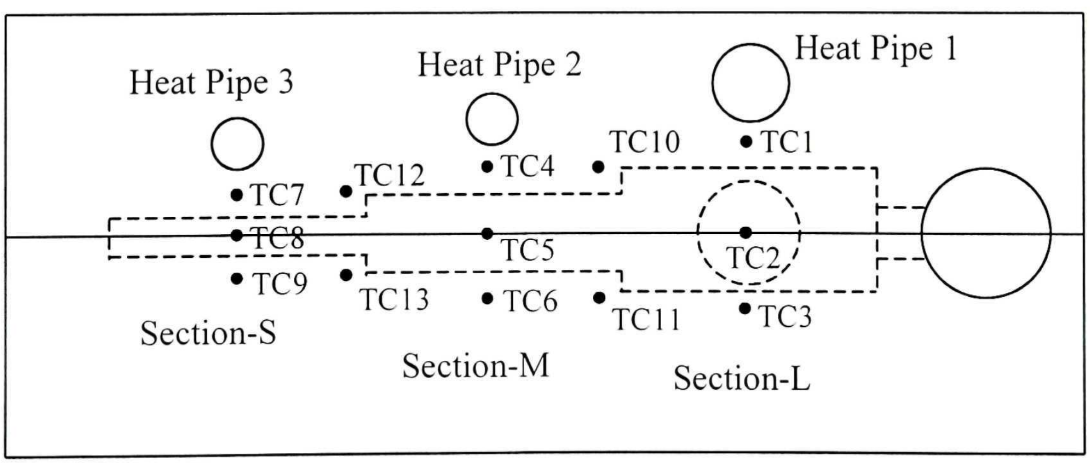


Figure 4.8 Thermocouple locations for temperature recording

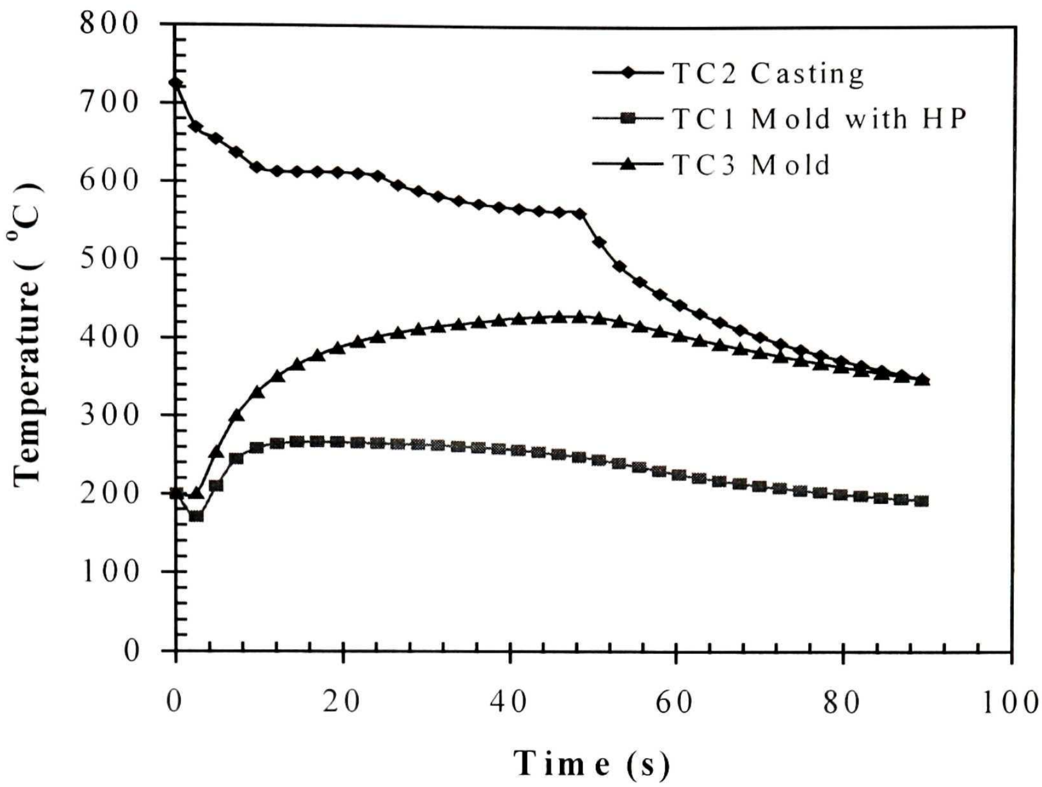


Figure 4.9 Cooling curves of the casting and mold from the model: $T_{mold\ preheating}$= 200 °C

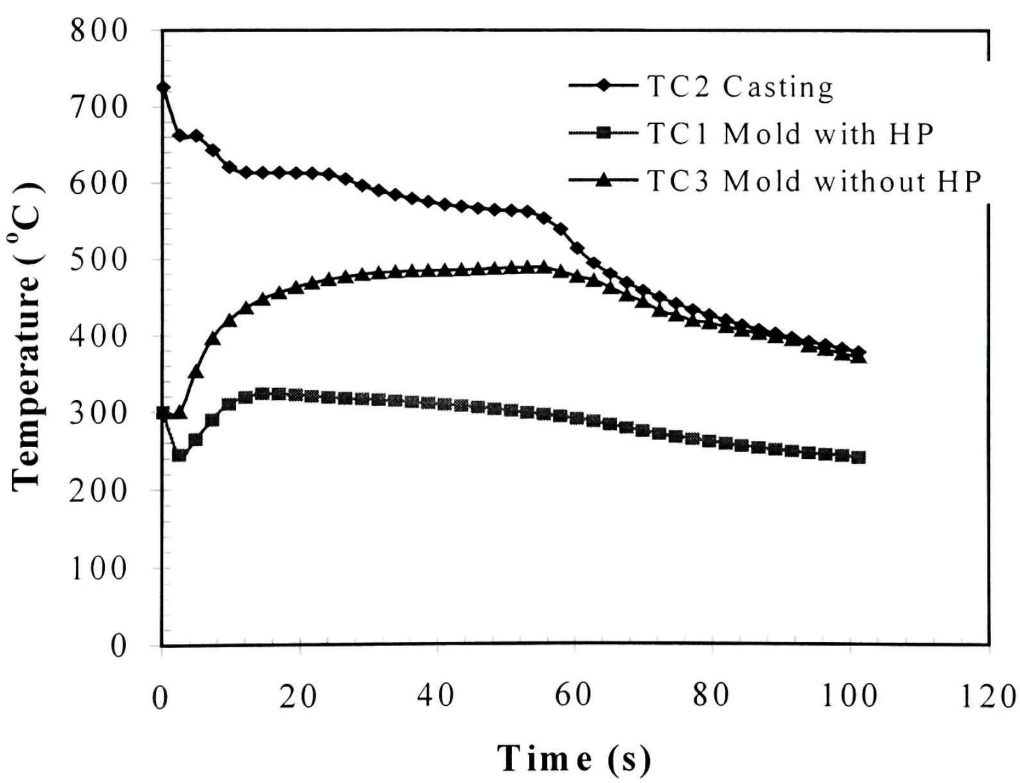


Figure 4.10 Cooling curves of the casting and mold from the model: $T_{mold\ preheating}$= 300 °C

4.3.4 Comparison of a water cooling channel and a heat pipe

Given the equivalence of the model results and the experimental results when the heat transfer coefficient was set at 20,000 W/m^{2}K, it is possible to deduce what the actual velocity of a water flow in a channel must be to achieve this condition. The heat transfer between a fluid flowing in a circular passage and the wall can be described for a turbulent, forced convection flow by the Dittus-Boelter equation (4-1) as:

$$\overline{Nu_D} = 0.023\,\mathrm{Re}_D^{0.8}\,\mathrm{Pr}^{0.4} \tag{4-1}$$

where

$\overline{Nu_D}$ — the average Nusselt number based on the pipe diameter, D

$\mathrm{Re_D}$ — the Reynolds number of the fluid

Pr — the Prandtl number of the fluid

In the experimental mold, the diameter of the passage for Heat Pipe #1 was 2.8 cm.

Equation (4-1) can be rewritten as:

$$\bar{h} = \frac{k}{D}(0.023)\left[\frac{\rho v D}{\mu}\right]^{0.8}\mathrm{Pr}^{0.4} \tag{4-2}$$

or

$$v^{0.8} = \frac{\bar{h}D^{0.2}}{(0.023)k}\frac{1}{\mathrm{Pr}^{0.4}}\left(\frac{\mu}{\rho}\right)^{0.8} \tag{4-3}$$

Thus

$$v = \left(\frac{\bar{h}D^{0.2}}{(0.023)k}\right)^{1.25}\frac{1}{\mathrm{Pr}^{0.5}}\left(\frac{\mu}{\rho}\right) \tag{4-4}$$

where

v — average velocity of the water flow, m/s

$\bar{h}$ — average heat transfer coefficient = 20,000 W/m^{2}K

D — internal diameter of the passage = 0.028 m

k — thermal conductivity of water = 0.647 W/mK

Pr — Prandtl number of water = 3.55

μ — viscosity of water 555.1x10-6 Ns/m^2

ρ — density of water = 988.1 kg/m^3

The properties of water were assumed for a temperature of 50 °C. Thus, substitution of the above values into Equation (4-4) yields

$$v = 5.6\, m/s$$

The mass flow rate of water at this velocity is then computed to be:

$$\dot{m} = \pi(0.014)^2 m^2 (5.6\, m/s)(988.1\, kg/m^3) = 3.4\, kg/s = 204\, kg/min$$

In other words, to duplicate the cooling that was achieved with Heat Pipe #1 would require a water flow of 204 kg/min. This is in marked contrast to the fact that the heat pipe only contained 100 g of water and this is confined in a sealed chamber. Moreover, the overall dissipation of heat from the heat pipe was with air.

As a final point, it is worth noting that the software package SOLIDCast recommends that if water is to be used as the coolant, the user should select a constant temperature of 60 °C and a heat transfer coefficient of 1,532 W/m^{2}K. A simulation was carried out with these parameters with a starting mold temperature of 200 °C. The results are shown in Figure 4.11. It is obvious when comparing these results to the corresponding experimental results that the heat pipe generates cooling which is significantly greater than the suggested rate of cooling as computed with SOLIDCast. Thus, one can conclude that this novel heat pipe is capable of achieving heat extraction rates that are difficult and costly to attain with conventional water cooling channels.

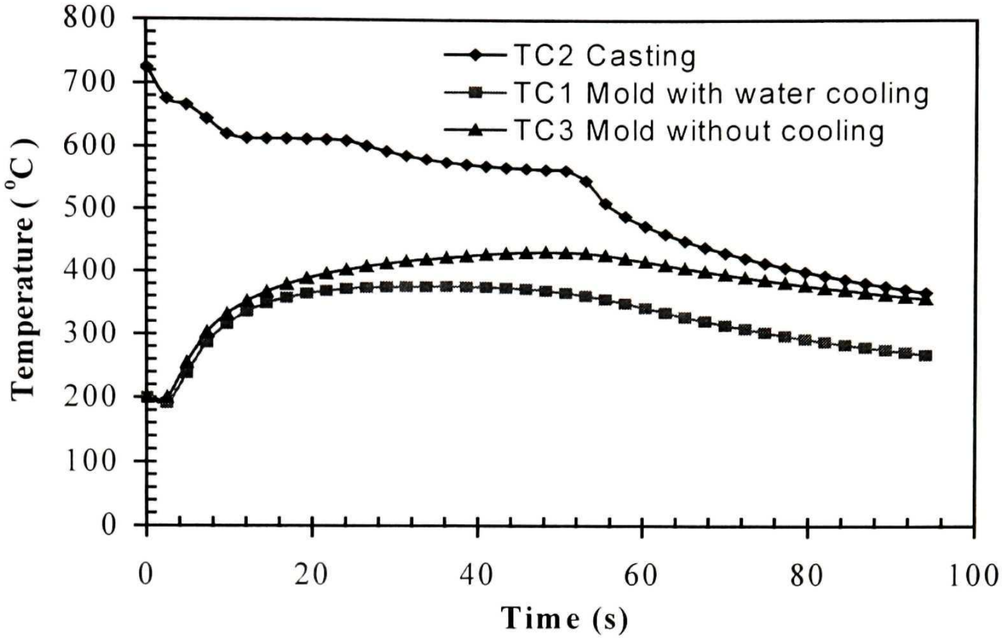
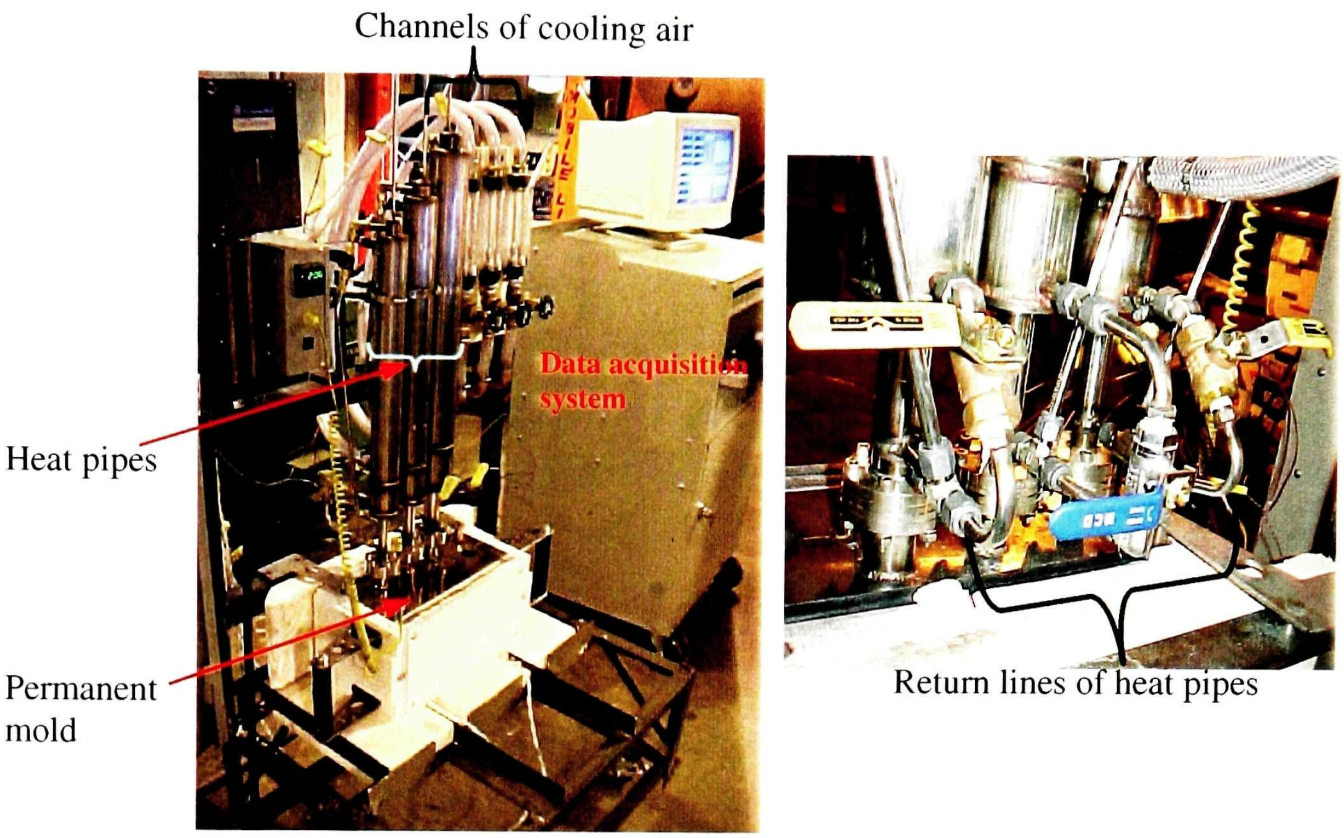


Figure 4.11 Cooling curves of the casting and mold with water cooling under conditions recommended by the SOLIDCast software: $T_{mold\ preheating}$= 200 °C

4.4 Laboratory Experiments on Permanent Mold Castings of Aluminum Alloys

4.4.1 Experimental Procedure

The experimental setup is shown in Figure 4.12 (75). Thermocouples were inserted both into the mold cavity itself, as well as in the mold near the heat pipes. These were used to measure the temperature effects caused by the heat pipe cooling, both during solidification of the casting itself, as well as in the mold material near the heat pipes. Temperature histories of the mold and castings were recorded by a data acquisition system.



(a) (b)

Figure 4.12 Experimental setup of permanent mold casting (75)

All permanent mold casting experiments were performed with A356 alloy, which is a commonly used alloy in aluminum casting manufacture. In this section, the experimental results on permanent mold castings are presented. Some typical experimental results on solidification time, shrinkage and dendrite arm spacing (DAS) of the castings are discussed. The components of this research are as follows:

1) Heat flux measurements for the cooling of the mold only (i.e. no casting) at starting temperatures of about 200 ^{o}C, 300 ^{o}C and 400 ^{o}C, and during cooling of the permanent mold casting at initial mold temperatures of about 200 ^{o}C and 300 ^{o}C.
2) Acquisition of experimental data for the casting of A356 alloy with heat pipe cooling.

3) Assessment of the effect of heat pipe cooling on the shrinkage distribution in castings produced in the permanent mold.
4) Evaluation of the influence of heat pipe cooling on casting solidification of the A356 alloy.
5) Determination of the effect of heat pipe cooling on solidification time of castings of A356 alloy with different types of mold coatings

4.4.2 Preliminary Experiments of Heat Pipe Cooling of the Permanent Mold Itself

4.4.2.1 Results of Mold Cooling by the Heat Pipes

This section summarizes some of the results that illustrate what magnitudes of heat fluxes one can extract with this newly developed heat pipe. The tests were conducted after preheating the mold. No metal was cast during this test phase. A large number of tests were conducted to assess the ability of the heat pipes to cool the permanent mold. All the heat pipes were tested individually and in some cases simultaneously at different starting mold temperatures. The mold was preheated by using the heating elements attached on both sides of the mold. The results for the cooling of the mold with a starting temperature slightly above 400 °C by Heat Pipe #1 are shown in Figure 4.13. From the cooling curves, we can see that the temperature of the mold with the heat pipe cooling decreased rapidly compared to the other location on the opposite side of the parting plane where TC11 was located. Even though the thermocouple, TC10, was over 3 cm away from Heat Pipe #1 (see Figure 4.8), it quickly responded to the intense cooling from the heat pipe. The transient heat flux for this test was calculated as a function of time based on the data shown in Figure 4.13. The curve of heat flux vs. time is given in Figure 4.14, and indicates a maximum heat flux of about 650 kW/m^2 for this case, and the maximum heat flow rate was calculated to be about 13 kW at the peak, A.

Results for starting mold temperatures of about 300 and 200 °C are shown in Figure 4.15 and Figure 4.17 respectively. Also shown in Fig 4.16 and Figure 4.18 are the corresponding computed heat flux curves for these tests. Testing with Heat Pipes #2 and #3 yielded similar results that are in keeping with the results shown for Heat Pipe #1.

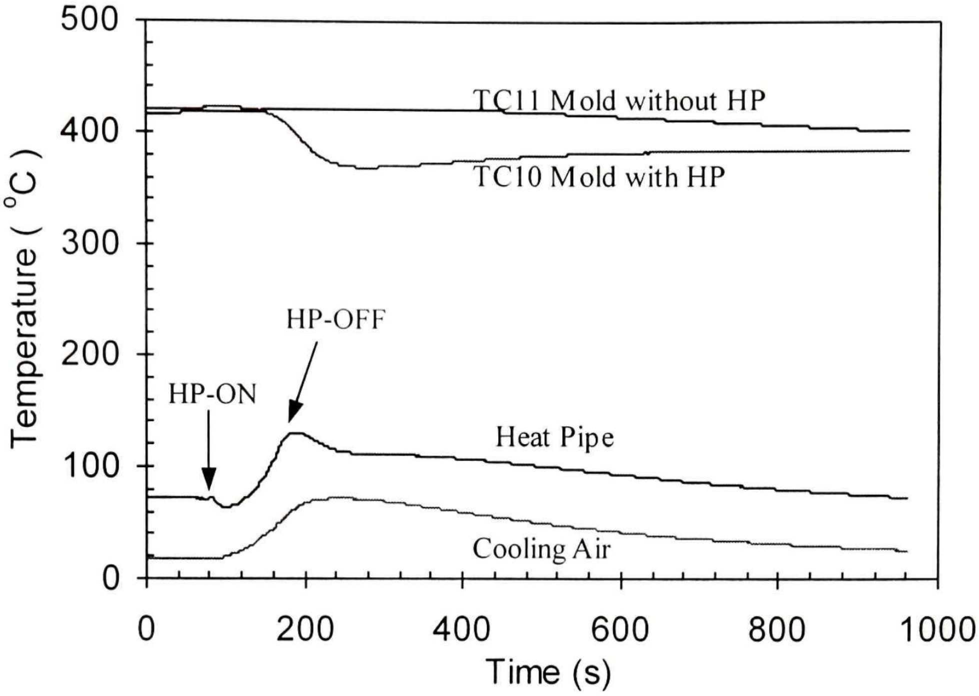


Figure 4.13 Results of mold cooling by the heat pipe with no casting: Flow of cooling air = 30SCFM, $T_{mold\ preheating}$= 420 °C

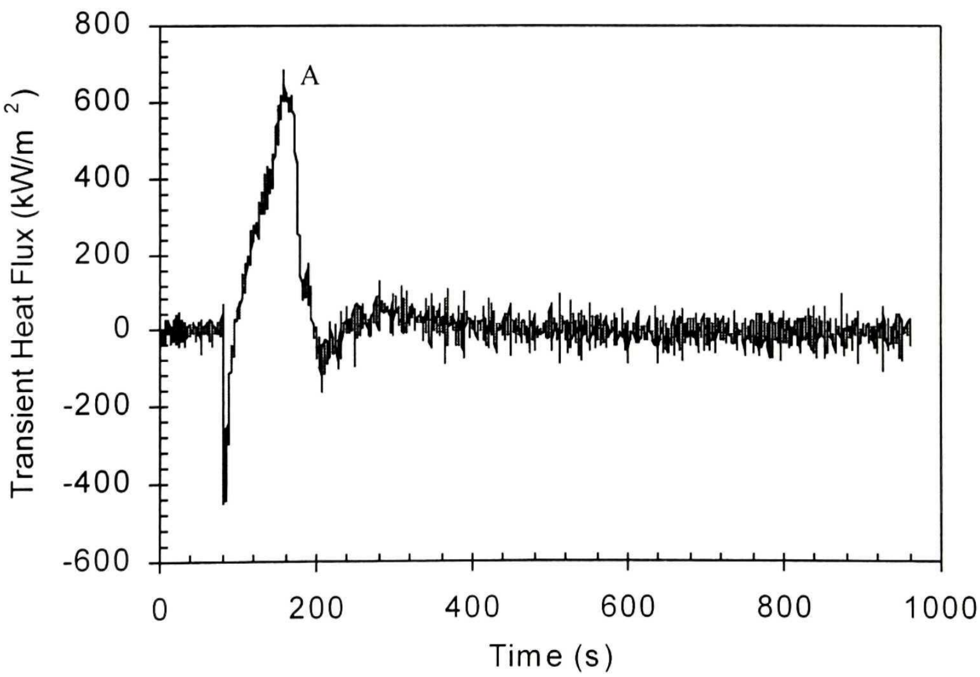


Figure 4.14 Transient heat flux on the entire heat pipe wall calculated from the data of Figure 4.13

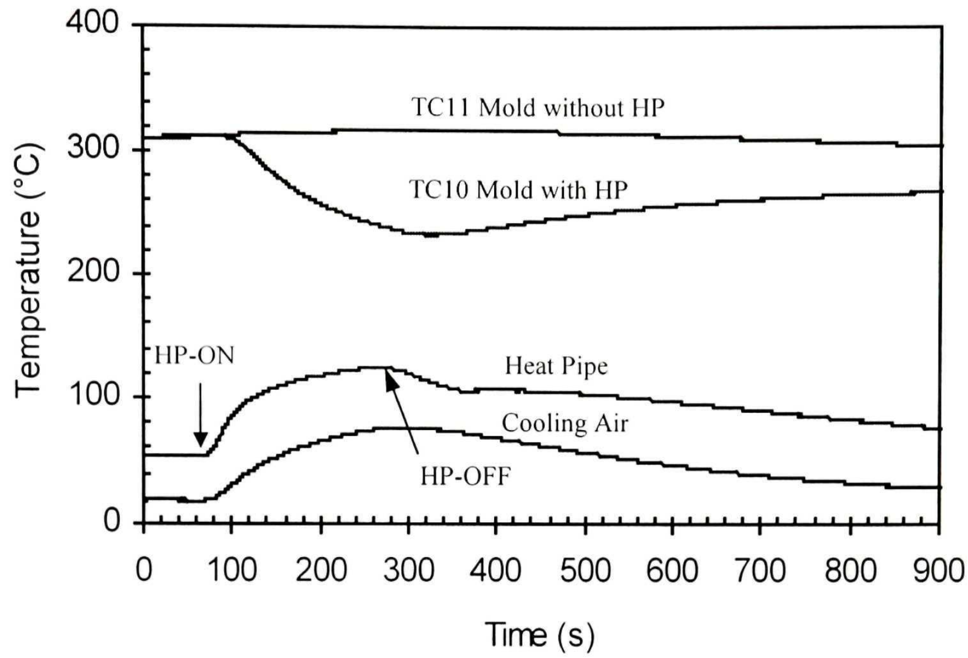


Figure 4.15 Results of mold cooling by the heat pipe with no casting: Flow of cooling air = 30SCFM, $T_{mold\ preheating}$= 300 °C

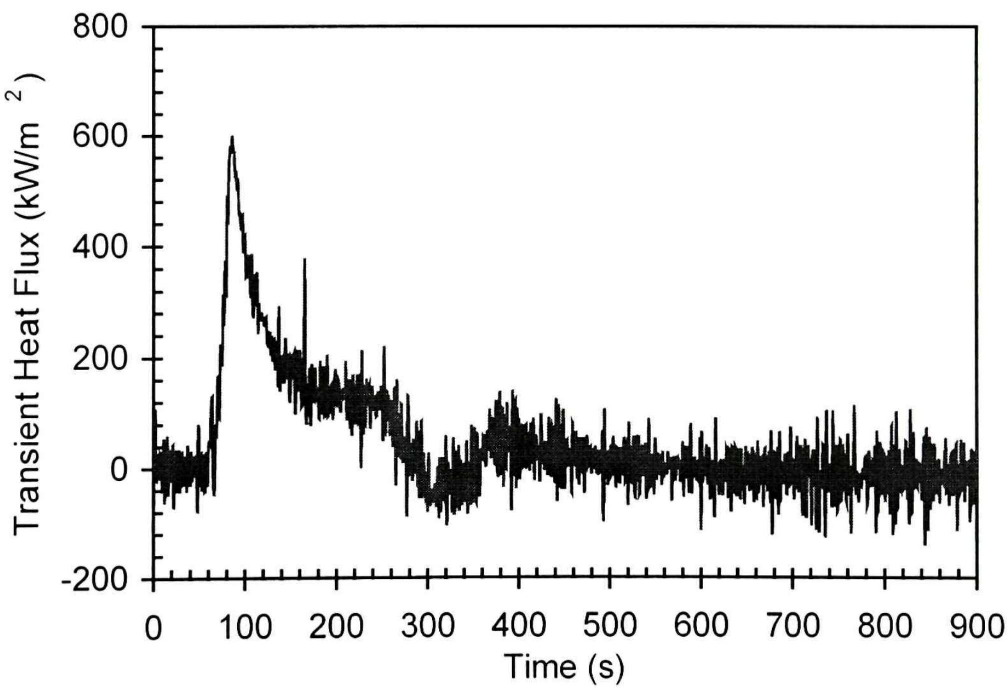


Figure 4.16 Transient heat flux on the entire heat pipe wall calculated from the data of Figure 4.15

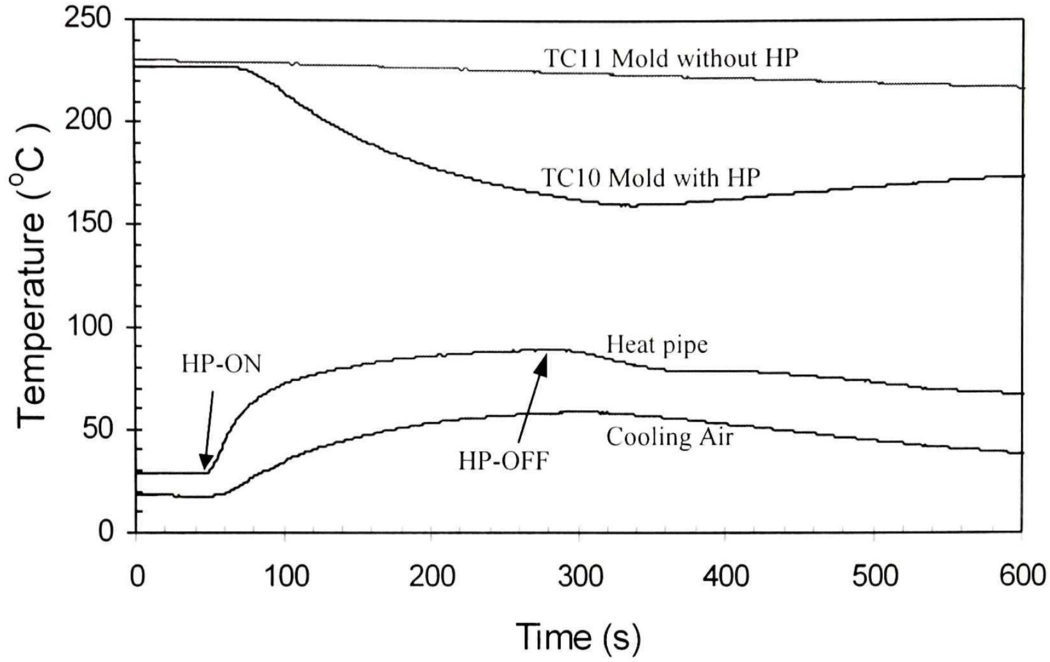


Figure 4.17 Results of mold cooling by the heat pipe with no casting: Flow of cooling air =30SCFM, $T_{mold\ preheating}$=230 °C

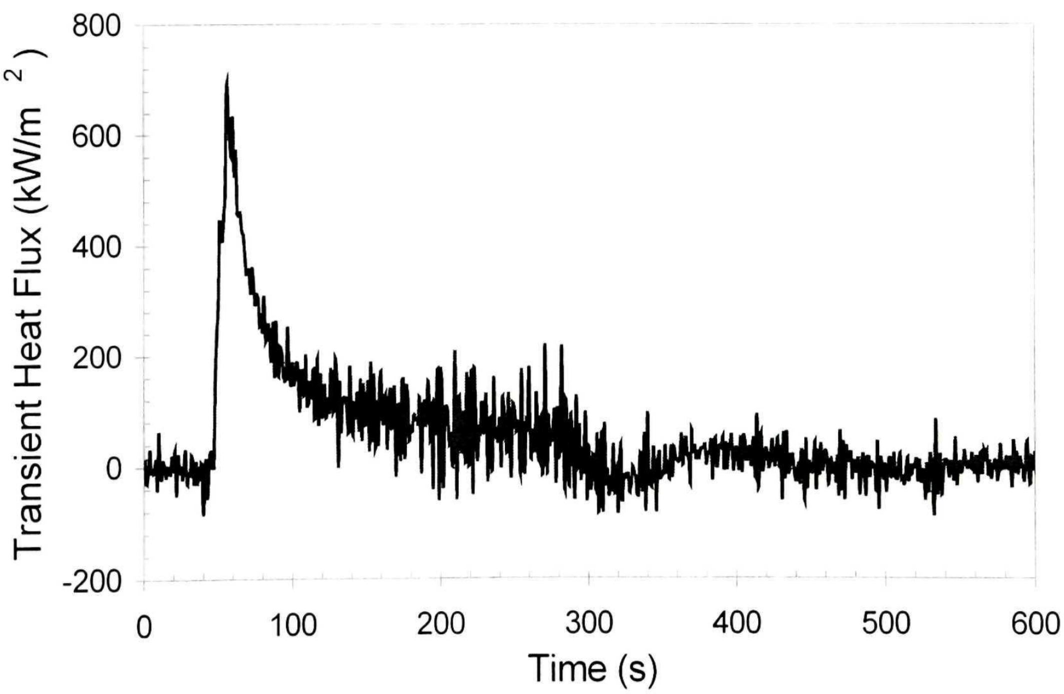


Figure 4.18 Transient heat flux on the entire heat pipe wall calculated from the data of Figure 4.17

Results for the cooling of the mold with a starting temperature about 320 °C and using all three heat pipes are shown in Figure 4.19. During this test, four thermocouples were inserted into the mold (TC10, TC11, TC12, TC13 are shown in Figure 4.8). Thermocouple TC10 was located 3 cm away from Heat Pipe #1 and Heat Pipe #2. Thermocouple TC12 was set up between Heat Pipe #2 and Heat Pipe #3 in the same way as thermocouple TC10. When the three heat pipes were switched on, the mold temperature (TC10, TC12) dropped very quickly under the enhanced cooling of the heat pipes. The cooling was so intense that it affected the temperatures at the other locations (TC11, TC13) on the opposite side of the parting plane. When the heat pipes were switched off, the mold was reheated rapidly.

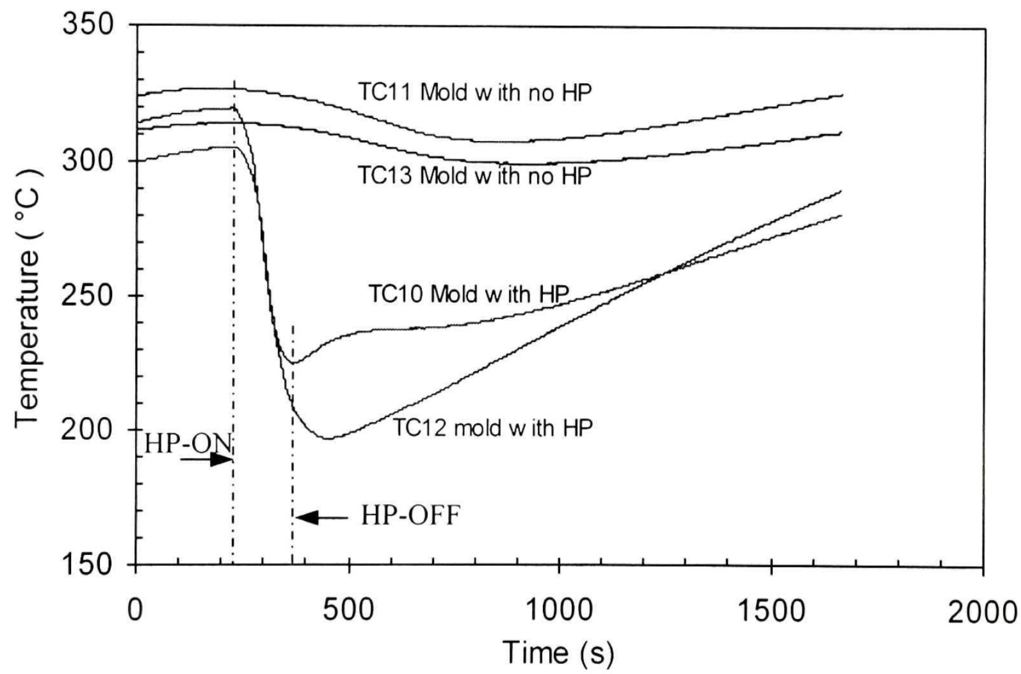


Figure 4.19 Results of mold cooling using the three heat pipes with no casting: Flow of cooling air: 30 SCFM For Heat Pipe #1 and #2, 40 SCFM for Heat Pipe #3, $T_{mold\ preheating} \approx 320$ °C

4.4.2.2 Improvement on Heat Transfer Behavior of the Heat Pipes by Adding a Surfactant

As discussed in Chapter 3, the heat pipe systems for the mold cooling originally did not work well until a small amount of surfactant was added into the working substance (water) in the heat pipes because of the effect of surface tension on water flow though the return line. Figure 4.20 indicates the results of mold cooling using Heat Pipe #2 only in operation before a surfactant was added into the working substance (water). From Point A when the heat pipe was turned on, to Point C when the heat pipe was turned off, there are two different slopes of the curves for the heat pipe temperature. The slope of the region AB is different from that of the region BC. The rate of increase of the temperatures of the heat pipe became greater around Point B. At this point, the surface tension of the water no longer dominates the water flow through the return line to the mold. Thus the heat flow through the heat pipe increased because there is enough water to cover the heated surface of the evaporator. The effect of this increased heat flow can be seen on the curve for mold temperature, TC10, where it is evident that the slope of the region OP is different from that of the region PQ. The curve of cooling air temperature from the condenser also reflects this feature of the heat pipe cooling behavior.

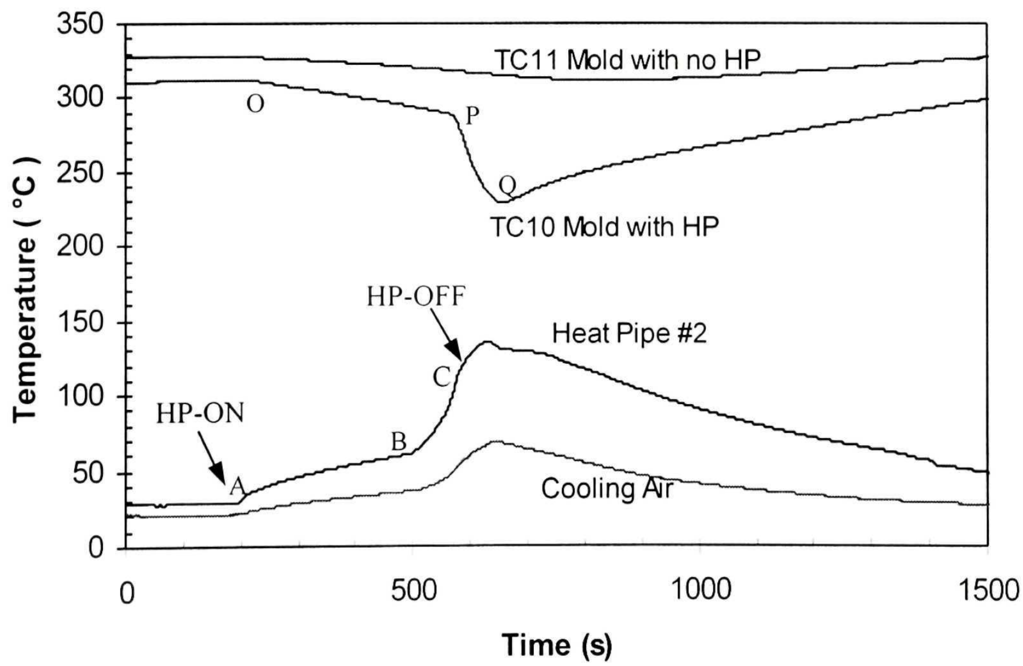


Figure 4.20 Results of mold cooling by Heat Pipe #2 with no surfactant added to the working substance (water)

When 3% surfactant (liquid soap for dishwasher, no bubbles) in volume was mixed with the working substance inside the heat pipe, the thermal behavior of the heat pipe was much improved. The results of the mold cooling test with the improved heat pipe are shown in Figure 4.21. A comparison of these results with those in Figure 4.20 shows that the average cooling rates of the mold in Figure 4.21 are five times higher than those in Figure 4.20. The improvement was obtained by increasing the water cover rates of the evaporator surface. The surface tension of water was decreased by the surfactant, resulting in the high water flow rates through the return line, and the heat flow from the mold through the heat pipes was increased.

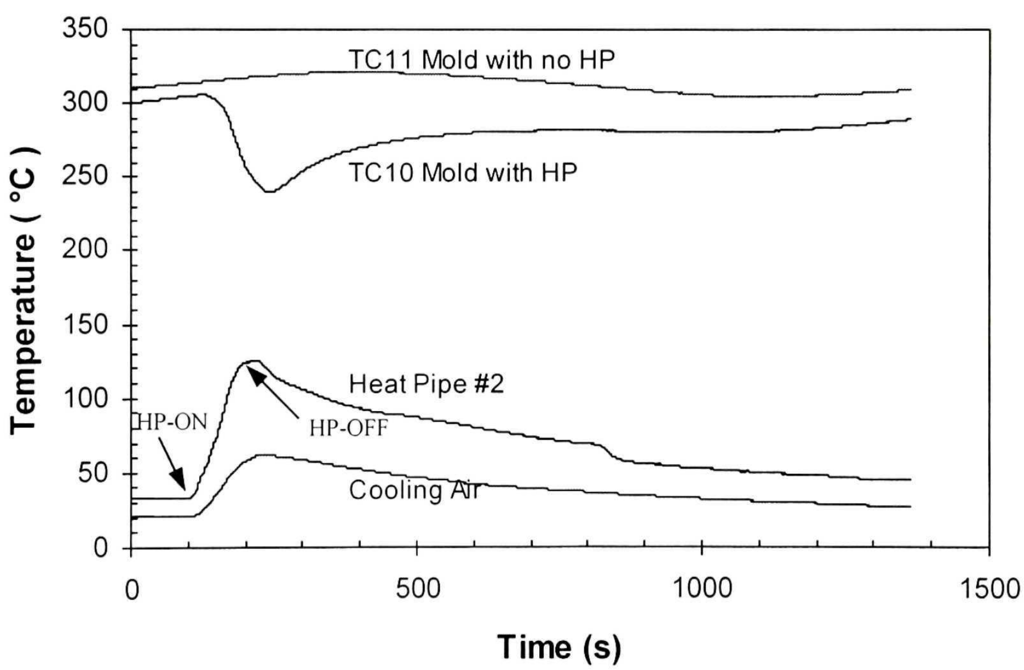


Figure 4.21 Results of mold cooling by Heat Pipe #2 by adding a small amount of surfactant (soap) into working substance (water)

4.4.3 Experiments of Permanent Mold Castings of A356 Alloy

4.4.3.1 The Effect of Heat Pipe Cooling on Temperature Distribution and Heat Flux

For these casting experiments, the permanent mold was preheated to about 200 °C and 300 °C. The surface of the mold cavity was coated with three different types of coatings obtained from FOSECO with different thermal conductivities. The effect of heat pipe cooling on the mold temperature distribution and casting solidification under the different boundary conditions brought on by the mold coatings was investigated, and will be discussed in Section 4.4.3.4. In this section only experiments in which DYCOTE11 was applied to the surface of mold cavity will be discussed. DYCOTE 11 is a commonly used graphite lubricating coating for permanent mold castings. More than fifty castings were produced. Temperature measurements were repeatable to within ±5 °C provided the experimental conditions were kept constant.

The heat transfer history during casting solidification was logged by the data acquisition system. The cooling curves of the mold and castings are shown in Figures 4.22, 4.23 and 4.25. The locations of thermocouples for temperature recording are indicated in Figure 4.8. The results presented in Figure 4.22 and Figure 4.23 were obtained with Heat Pipe 1 only operating, while the experiment shown in Figure 4.25 was conducted with three heat pipes operating during the casting process.

From the cooling curves, we can see that the temperatures of the mold with the heat pipe cooling (TC1) did not increase on casting, and even decreased due to the heat pipe cooling. However, the temperatures of the mold on the opposite side of the parting plane (TC3) increased more than 100 °C when the metal was cast into the mold. The temperature differential between these two locations in the mold indicates that the heat pipes were very effective in cooling the mold as it extracted the incoming heat from the liquid metal. The curve of heat flux vs. time is shown in Figure 4.24 calculated from the data of Figure 4.23, and it indicates a maximum heat flux of about 630 kW/m^2.

With the three heat pipes operating at the same time, the temperatures of the mold were much lower during the casting process due to the more intensive cooling by the three heat pipes (Figure 4.25). Before casting, the mold temperature decreased approximately to 150 °C, which was just 20 °C higher than the operating temperature of the heat pipes. This caused the driving force for heat transfer between the mold and the heat pipes to be so small that the mold temperature reached steady state.

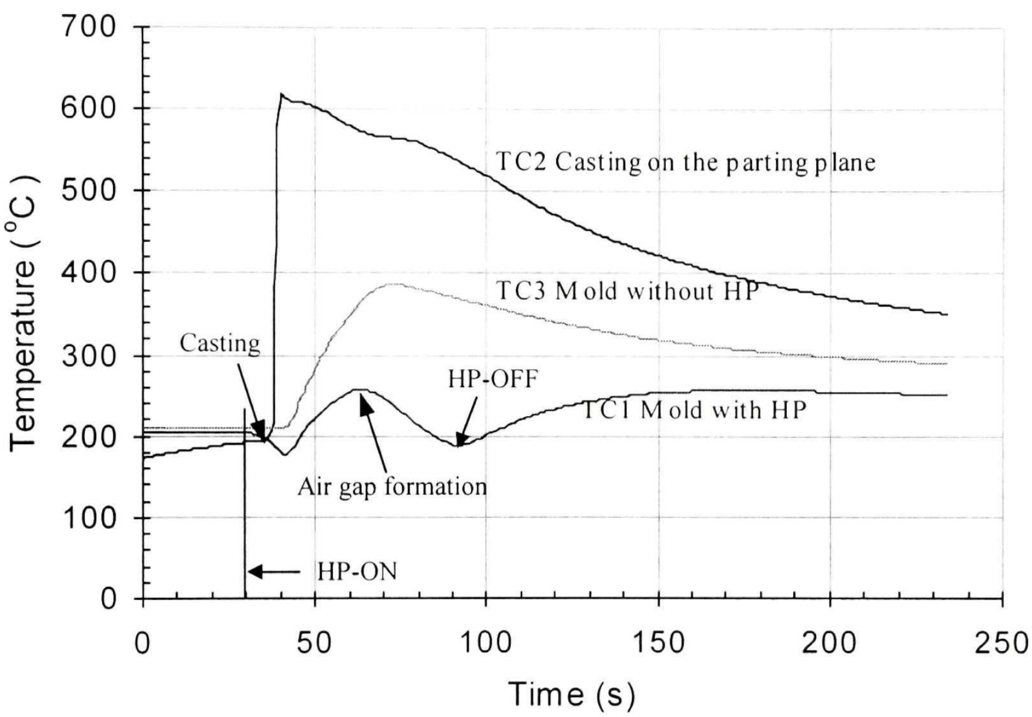


Figure 4.22 Cooling curves of the casting and mold. Flow of cooling air = 30SCFM, $T_{mold\ preheating}$= 200 °C, $T_{casting}$ = 730 °C, Heat Pipe 1 operating only

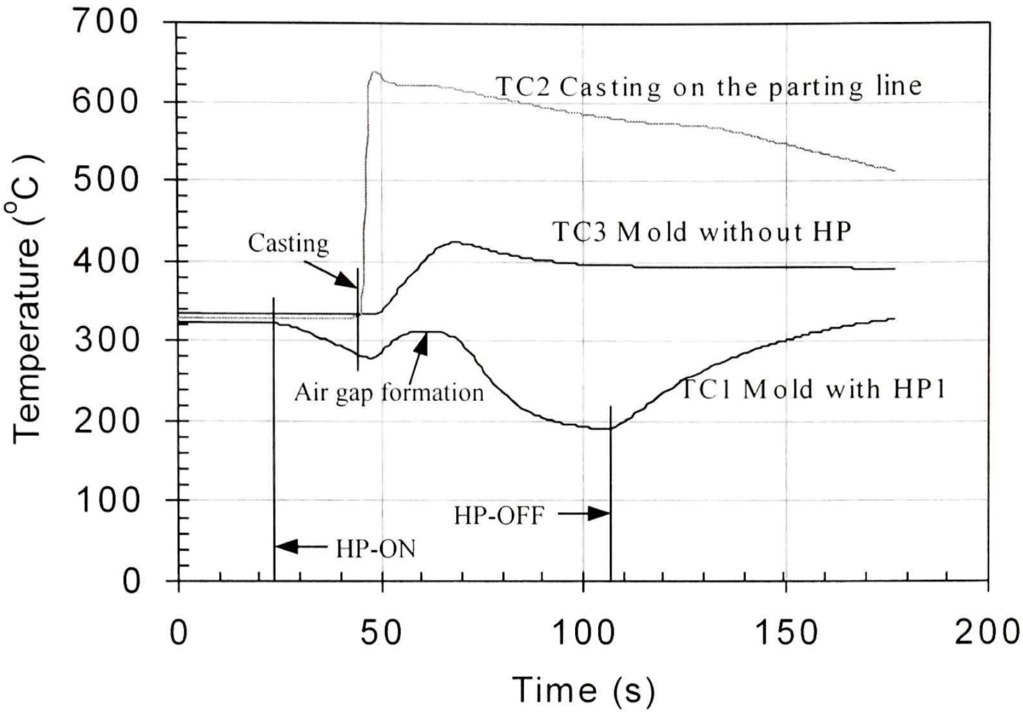


Figure 4.23 Temperature history of the casting and mold. Flow of cooling air = 30SCFM, $T_{mold\ preheating}$= 300 °C, $T_{casting}$ = 730 °C, Heat Pipe 1 operating only

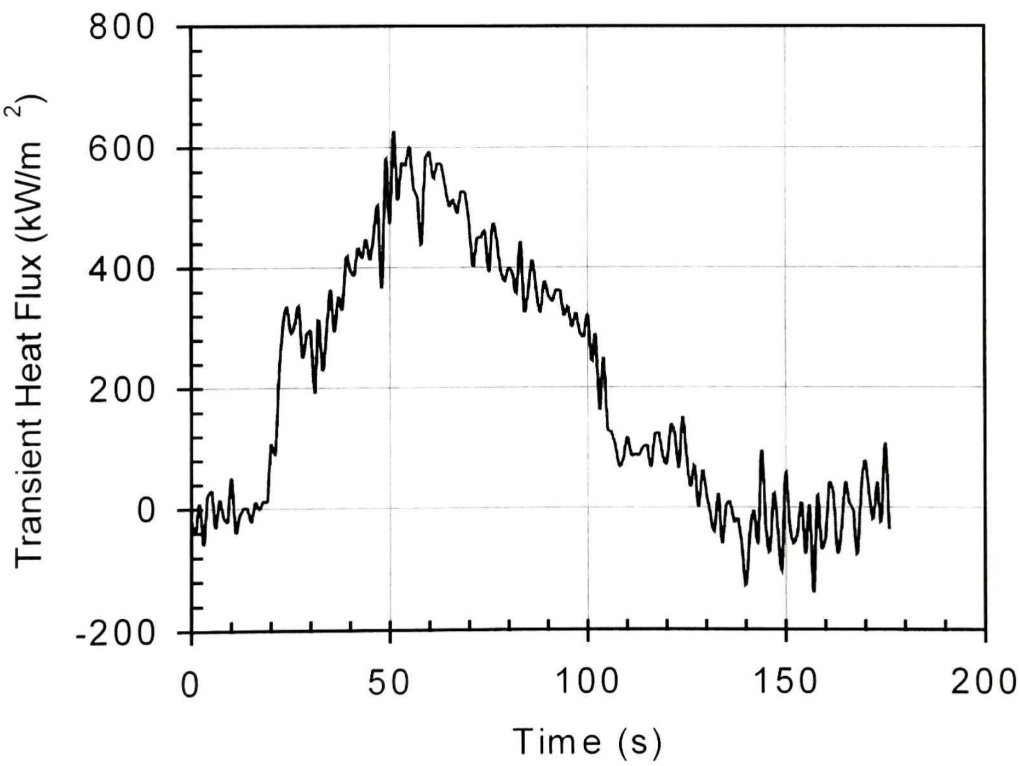


Figure 4.24 Transient heat flux on the entire heat pipe wall calculated from the data of Figure 4.23

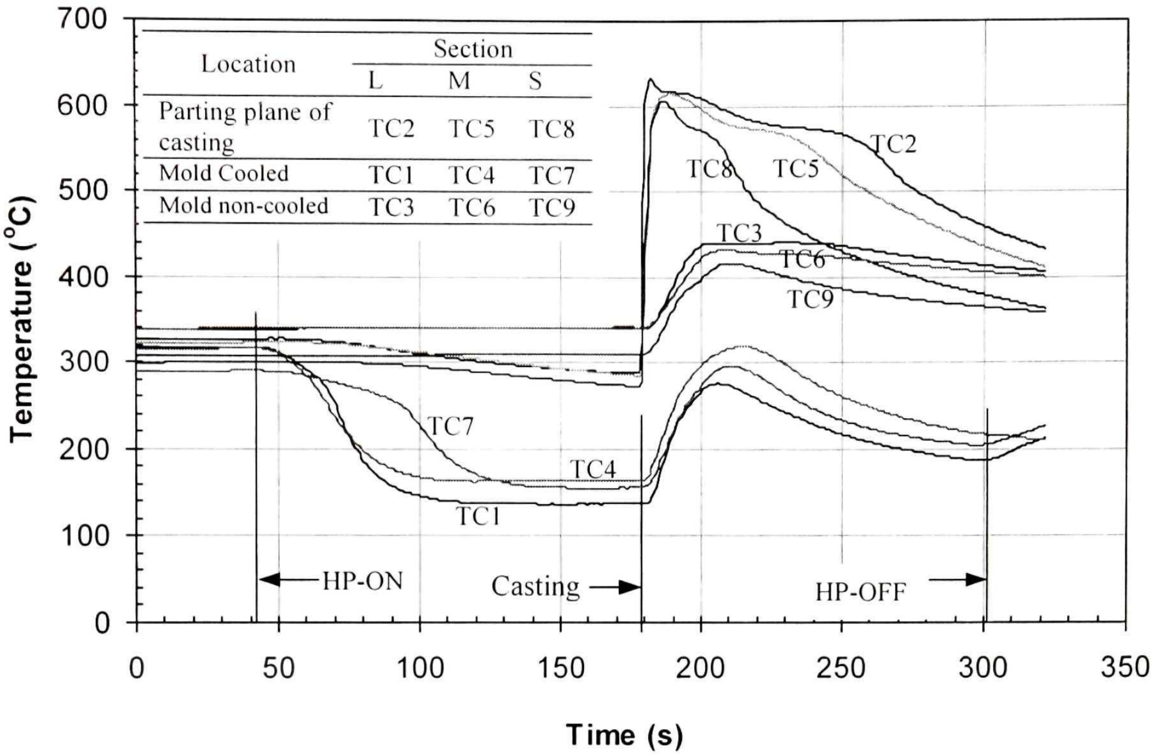


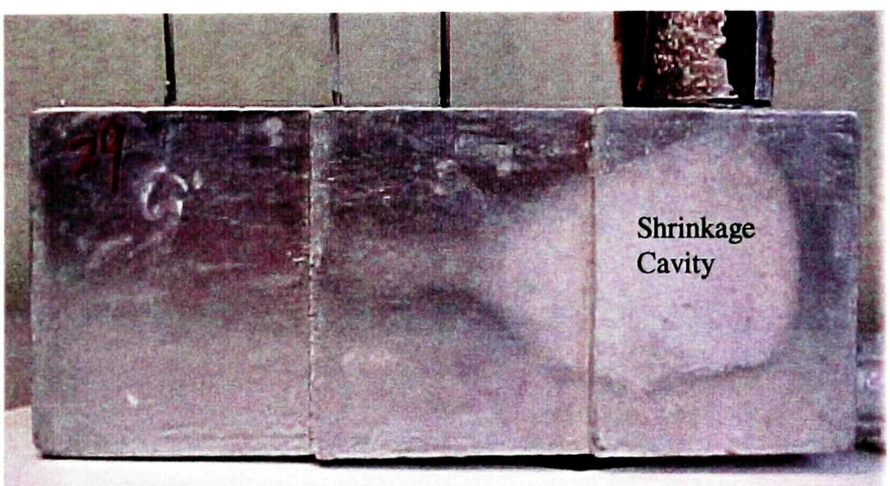
Figure 4.25 Temperature history of the casting and mold. $T_{mold\ preheating}$= 300 °C, $T_{casting}$ = 730 °C, three heat pipes operating

In Figures 4.22 and 4.23, we note that the temperature of the mold on the side with heat pipe cooling decreases after the initial increase when the metal is cast. This is due to the formation of an air gap at the interface between the casting and the mold. After the air gap forms, the intensity of heat transfer from the cast metal decreases while the heat pipe continues to extract heat from the mold. As a result, the temperature of the mold shows a marked drop. The formation of the air gap is complete when the temperature readings near the heat pipe reach a maximum as seen in Figures 4.22, 4.23 and 4.25.

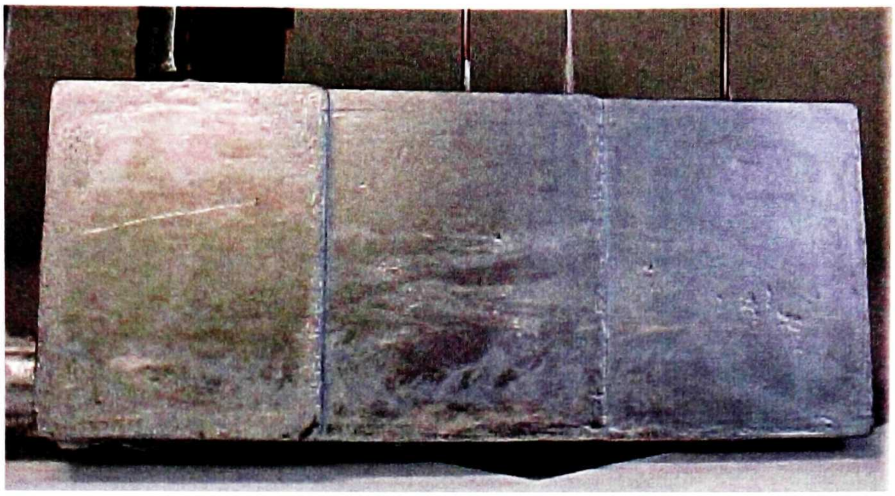
4.4.3.2 The Effect of Heat Pipe Cooling on Shrinkage Distribution

It is well known that the feeding behavior greatly affects shrinkage distribution in castings. Besides this factor, the temperature distributions in the mold and the casting during solidification also influence the shrinkage that forms. Typical surface profiles of the experimental casting are shown in Figure 4.26. It is evident that there is a large difference in the surface quality of the casting on the sides with and without cooling. When heat pipes were used in the present mold on one side, the casting solidified faster than at the other side due to the high cooling rates caused by the heat pipes. Solidification was directed to the non-cooled side, and as a result, shrinkage was generated on this side without heat pipe cooling, i.e. on the side which was the last to freeze. By heat pipe cooling, shrinkage in castings can be redistributed. If heat pipes are used to cool molds, it is clear that their effect on the entire feeding and riser system must be evaluated and taken into consideration in the design of the running and riser systems.

The progress of shrinkage redistribution by heat pipe cooling is clearly shown in Figure 4.26 and Figure 4.27. In the casting process, heat pipe cooling was employed from Section S to Section L. Directional solidification happened in the castings, from Section S to Section L, and from the side with heat pipe cooling to the side with no heat pipe cooling. As a result, the shrinkage was redistributed into the locations which solidified last.

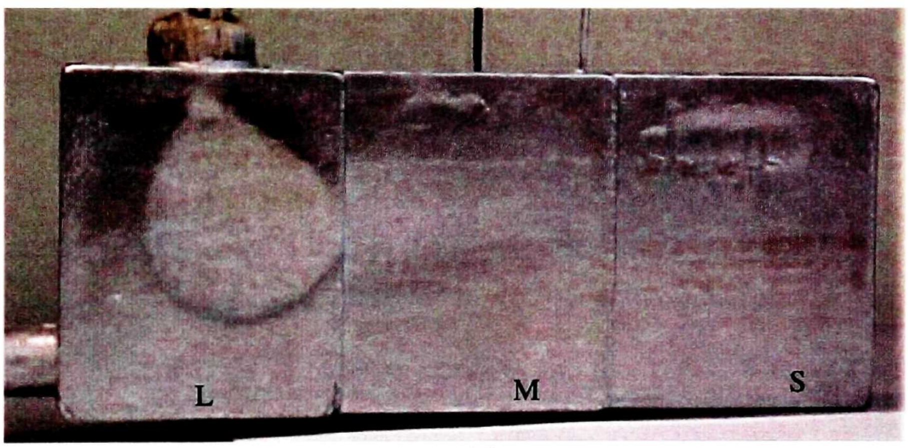


(a)

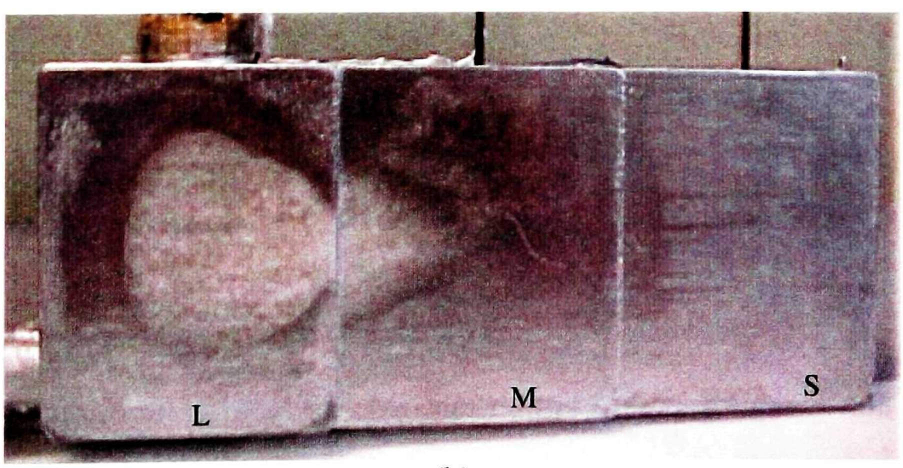


(b)

Figure 4.26 The surface profiles of the casting of A356 alloy cooled by three heat pipes: (a) Side without heat pipe cooling; (b) Side with heat pipe cooling



(a)



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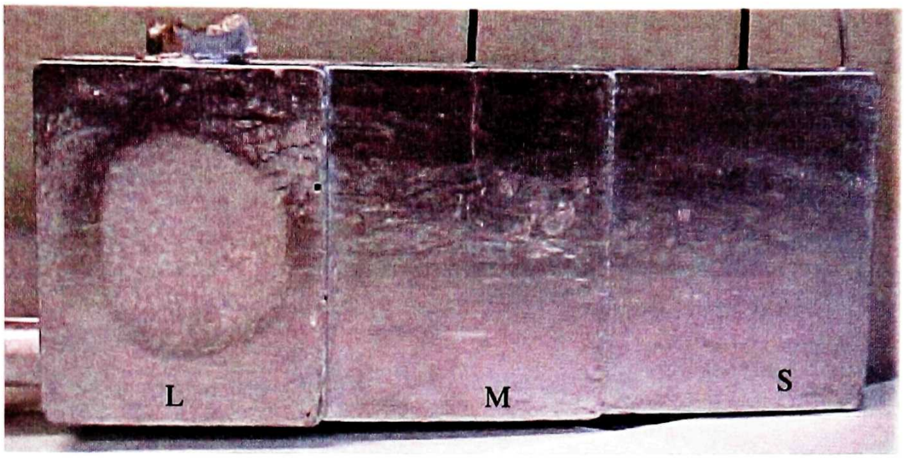


(c)

Figure 4.27 Effect of directional solidification by heat pipe cooling on the shrinkage distribution in the casting: (a) with no heat pipe cooling, (b) Section S cooled by the heat pipe, (c) Sections S and M cooled by the heat pipes

4.4.3.3 The Effect of Heat Pipe Cooling on Dendrite Arm Spacing (DAS) of A356 Alloy

Nine locations shown in Figure 4.28 of the step casting were selected for microstructure analysis. A casting with no heat pipe cooling was used as a reference in order to evaluate the effect of heat pipe cooling on the DAS. The DAS measurements were made by the line intercept method, which was performed using an optical microscope with digital image analysis system (CLEMEX Vision ^{TM}).

The micrographs of the samples from Section L are presented in Figure 4.29 and Figure 4.30. Figure 4.29 presents the DAS of A356 alloy with no heat pipe cooling while the results of the DAS with heat pipe cooling are shown in Figure 4.30. The dendrite arm spacing (DAS) measurements at the nine locations for each sample are summarized in Table 4.1.

As the cooling rate is a function of location, and it is well known that the DAS is a function of cooling rate as described in Equation (1-3), the DAS decreases at all points when the heat pipes are operating. The DAS at Point C with heat pipe cooling is 27±2 μm which is much smaller than that point without heat pipe cooling (46±7μm). This corresponds to a 41% decrease in DAS. By comparing the DAS values in Figures 4.29 and 4.30, and Table 4.1, it is seen that heat pipe cooling affects the whole cross sections of the casting, from Point C to Point A, even though the thickness of Section L is 40 mm.

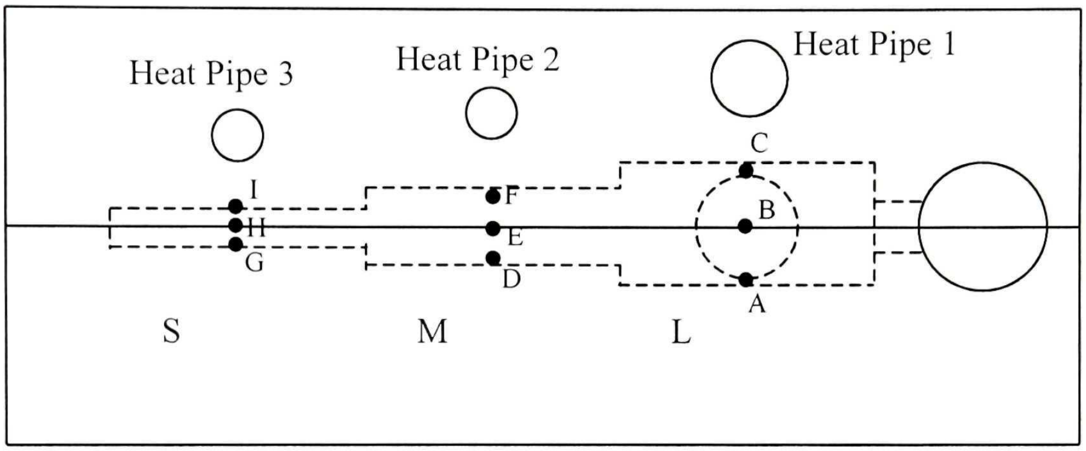
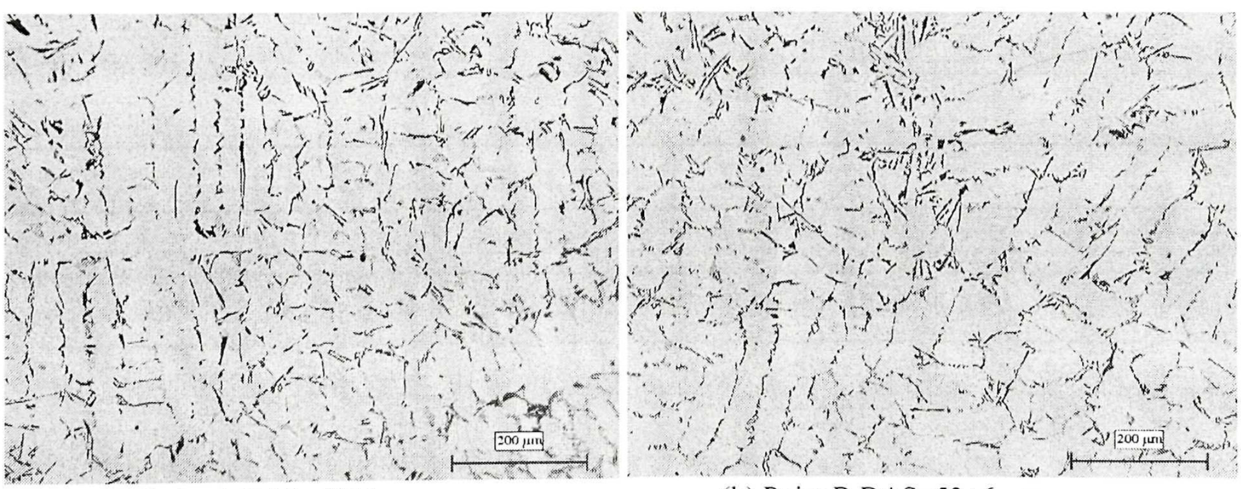
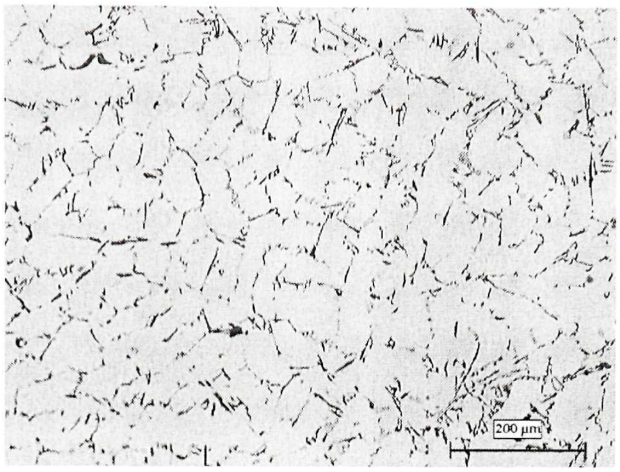


Figure 4.28 The selected locations for microstructure analysis



(a) Point A DAS=42±4 μm (b) Point B DAS=53±6 μm



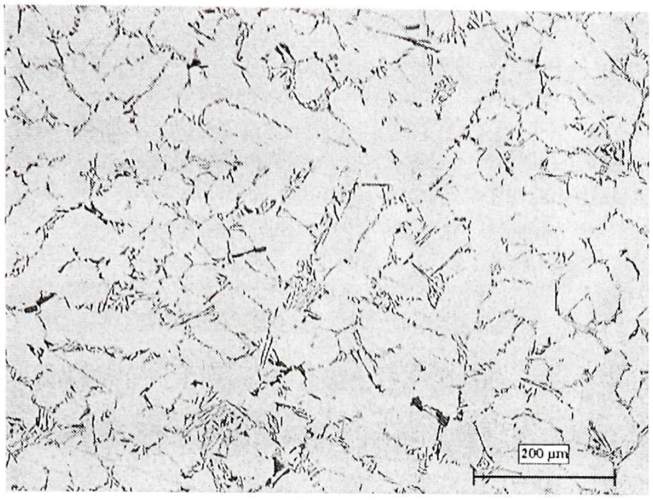
Alloy A356
T_{mold}= 300°C

(c) Point C DAS=46±7 μm

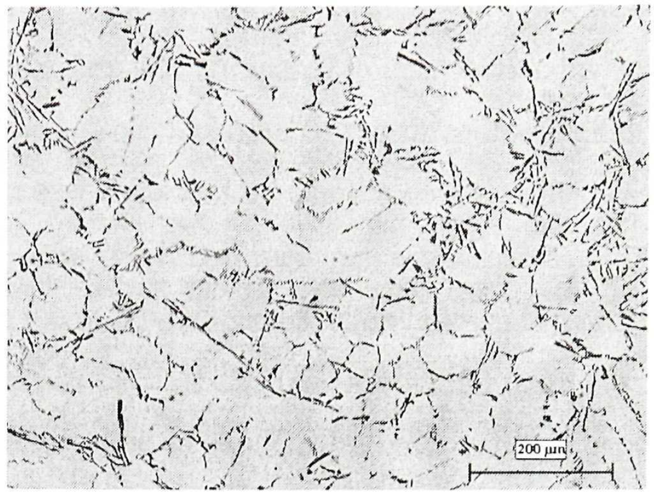
Figure 4.29 Micrographs of the permanent mold casting of A356 alloy with no heat pipe cooling

Table 4.1 Effect of heat pipe cooling on DAS of A356 alloy

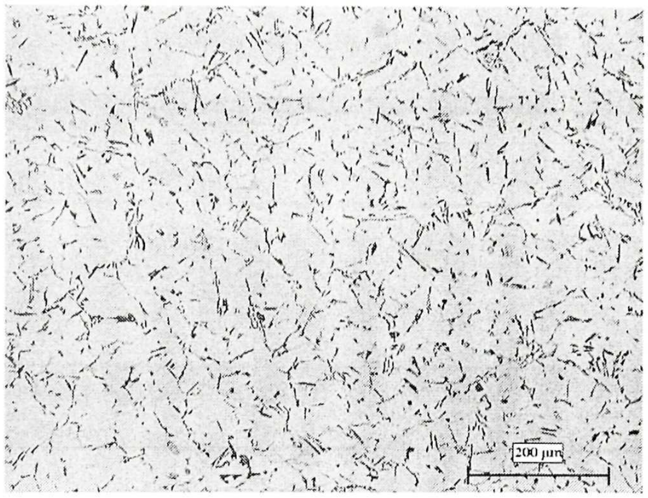
Casting	Cooled Section	Section								
		S			M			L		
		HP (I)	Middle (H)	No HP (G)	HP (F)	Middle (E)	No HP (D)	HP (C)	Middle (B)	No HP (A)
1(Ref)	None	31±5	38±5	32±4	41±3	55±8	39±3	46±7	53±6	42±4
2	S, M, L	25±2	34±4	30±2	28±2	34±3	33±3	27±2	41±5	39±4
Decrease of DAS		21%	11%	6%	32%	38%	15%	41%	23%	7%



(a) Point A DAS=39±4 μm



(b) Point B DAS=41±5 μm



Alloy A356
Tmold= 300 °C

(c) Point C DAS=27±2 μm

Figure 4.30 Micrographs of the permanent mold casting of A356 alloy with heat pipe cooling

4.4.3.4 The Effect of Heat Pipe Cooling on Casting Solidification Time with Different Mold Coatings

In order to study the effect of heat pipe cooling on casting solidification under different boundry conditions, three different mold coatings were used: DYCOTE 11, DYCOTE 14-ESS and DYCOTE 6 from FOSECO. The properties of the permanent mold coating are listed in Table 4.2 These coatings are respectively conductive, medium insulation and high insulation specially used for permanent mold casting. Castings were produced with the two coatings, and the thermal data was compared to that obtained when the conductive coating, DYCOTE 11, was used. The thickness of the three coatings on the surface of the mold cavity was controlled and measured by using a coating thickness gauge (Elcometer 456). The average thickess was confined to around 100 μm. Solidification time at the locations B, E, H in the middle of each section (shown in Figure 4.28) was obtained from the thermocouple outputs (TC2, TC5, TC8 shown in Figure 4.8). The effect of different coatings on solidification time of A356 alloy with no heat pipe cooling is shown in Figure 4.31, while the effect of heat pipe cooling on solidification time of A356 alloy with different coatings are shown in Figure 4.32.

Table 4.2 The Properties of Permanent Mold Coatings

Coating Type	Insulation	Durability	Texture	Characteristics	DYCOTE: Water Dilution
DYCOTE 11	Very Low	Low	Smooth	Release	1:4
DYCOTE 14-ESS	Medium	High	Smooth	Low Pressure Permanent Mold Coating	1:3
DYCOTE 6	Very High	Medium	Medium	Riser & Gates	2:3

With heat pipe cooling, the local solidification time of A356 alloy decreased considerably. The cooling rate is a function of distance from the location to the heat pipe, and consequently solidification time in the middle of Section S decreased much more than that in the middle of Sections L and M. The conductivity of the coatings influences the heat transfer at the interface between the casting and the mold. Although the solidification time is reduced when the heat pipes are operating, the percentage change in freezing time is approximately the same for each type of coating with the exception of the thinest Section S (Refer to Table 4.3). In this section, the thermocouple is closer to Heat Pipe 3 and the effect of differences in the coating is diminished somewhat.

Table 4.3 The effect of heat pipe cooling on solidification time of A356 alloy with different coatings

Casting Trial #	Coating	Cooled Sections	Decrease of Solidification Time		
			Point B	Point E	Point H
4	Conductive	S, M, L	26%	32%	41%
5	Medium insulation	S, M, L	25%	31%	32%
6	High insulation	S, M, L	26%	34%	30%

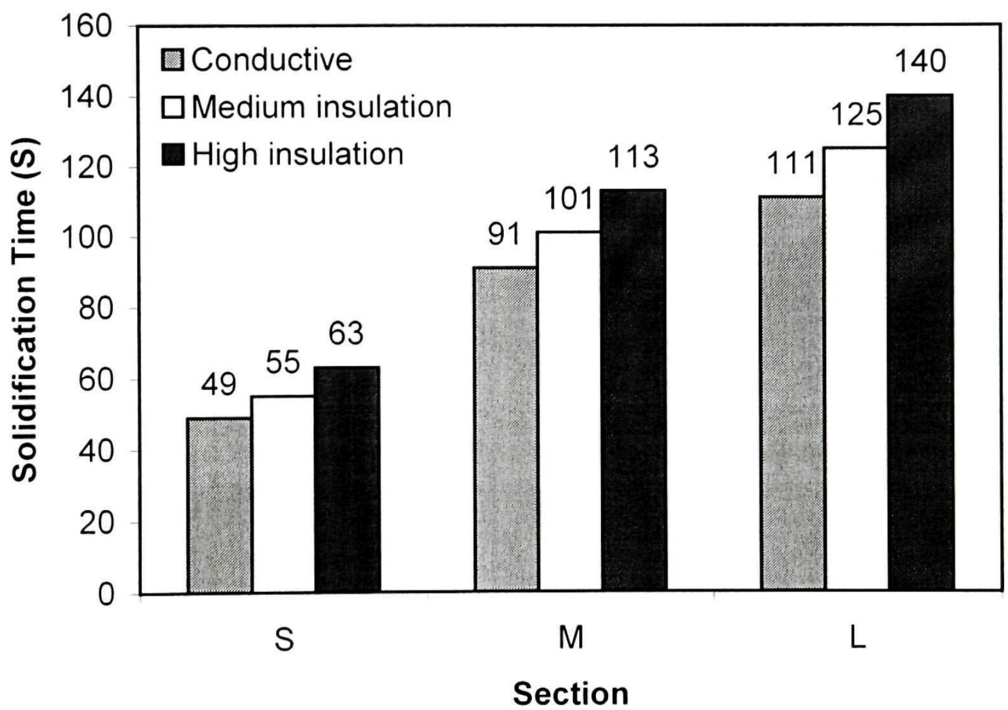


Figure 4.31 Effect of different coatings on solidification time of A356 alloy with no heat pipe cooling

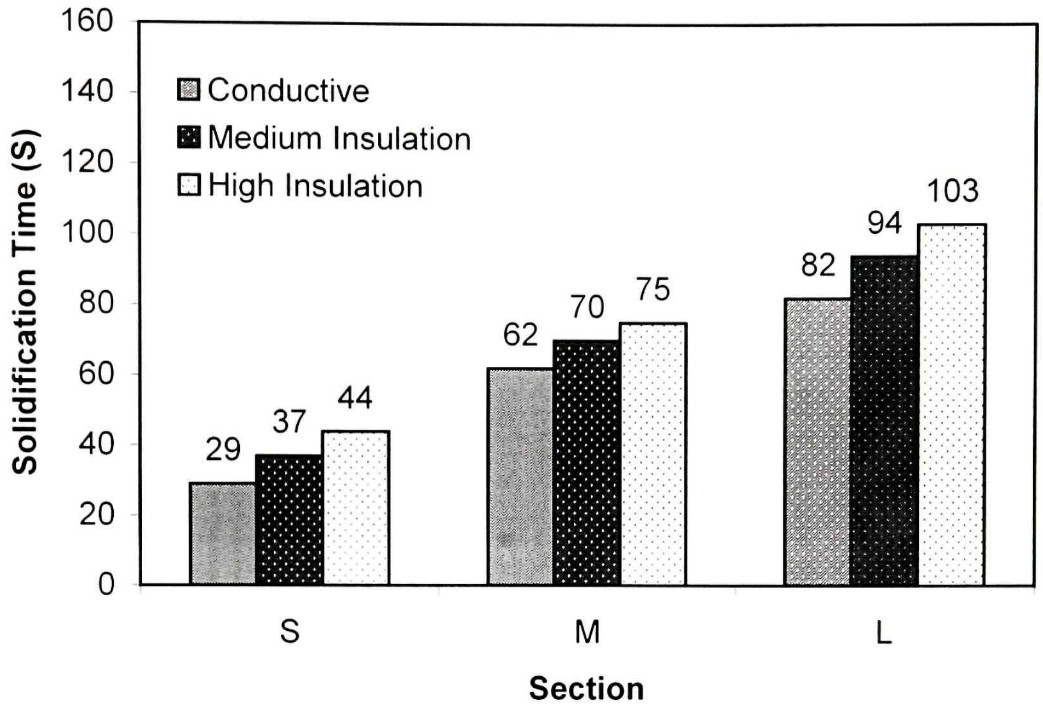


Figure 4.32 Effect of Heat Pipe Cooling on Casting Solidification Time with Different Coatings

Chapter 5 Application of Controllable Heat Pipe Cooling During the Low Pressure Die Casting of Aluminum Alloys

5.1 Introduction

The potential for aluminum is apparently unlimited since it is the most abundant element in the earth's crust. Particularly in the automobile and aerospace industries, the use of aluminum products has increased substantially in the past decade because of the appealing properties of aluminum. As mentioned in Chapter 2, gravity permanent mold casting is suitable for high volume production of small, simple castings with fairly uniform wall thickness and limited complexity. With the permanent mold casting process, it is sometimes difficult to produce sections with small thicknesses because of the low hydrostatic pressure of the liquid metal. The low pressure die casting process is a well established technique, which can produce more complex aluminum components with high quality and high integrity. The low pressure casting process is ideally suited to high strength automotive and aerospace components as well as other products. Improving the castability of small thickness sections will increase the viability of this process for other applications.

As shown in Figure 5.1, the process involves the introduction of the molten aluminum alloy into the mold cavity through a vertical gating system connected to a pressure sealed holding furnace by applying low pressure on the surface of the molten bath. The casting solidifies progressively from the mold towards the gating system. When the solidification of the casting is complete, the pressure above the surface of the molten aluminum is released. Then the mold is opened and the casting is ejected. The advantages of the process compared to sand casting are better metallurgical properties, improved surface finish, closer tolerances, higher productivity and more economical production (76). In order to obtain sound castings, like all casting processes, a number of processing parameters must be controlled precisely. The temperature distribution in the mold and the casting, and casting solidification are two of the more critical parameters in the control of this process.

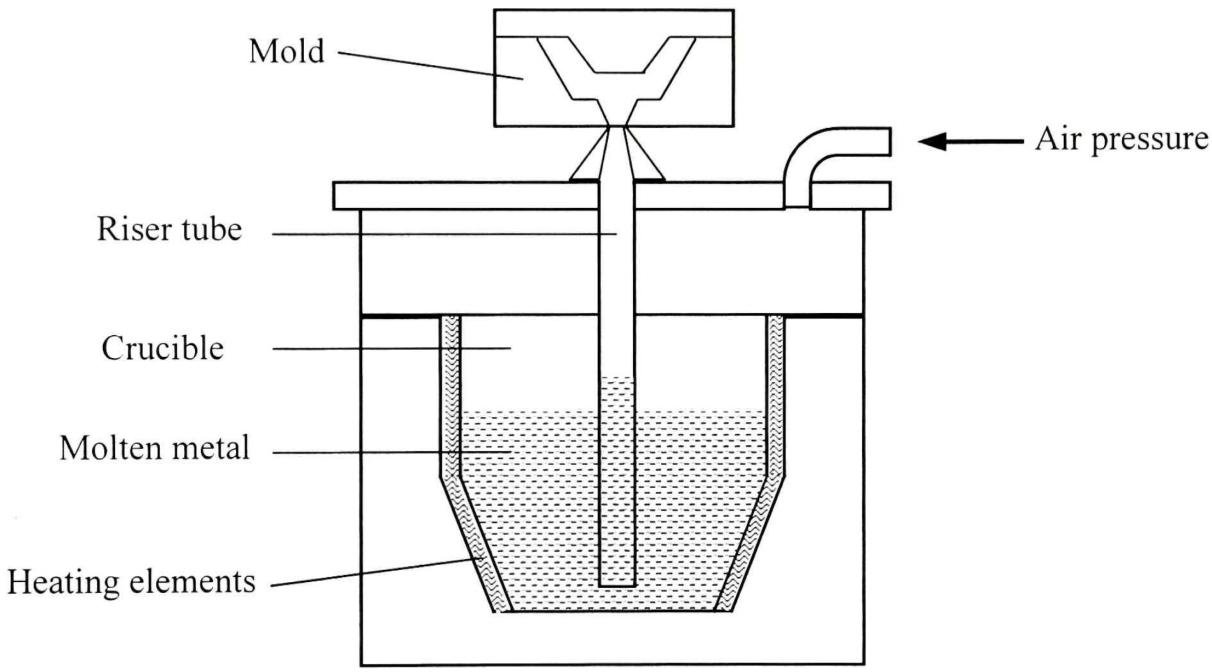


Figure 5.1 Schematic of low pressure die casting process

Adequate thermal control is essential in the low pressure die casting process (77). With the correct temperature distribution within a mold and a casting, solidification takes place progressively towards feeders and running systems, which in turn reduces shrinkage and porosity, or other solidification related defects. The solidification rates are increased so as to obtain finer grain sizes and microstructures and thus improve mechanical properties. In addition, thermal stresses in the molds are reduced by controlling the internal temperature gradients, and the service life of the molds is thereby lengthened.

To achieve the proper temperature profiles of the mold and the casting in low pressure die casting, cooling channels are often incorporated into the mold to generate the desired solidification sequence. The current technologies for controlled thermal behavior in the low pressure die casting process are air or water cooling passages and chill inserts. As discussed in Chapter 2, each of these cooling methods presents certain disadvantages, and none offer optimum cooling control.

After the successful demonstration and investigation of controlled cooling in an experimental permanent mold at McGill University, Grenville Castings Ltd, Smiths Falls, Ontario, expressed a desire to evaluate this new flexible heat pipe cooling system on an industrial scale low pressure die casting machine. In this study, a novel controllable mold cooling – heat pipe technology has been developed to avoid many of the existing problems associated with traditional cooling methods in the low pressure die casting process. Preliminary and industrial tests of the heat pipe cooling system have been performed. This chapter presents data on the cooling rates obtained by using the novel heat pipe cooling system, and traditional air and water cooling methods, as well as microstructures and measurements of the dendrite arm spacing.

5.2 Basic Configuration and Features of a New Version Flexible Heat Pipe

A novel water-based heat pipe has been developed which can provide sufficient heat extraction in the cooling of permanent mold castings of aluminum alloys (65, 74, 75). This is known as the McGill Heat Pipe. Normally, the space around the mold installed on a low pressure die casting machine is very limited, and it is often very difficult to install the heat pipe in the specific desired location in the mold. Based on these considerations, a new version, flexible heat pipe has been developed for the low pressure die casting process, shown in Figure 5.2 (78). In the new design, flexible connections are applied between the evaporator and the condenser of the heat pipe. The advantages of the flexible heat pipe design facilitate installation into restricted areas and simplify access so as to improve the feasibility of the heat pipe application for the industrial casting process.

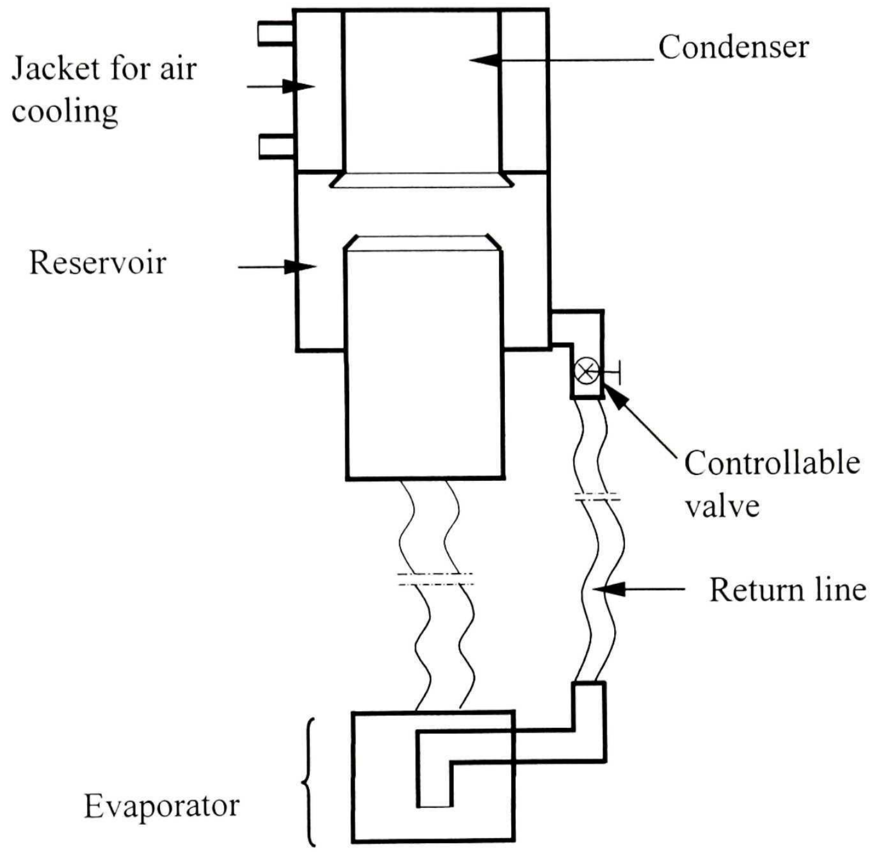
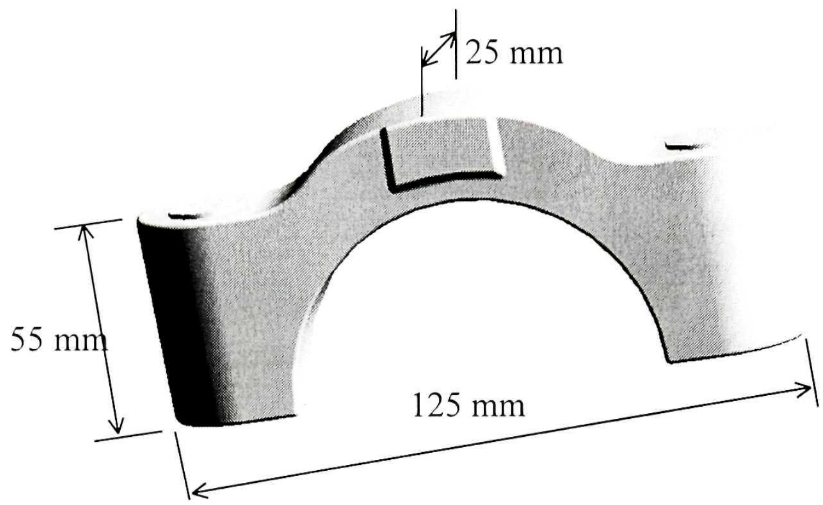


Figure 5.2 Basic configuration of the flexible heat pipe

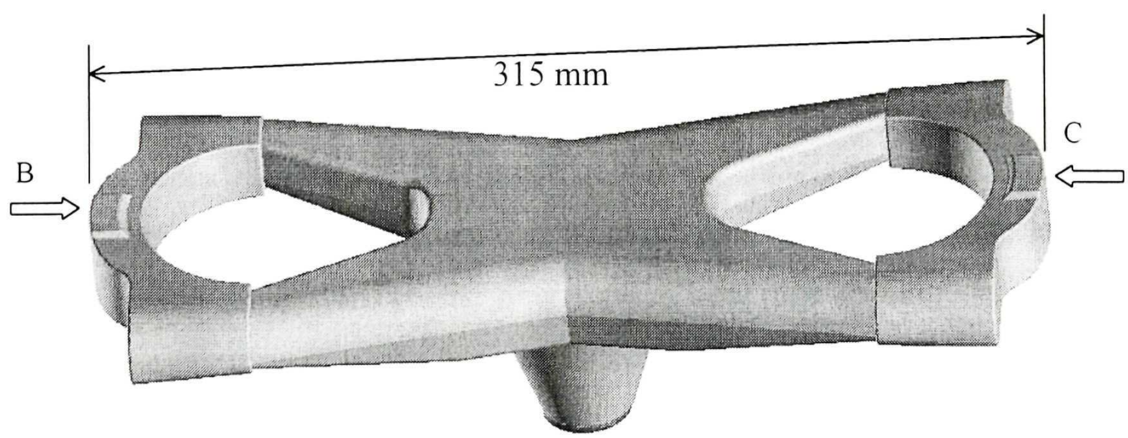
As shown in Figure 5.2, the design and concept of the other components of the flexible heat pipe are the same as the McGill Heat Pipe used in the cooling of permanent mold castings of aluminum alloys in the laboratory. Besides the features of the heat pipe discussed in Chapters 3 and 4, the new version McGill Heat Pipe has flexible connections between the evaporator and the condenser.

5.3 Experimental Setups and Procedures

The experimental program featured both preliminary tests in the laboratory and industrial trials at the commercial foundry. A full scale industrial mold was selected to cast a commercial aluminum bearing cup (shown in Figure 5.3) by low pressure die casting. The configuration of the bottom die block is shown in Figure 5.4. The die has two cavities to produce two castings with each shot. In the original design of the mold, water cooling circuits were installed in each moving slide of the mold in order to obtain finer grain sizes and microstructures, and thus improve mechanical properties at locations B and C of castings.

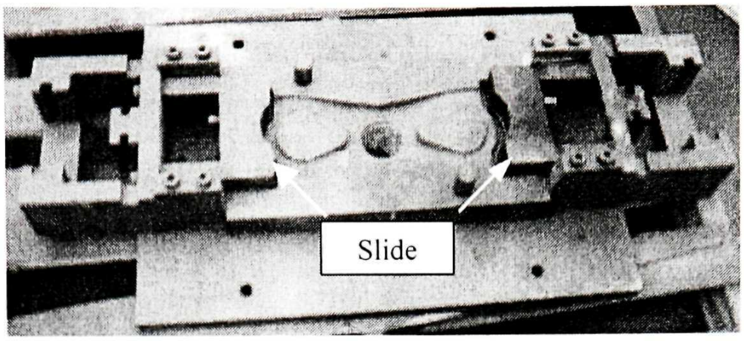


(a) The casting of bearing cup

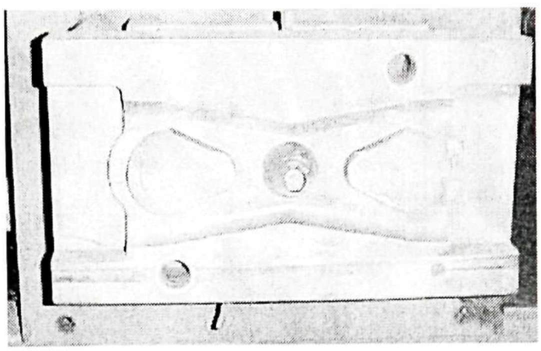


(b) The castings of bearing cups with gating system

Figure 5.3 The castings of bearing cups



(a) The bottom die block with the slides installed



(b) The bottom die block without the slides

Figure 5.4 Configuration of the bottom die block

5.3.1 Design of Cooling Control for the Low Pressure Die Casting with a Heat Pipe

The water cooling in one of the slides of the mold corresponding to Location C of the casting was replaced with the heat pipe cooling system. Based on the investigation of controlled cooling for permanent mold castings of aluminum alloys in the laboratory, the exact design and dimensions of the new version heat pipe cooling system for the low pressure die casting were worked out as shown in Figure 5.5. In order to avoid contact thermal resistance between the heat pipe and the mold wall, and to improve heat transfer between the heat pipe and the mold, the heat pipe was made as part of the mold. A hole was drilled in the middle of the slide as shown in Figure 5.6, and the extension was attached to the hole such that the hole constituted the evaporator and the extension was connected to the condenser by flexible steel hoses. The configuration of the heat pipe cooling system for the mold in the low pressure die casting is shown in Figure 5.7.

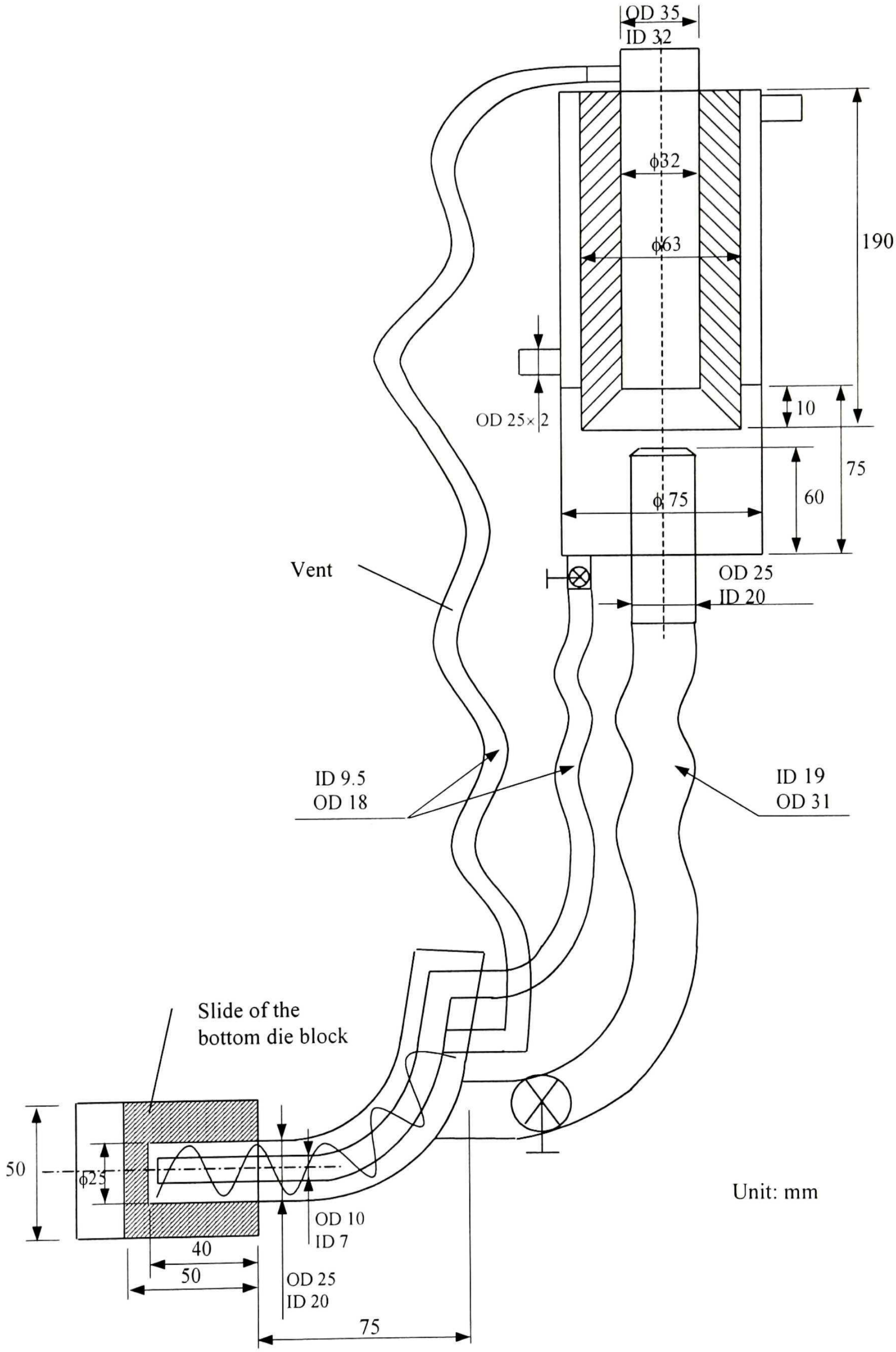
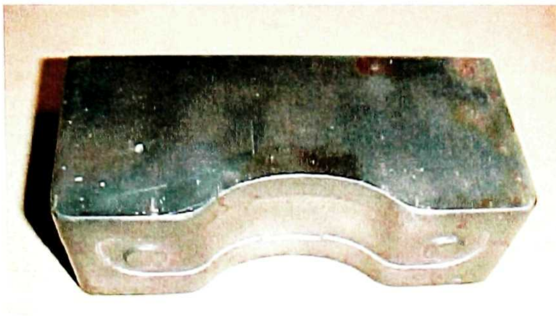
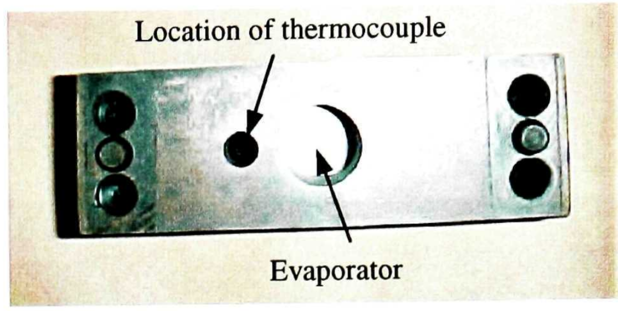


Figure 5.5 Design of flexible heat pipe cooling system for the low pressure die casting

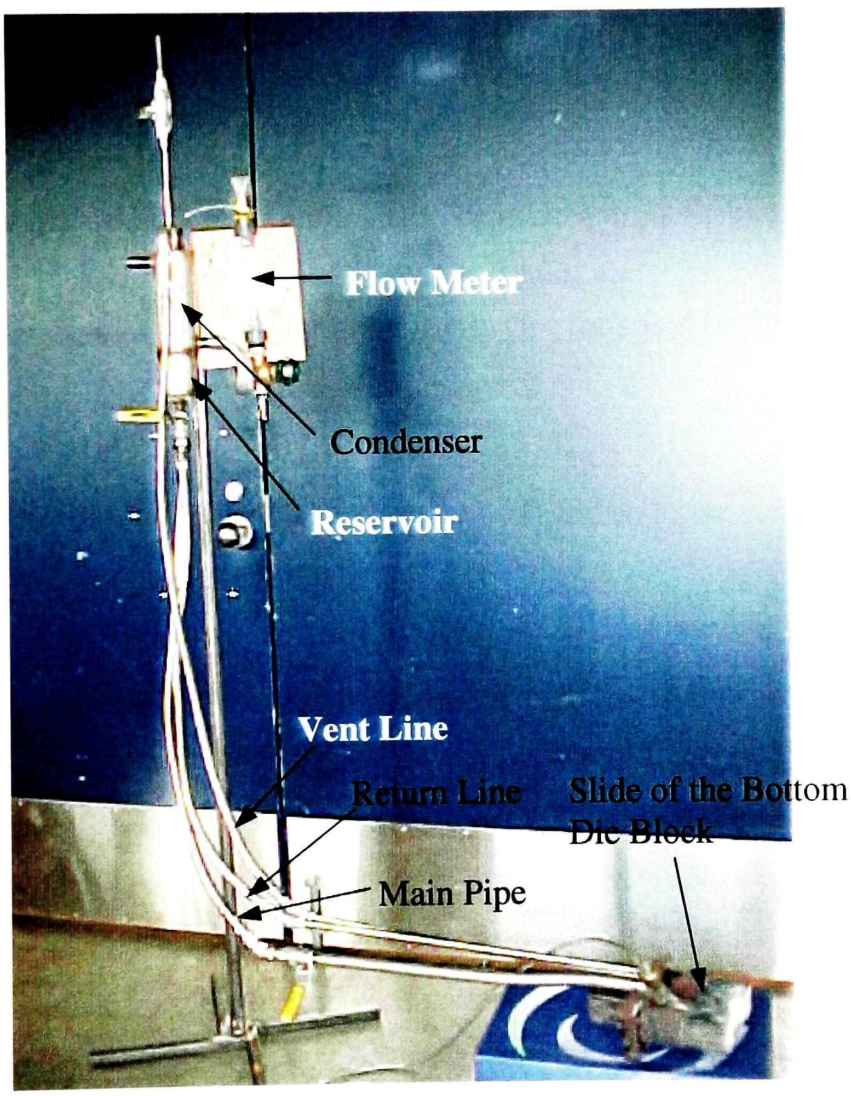


(a) The slide of the mold

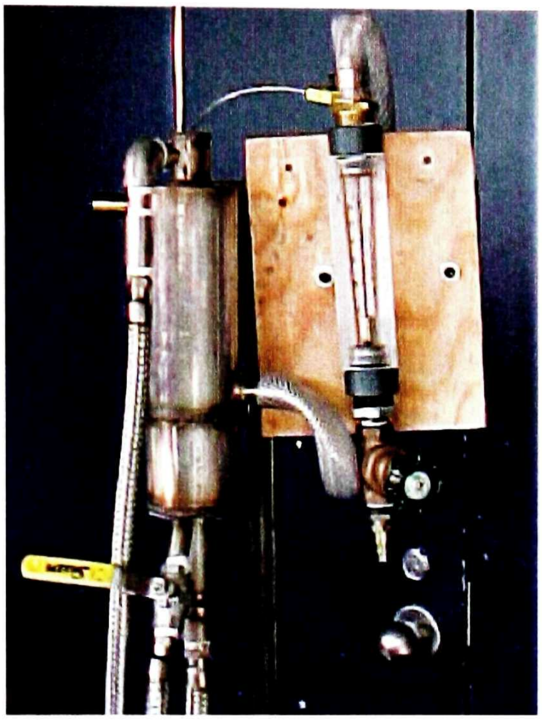


(b) Locations of the evaporator and the thermocouple

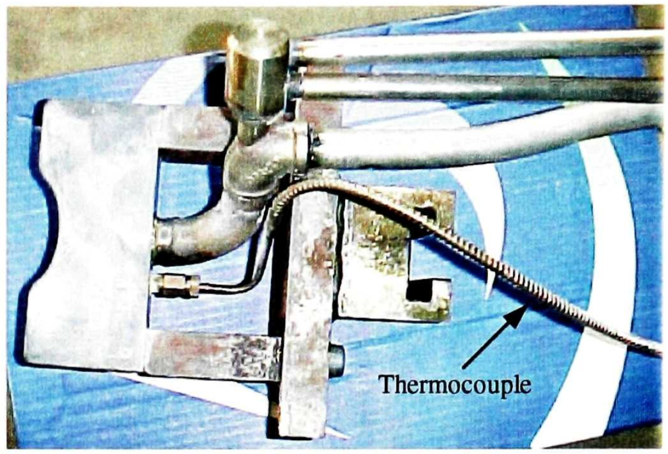
Figure 5.6 The slide of the mold with built-in evaporator



(a) Setup of heat pipe cooling for the slide



(b) Condenser attached cooling air circuit



(c) The slide with built-in evaporator section

Figure 5.7 Configuration of the novel cooling system for the mold in the low pressure die casting

5.3.2 Laboratory Setup and Preliminary Tests

Before the industrial trials, the heat pipe cooling system for the low pressure die casting was tested and debugged in the laboratory to make sure that it would satisfy the required performance characteristics. The slide of the mold (evaporator section) was heated by inserting it into an electric furnace at a temperature of 700 ^{o}C, and the condenser was hung up on a stand. The laboratory setup is shown in Figure 5.8. A thermocouple was inserted into the slide system, and temperature histories of the mold, the heat pipe and cooling air were logged by a data acquisition unit.

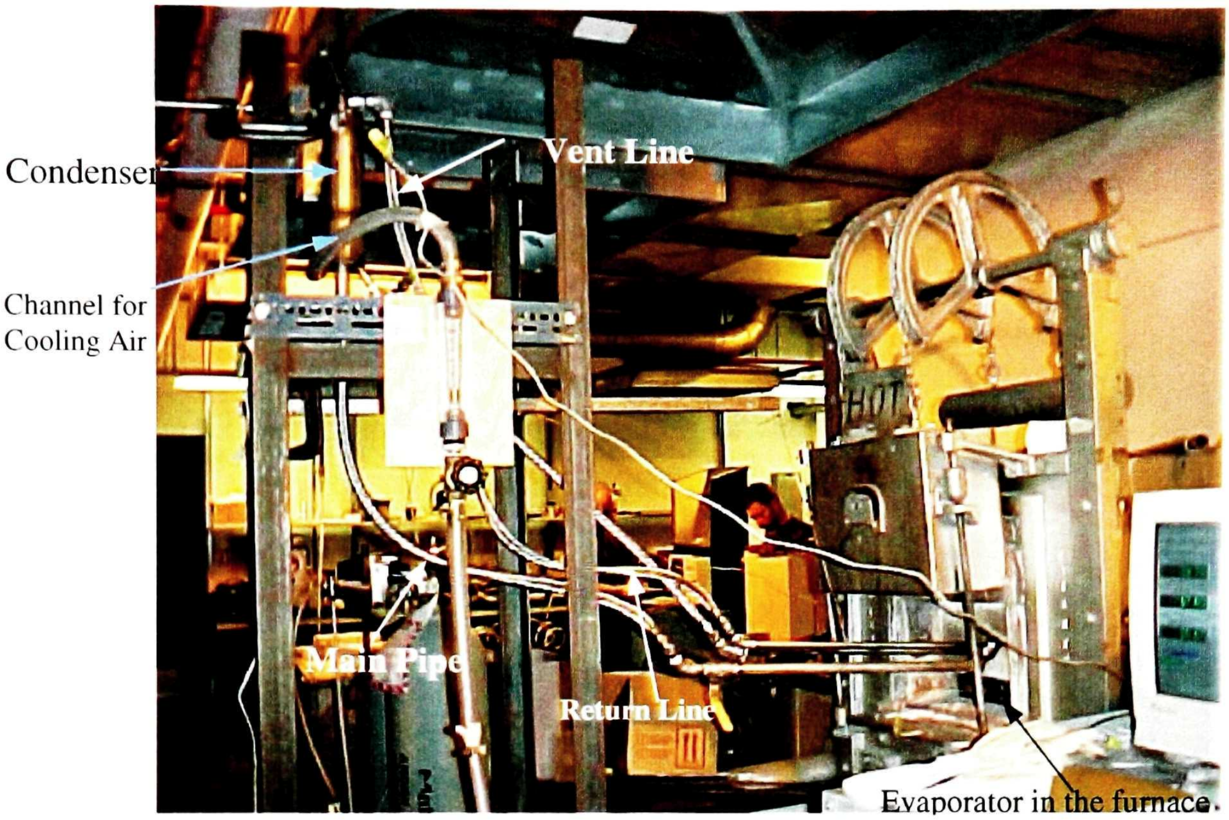
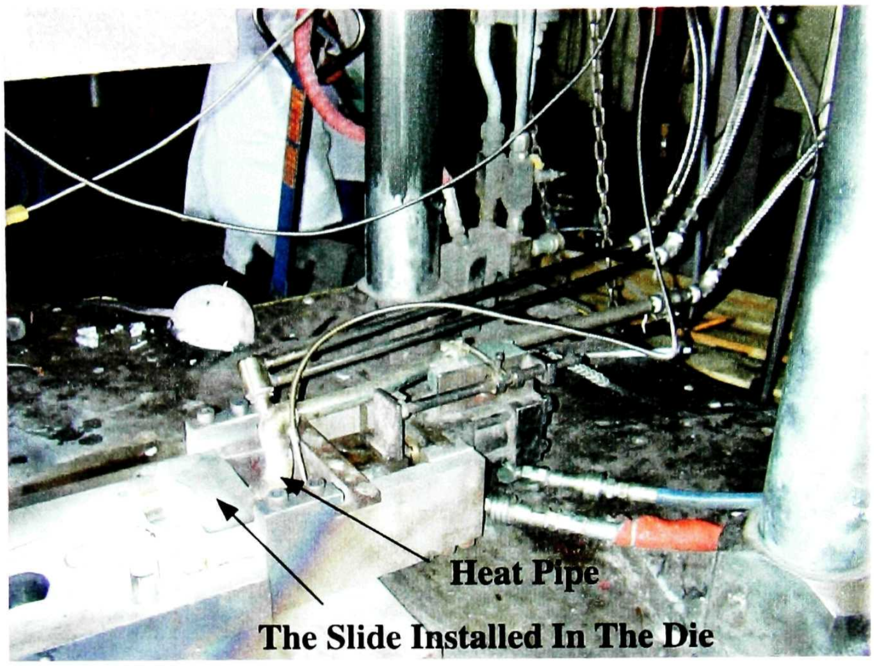


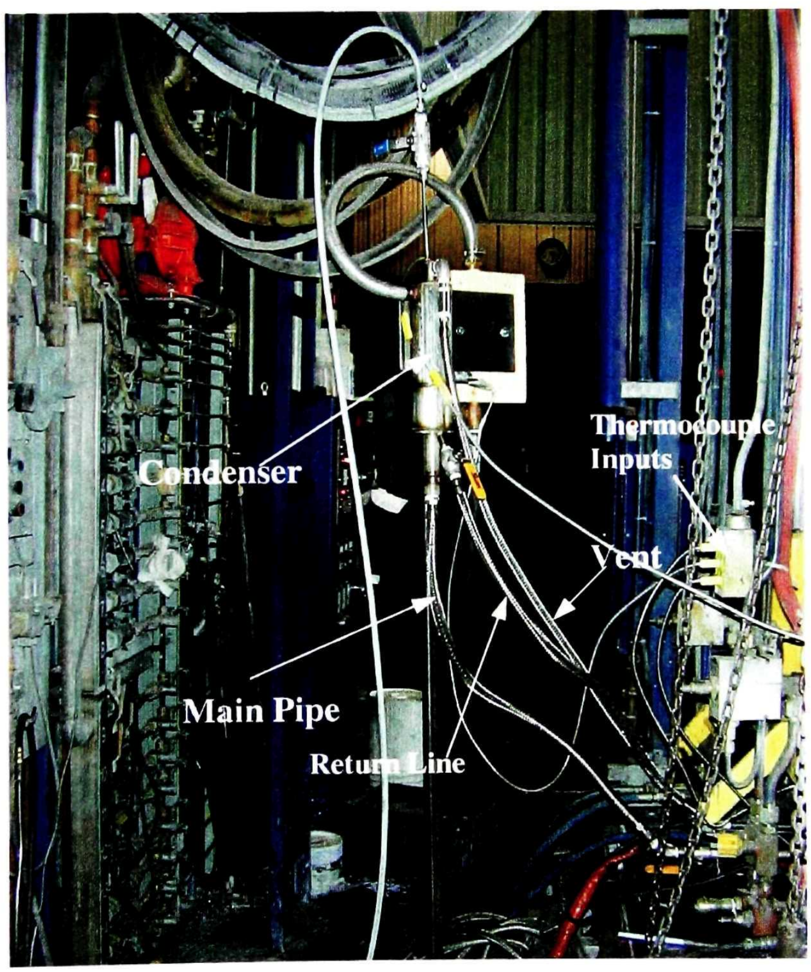
Figure 5.8 Laboratory setup for preliminary tests

5.3.3 Industrial Setup and Experimental Procedures

Industrial experiments were performed in a commercial foundry. As shown in Figure 5.4, the mold had two cavities. During the low pressure die casting process, one casting was cooled by water or air at location B, while the other was cooled by the heat pipe at location C. The design of the bottom mold block is centrally symmetric to allow evaluation of the effect of the three different cooling methods on the mold and the castings. The industrial setup is shown in Figure 5.9. All experiments were conducted with 0.016% strontium modified A356 alloy, which is currently used to produce the bearing cups. During the low pressure die casting process, four thermocouples were installed in the mold blocks. The locations of the thermocouples are shown in Figure 5.10. The other two thermocouples were used to measure the temperatures of the heat pipe and cooling air in order to monitor the working status of the heat pipe.



(a)



(b)

Figure 5.9 Setup of the heat pipe on the low pressure die casting machine

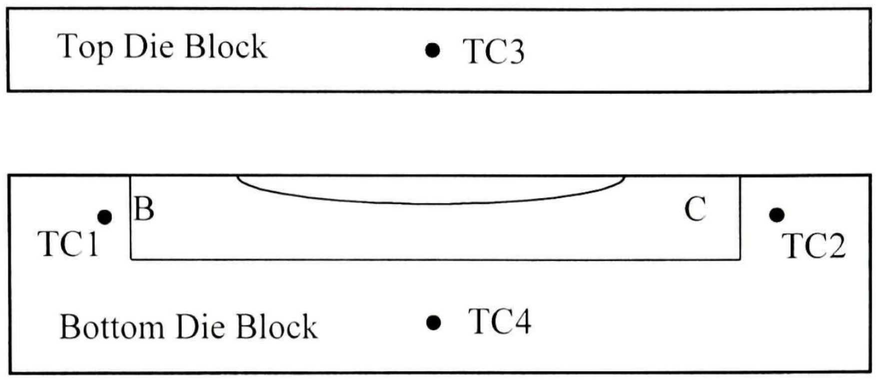


Figure 5.10 Locations of thermocouples in the die blocks

5.4 Results and Discussion

5.4.1 Results of Preliminary Experiments of Cooling Control by Heat Pipe for the Low Pressure Die Casting

In order to show the capability of the heat pipe cooling system for thermal management of the mold in the low pressure die casting process, the results for two preliminary tests are reported, for the cases when the slide block of the mold was preheated to temperatures of about 350 and 420 ^{o}C. The results are shown in Figure 5.11 and Figure 5.12 respectively. The location of thermocouple TC2 for temperature recording as indicated in Figure 5.6 (b), Figure 5.7 (c) and Figure 5.10 is about 1 cm away from the heat pipe. From the temperature-time plot, we can see that the temperature of the slide decreased rapidly when the heat pipe was switched on even though the furnace was continuously operating at 700 ^{o}C. The heat pipe extracted all the incoming heat from the furnace, as well as the heat stored in the slide. When the heat pipe was switched off, the slide reheated rapidly.

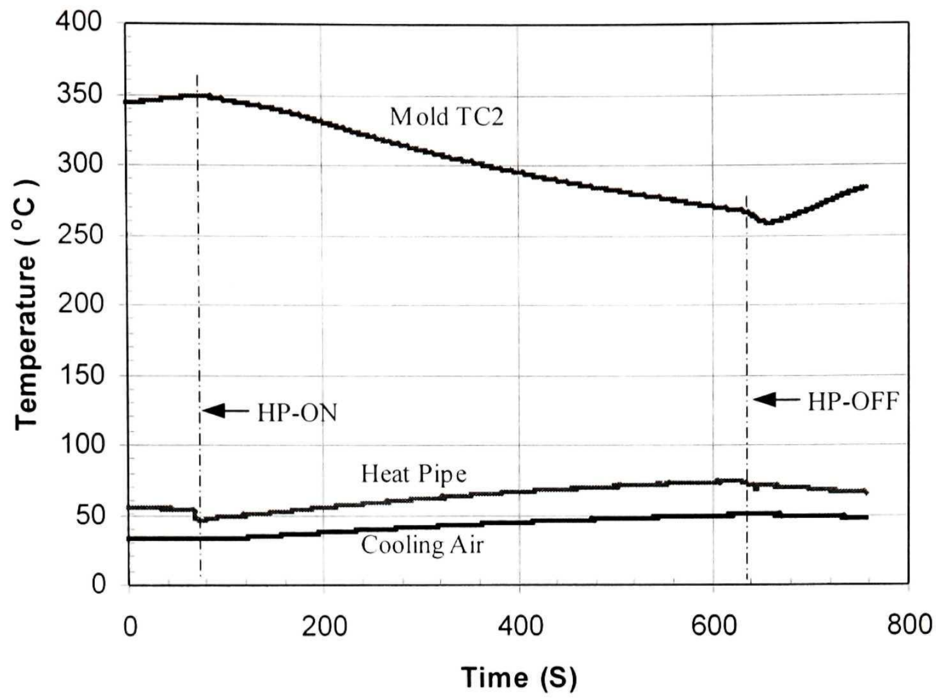


Figure 5.11 Mold cooling using heat pipe with no casting: Flow of cooling air = 20SCFM, $T_{mold\ preheating}$= 350 °C

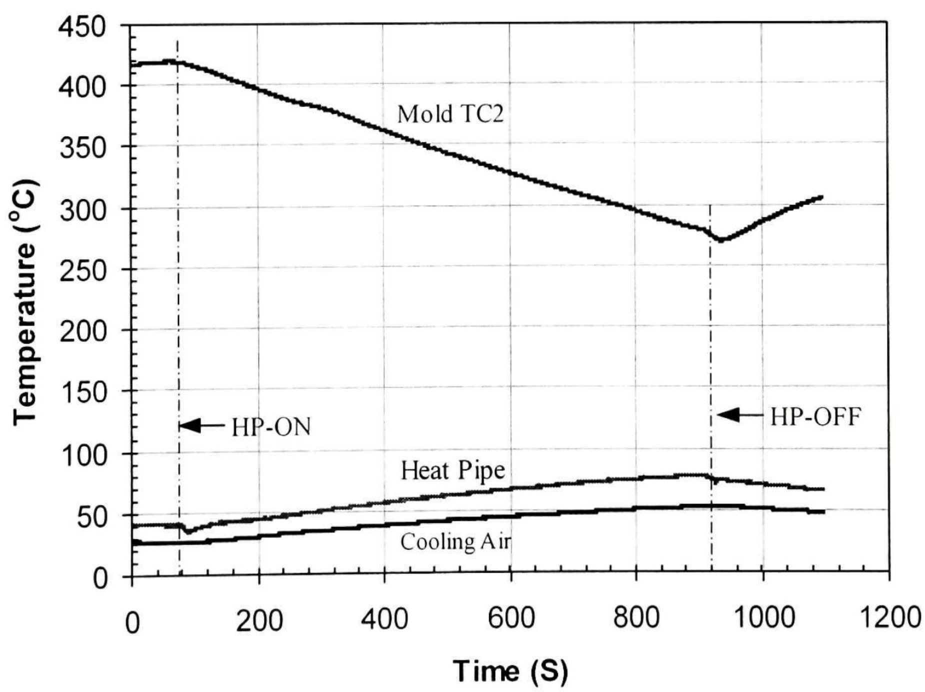


Figure 5.12 Mold cooling using heat pipe with no casting: Flow of cooling air = 20SCFM, $T_{mold\ preheating}$= 420 °C

5.4.2 Experimental Results Obtained from Industrial Trials

5.4.2.1 Effects of Three Different Cooling Methods on the Temperature Distribution of the Die

In the industrial tests, three cooling methods were applied to control the temperature distribution of the mold. More than 50 casting cycles were performed. The temperature history during the casting cycles is shown in Figures 5.13 and 5.14. The locations of thermocouples are indicated in Figure 5.10. The results presented in Figure 5.13 were achieved by water cooling at location B and heat pipe cooling at location C (See Figure 5.3). The cyclical nature of the outputs of TC1, TC2, TC4 reflects the temperature changes which took place during the casting cycles. The water cooling was automatically controlled by a computer program installed in the casting machine. After molten aluminum was injected into the mold, the water cooling was turned on for 15 seconds at the flow rate of 6 l/min. From the cooling curves, the temperature of the mold with heat pipe cooling is found to be much lower than that with water cooling used in the standard plant practice. With heat pipe cooling, the mold temperature (TC2) quickly approached the steady state after only two shots compared with that (TC1) with the water cooling. When the heat pipe was switched off, the mold temperature (TC2) increased very rapidly due to the incoming heat from casting solidification. For water cooling, to duplicate the cooling that was achieved with the heat pipe cooling would have required a water flow rate several times larger that what was used in the trials (74). This is in marked contrast to the fact that the heat pipe only contained 0.3 l of water and this was confined in a sealed chamber. During the test the water cooling was increased and turned on continuously to duplicate the heat pipe cooling. A leak in the water channel caused the water cooling to be turned off.

The casting cycles shown in Figure 5.14 were conducted with air cooling at location B and heat pipe cooling at location C (See Figure 5.3). The continuous air cooling was supplied by online compressed air of 100 psi for a 1 cm diameter hose. One point that needs to be mentioned is that the total of all the heat extracted from the mold by the heat pipe is eventually dissipated by air. The flow rate of cooling air for the condenser of the heat pipe is only 20 SCFM. However, it is inefficient to use air directly to cool the hot mold even at a high flow rate. The differential of the temperatures in the mold between the heat pipe cooling and the air cooling is large, and in the order of 100-150 °C. Moreover, with air cooling the average temperature increases with time while with heat pipe cooling the average temperature of the mold is stable.

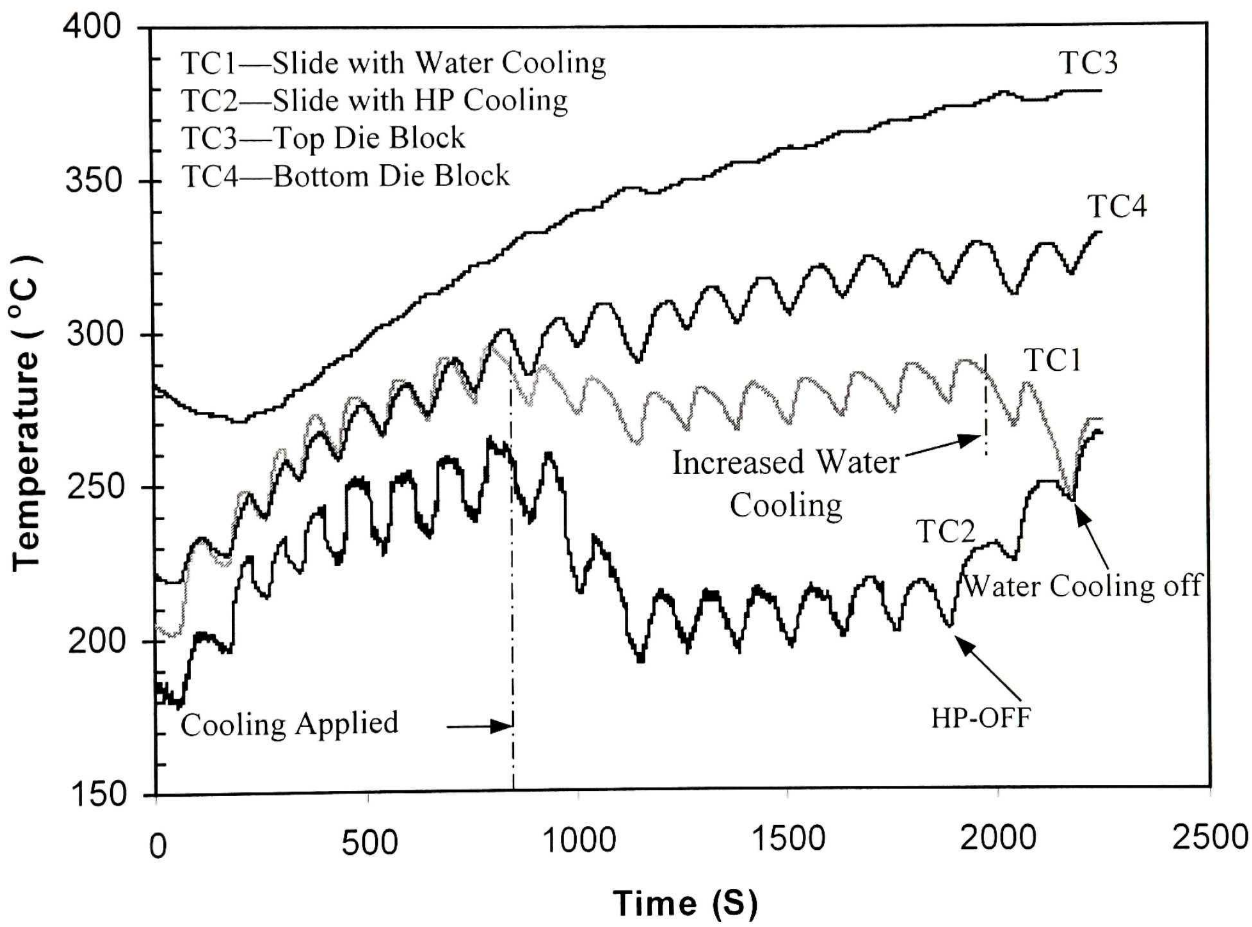


Figure 5.13 Cooling curves of the die blocks under water cooling and heat pipe cooling

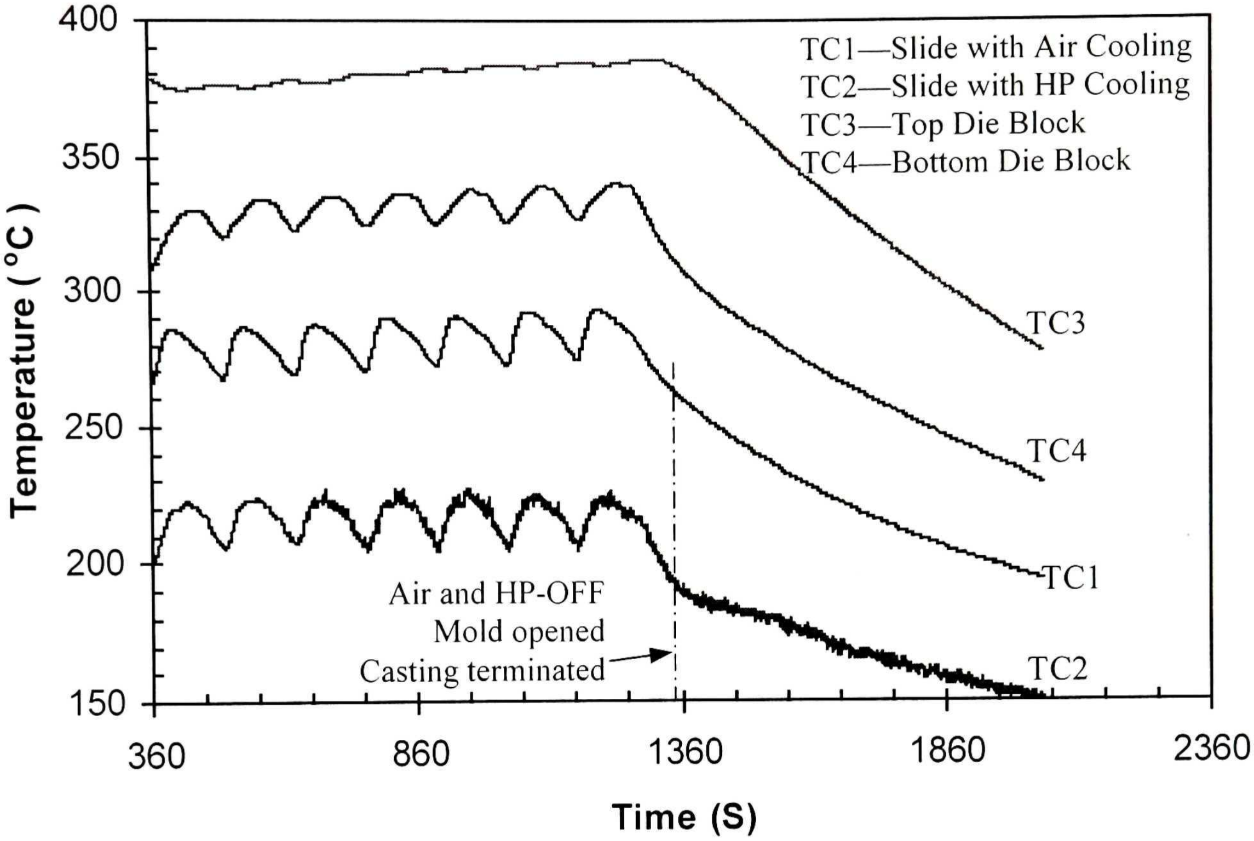


Figure 5.14 Cooling curves of the die blocks under air cooling and heat pipe cooling

5.4.2.2 Effects of the three different cooling methods on Dendrite Arm Spacing of A356 Alloy

Three points in the cooled area of each casting with different cooling media as shown in Figure 5.15 were selected for microstructure analysis. Two castings with no cooling were used as references. The DAS measurements were made by the line intercept method, which was performed using optical microscopy with a digital image analysis system CLEMEX Vision TM. The micrographs for Point E of the samples are presented in Figure 5.16, and the dendrite arm spacings (DAS) at the three locations for each sample are given in Table 5.1. As the cooling rate is a function of location, the DAS decreases from Point E to Point G when the cooling is operating. Different cooling methods affect

DAS to different extents. The heat pipe cooling is the best in terms of refining the DAS. The DAS at Point E with heat pipe cooling is around 19±1μm which is much smaller than that without any cooling (28±3μm). This corresponds to a 30% decrease in DAS (see Table 5.2). However, the DAS at Point E with water cooling is 25±2, which is a decrease of only 11%. By comparing the values of DAS at Point G with heat pipe cooling with those at Point G with no any cooling in Table 5.1 and Table 5.2, it is seen that heat pipe cooling affects the whole cross section of the casting.

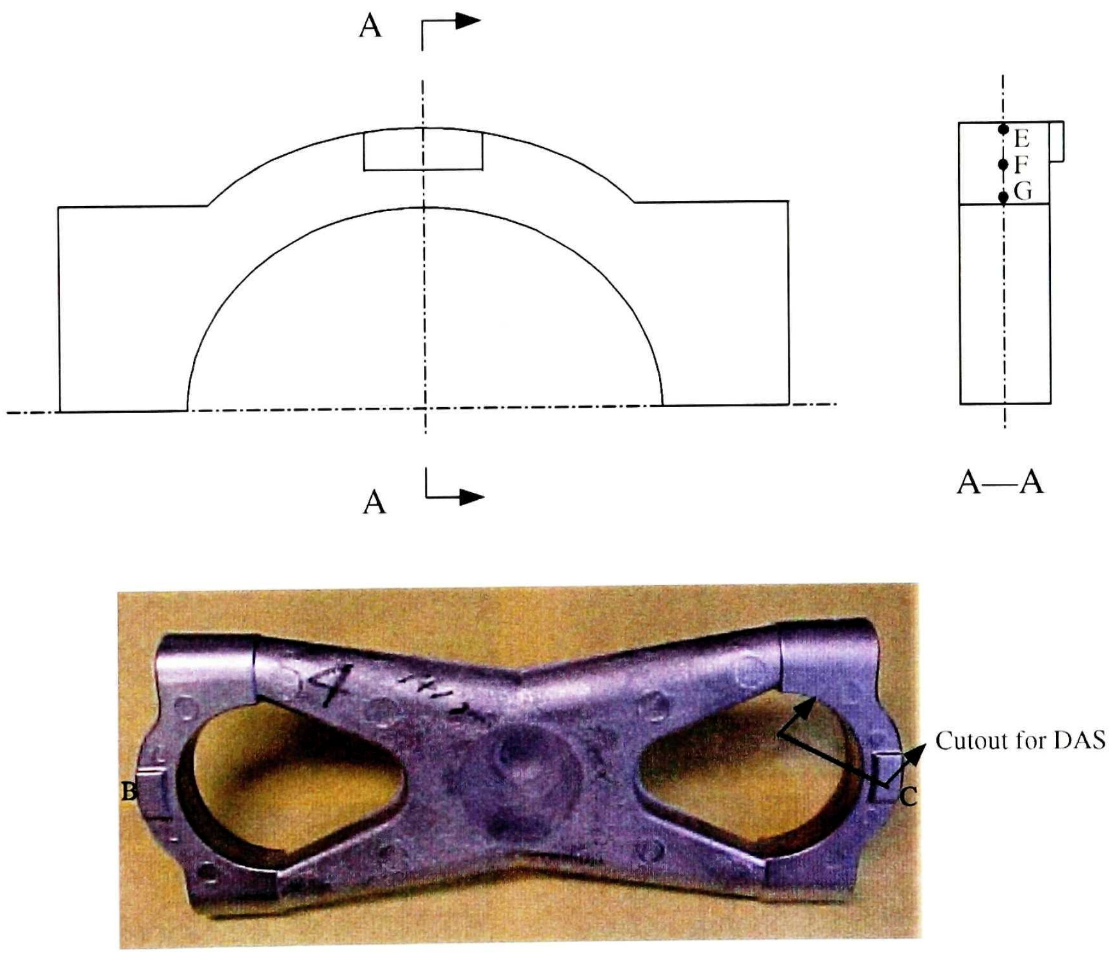
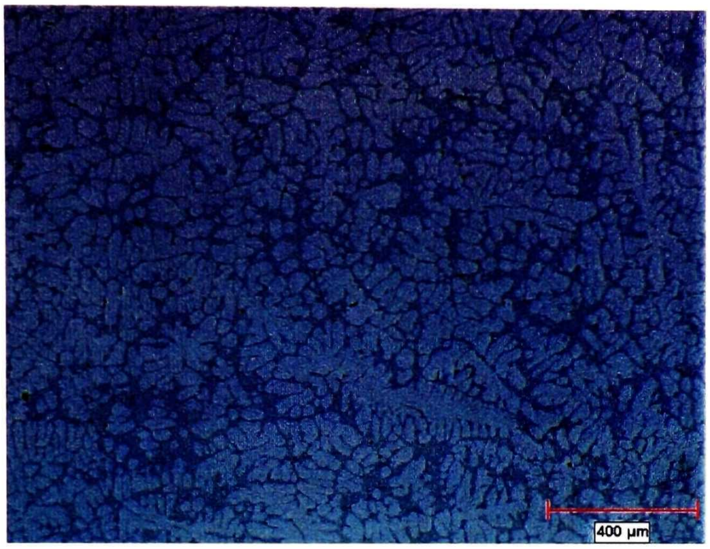
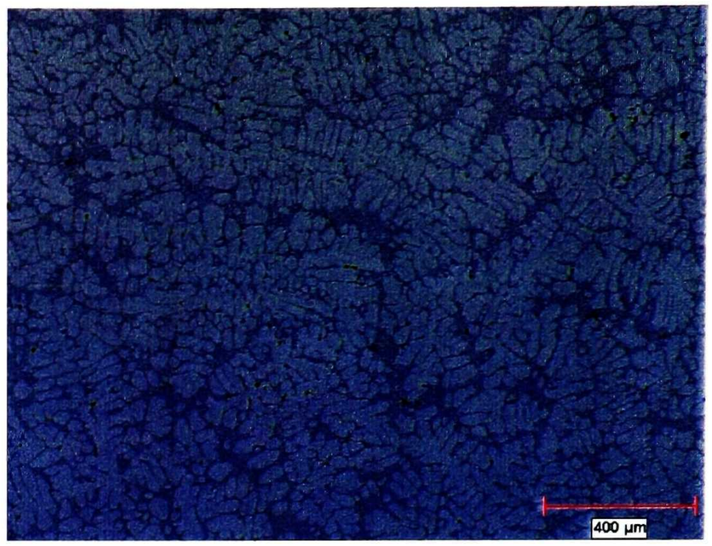


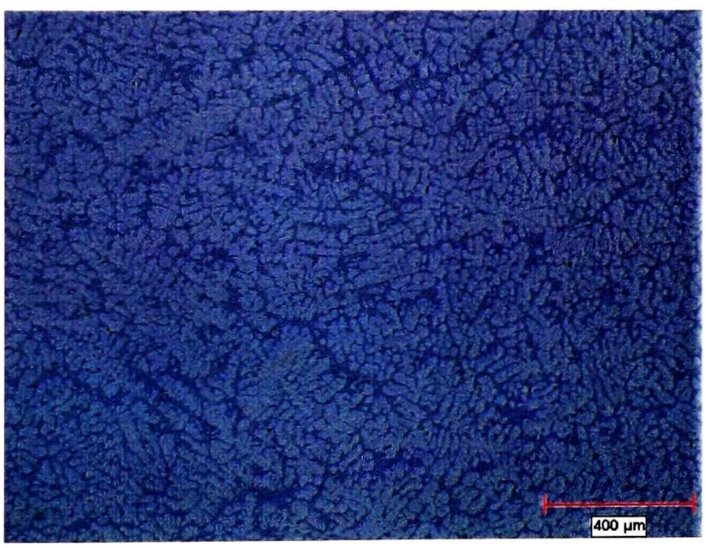
Figure 5.15 Selected locations for DAS measurements



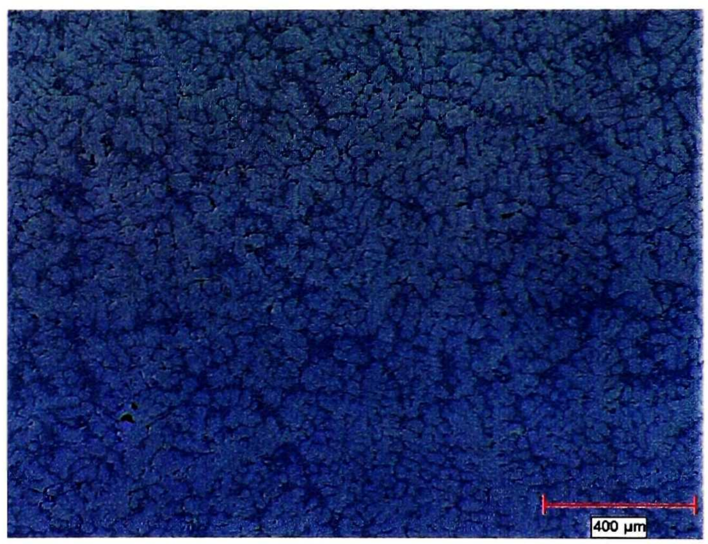
(a) With no cooling (28±3µm)



(b) With water cooling (25±2µm)



(c) With heat pipe cooling (19±1µm)



(d) With air cooling (24±3µm)

Figure 5.16 Micrographs of the low pressure die casting of A356 alloy with different cooling, Location E

Table 5.1 Effect of different cooling on DAS

(Unit: μm)

Casting No.	Part B				Part C			
	Cooling	Location			Cooling	Location		
		E	F	G		E	F	G
1	No	28±3	28±2	27±3	No	27±3	28 ±3	28±2
2	No	28±3	29±2	28±3	No	26±3	28±4	26±3
3	Water	25±2	26±2	26±2	Heat Pipe	19±2	21±2	21±3
4	Water	25±2	26±3	25±2	Heat Pipe	19±1	21±3	21±2
5	Air	22±3	27±2	24±2	Heat Pipe	19±1	22±2	22±1
6	Air	24±3	26±2	25±2	Heat Pipe	20±1	22±2	22±3

Table 5.2 Percentage Decrease of DAS by the Three Cooling Methods

(Unit: μm)

Casting No.	Part B				Part C			
	Cooling	Location			Cooling	Location		
		E	F	G		E	F	G
2 (Ref.)	No	28±3	28±2	27±3	No	27±3	28±3	28±2
3	Water	11%	7%	4%	Heat Pipe	30%	25%	25%
4	Water	11%	7%	7%	Heat Pipe	30%	25%	25%
5	Air	21%	4%	11%	Heat Pipe	30%	21%	21%
6	Air	14%	7%	7%	Heat Pipe	26%	21%	21%

Chapter 6 Conclusions

Aiming to solve existing mold cooling problems and offer an optimum cooling control technology for permanent mold casting process, a novel, advanced and water-based heat extraction device – McGill Heat Pipe has been successfully developed. The application of the heat pipe for the thermal management of permanent mold casting has shown both success and potential. The reliability and flexibility of the McGill heat pipe have proven to have valuable attributes that make heat pipe applications feasible for industrial casting processes and typically will contribute to improved cooling performance. In particular, the industrial demonstration for low pressure die casting should encourage the casting industries to consider heat pipes as a thermal management tool in commercial foundries. Based on the theoretical and experimental investigation, conclusions drawn from the present research may be summarized as follows.

1 Development and Characteristics of the Novel Heat Pipe — McGill Heat Pipe

- By the introduction of a flow modifier into the evaporator of a water-based heat pipe, the heat transfer capability has been enhanced by an order of magnitude or more because of the swirling motion generated by the flow modifier. This new heat pipe can handle high heat flux loading up to 1 MW/m^2, which is much higher than that which can be handled by a conventional heat pipe. To date such heat fluxes could only be handled with high velocity water flow passages. Shifting of the operation to the nucleate boiling regime from the film boiling regime is the main reason for the success of the McGill Heat Pipe.

- The experimental results of the heat pipe showed that the use of a wick in the evaporator is undesirable in the presence of a flow modifier fitted in the evaporator because it develops a layer of vapor film between the sidewall and wick under the centrifugal force from the vortex motion.

- By mounting a reservoir under the condenser, the heat pipe can be charged with more liquid with the excess collected in the reservoir for the potential use when higher heat fluxes are applied. Excess working fluid helps supply the evaporator and prevents the evaporator from drying out.

- By positioning a return line at the bottom of the liquid reservoir and extending to the end of the evaporator, the McGill heat pipe operates in the co-current flow pattern of liquid and vapor. As a result, the shear force from the reverse two-phase flow streams existing in the classical heat pipe is eliminated.

- By introducing a valve on the return line, ON/OFF capability or controllability of heat extraction has been realized.

- For the heat buffer style condenser in the ON mode, the external chill absorbs virtually all of the heat generated by the casting during solidification; cooling air dissipates the heat stored in the chill during the OFF mode.

2 Controlled Cooling of Permanent Mold Casting by the Heat Pipes

- The experimental results for the cooling of permanent molds reveal that the surface tension of water dominates the water flow through the return line to the mold at the beginning of the heat pipe start-up if the diameter of the return line is less than 1 cm. By adding 3% surfactant in volume into the working substance (water) in the heat pipes, the average cooling rates of the mold have been improved five fold.

- Accelerated heat transfer rates have been brought about by having the evaporator of the heat pipe become part of the mold itself.

- As the liquid (water) collected in the reservoir attempts to flow through the hot return line in the mold when the heat pipe is turned on, counter current flow between liquid and vapor will be generated in the return line. By the installation of a vent line on the return line, upward flow of vapor is diverted as the vapor escapes through the vent line to the top of the condenser.

- Laboratory experiments show that the cooling by heat pipes is very effective in controlling the microstructures of the castings and the mold temperature. The evidence for this lies in the facts that:

  - The DAS of A356 alloy is refined considerably by heat pipes, corresponding to a maximum 41% decrease for the step permanent casting of A356 alloy at an initial mold temperature of 300 ^{o}C and a pouring temperature of 740 ^{o}C.

  - Changes in the shrinkage pattern are provided by the dramatic changes in the heat flow patterns

  - The heat pipe can be used to determine the time when the air gap forms at the interface between the mold and the casting.

- The conductivity of coatings influences considerably the casting solidification time of A356 alloy with no heat pipe cooling. However, the influence becomes smaller when intense heat pipe cooling is used.

- Modeling for permanent mold casting of aluminum alloy A356 was performed with the SOLIDCast software package. The simulated results indicate heat pipe cooling for the mold is effective and in agreement with the experimental results.

3 Industrial Trials of Cooling Control by Heat Pipe for the Low Pressure Die Casting

- Based on the considerations that the space around the mold installed on a low pressure die casting machine is very limited, and it is often very difficult to install the heat pipe in the specific desired location in the mold. A new version flexible heat pipe cooling system has been developed for low pressure die castings. The flexible connections are applied between the evaporator and the condenser of the heat pipe to improve the feasibility of the heat pipe application for the industrial casting process.

- This is the first time that heat pipes have been used successfully on a commercial low pressure die casting machine.

- The industrial tests show that the heat pipe can provide higher cooling rates than the current water cooling and air cooling typically used in low pressure die casting.

- The DAS of commercial bearing cups of A356 by the heat pipe cooling is much finer than that obtained with water cooling and air cooling as are currently being used in commercial foundries.

Statement of Originality

Prior to this study, the high temperature, high heat flux, heat pipe for metallurgical applications (i.e. the cooling of permanent mold casting) did not exist. Development of the high heat flux, heat pipe is the highlight of this thesis. The major original contributions to knowledge made in this research can be considered as follows:

1. Development of a novel, controllable, water-based heat pipe

- High heat flux loadings up to 1 MW/m^2 can be handled by this new heat pipe. A conventional heat pipe can only handle a fraction of this heat flux.
- The novel heat pipe is made to operate in the nucleate boiling regime instead of the film boiling regime where a conventional heat pipe may operate. This was accomplished by introducing a flow modifier in a section of the evaporator.
- Incorporating a reservoir below the condenser allows for the use of excess working substance in the heat pipe and thus the heat pipe never dries out.
- A method has been developed for preventing the heat pipe from operating as a counter-current flow unit whereby two phases (vapor and liquid) move up to the condenser while one phase (liquid) moves down to the evaporator. The novel heat pipe operates as a co-current flow unit instead. This has been accomplished by installing a return line between the reservoir and the leading end of the evaporator.
- In order to understand heat transfer in the boiling regime, a very effective way to determine if film boiling dominates the operation of a heat pipe is created by freezing the heat pipe in zinc after switching off the power to the melting furnace.

- For the first time, it was shown that the use of a wick is not required in many cases because of the presence of a flow modifier that is fitted in the evaporator. This is contrary to the prevalent thoughts of heat pipe experts.
- By adding a surfactant, the problem that the surface tension of the water dominates the water flow through the return line to the evaporator has been eliminated.
- The controllability of the heat extraction is achieved by incorporating a valve on the return line.

2. Heat pipe cooling of permanent mold castings

- The design of a double step, symmetric permanent mold allows, for the first time, to evaluate the effects of heat pipe cooling on permanent mold casting.
- It is the first time that the chill has been moved from the interior of the mold to the exterior based on heat pipe technology. The chill operates as an energy buffer. The cooling potential in this way is much larger than that of a conventional chill insert as used in the permanent mold casting of aluminum alloys.
- For the first time, a heat pipe has been used to detect the formation of an air gap at the interface between the casting and the mold.
- The effects of the conductivities of different mold coatings on casting solidification were studied.
- In the study of the modeling of permanent mold casting of aluminum alloys with heat pipe cooling, the effects of heat pipe cooling were simplified by setting proper boundary conditions.
- A better understanding of the relationships between temperature distribution, cooling rate during casting processes and microstructure was obtained.

3. Industrial trials for the cooling of low pressure die casting based on heat pipe technology

- For the first time, heat pipes have been successfully used for the cooling of a low pressure die casting in a commercial foundry.
- The effectiveness of the novel heat pipe cooling was compared with the traditional cooling technology- water and air cooling being used in commercial foundries.
- A decrease of cycle time and increase of productivity in industrial permanent mold casting can be achieved through the use of heat pipes located in specific critical areas.

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