HEAT PIPE STUDIES

A THESIS

Submitted in partial fulfilment of
the requirements for the award of the degree
of
MASTER OF ENGINEERING
in
CHEMICAL ENGINEERING

By
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CERTIFICATE

It is certified that the thesis entitled " HEAT PIPE STUDIES" which is being submitted by Sri Subhash Sharma in partial fulfilment of the requirements for the award of the degree of MASTER OF ENGINEERING IN CHEMICAL ENGINEERING (EQUIPMENT AND PLANT DESIGN) of University of Roorkee, Roorkee is a record of candidate's own work carried out by him under the supervision and guidance of the undersigned. The matter embodied in this thesis has not been submitted for award of any other degree.

This is further certified that he has worked for a period of about eight months for preparing this thesis at this University.

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ABSTRACT

This thesis presents an experimental investigation on the performance of the heat pipe under the conditions of various orientations, working fluid quantities, heat inputs and the coolant flow rates. Heat pipe was a stainless steel pipe having a wick which was made by wrapping several layers of cotton-cloth over a tube, perforated at both ends. The pipe was of 30 mm outside diameter and 620 mm long, having evaporator section of 150 mm, adiabatic section of 370 mm and condenser section of 100 mm. The evaporator section had an electric heater which was made by wrapping nichrome wire coils over the evaporator section length. The condenser section had a swirling chamber for the circulation of the coolant (water) around it. Distilled water was used as the working fluid.

Calibrated Copper-Constantan thermocouples (24 gauge) mounted along the length of the heat pipe measured the temperature in the vapour core and that of the wick with the help of a digital multimeter. The coolant flow rate was measured by means of a calibrated rotameter and the heat input by a calibrated wattmeter. Heat pipe orientation was varied from 0° to 10° with respect to horizontal axis. The coolant flow rate varied from 111.25 c.c. to 191 c.c./min. heat input from 40W to 80W and the working fluid quantity from 130 c.c. to 170 c.c.

The temperature profiles along the length of the heat pipe during transient and steady state conditions were found to have almost uniform temperatures in the evaporator section and a sharp decrease in the condenser section. The temperature along the heat pipe decreased with the increase in coolant flow rate and also with the decrease in heat input. This resulted in a linear variation of the performance of heat pipe with the heat input. Orientation of the heat pipe affected the vapour temperature significantly: temperature increased in the evaporator section but decreased in the condenser section when the heat pipe was tilted against gravity (evaporator section above the condenser section). The performance of the heat pipe was found to decrease with the increase in tilt of the heat pipe. The working fluid quantity also changed the vapour temperature and the performance of the heat pipe.

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C O N T E N T S

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NOMENCLATURE

A	heat transfer area	m^2
C	specific heat	J/kg.K
D	diameter of the heat pipe	m
g	acceleration due to gravity	m/s^2
h	heat transfer coefficient	W/m^2K
k	thermal conductivity	W/mK
L	length of heat pipe	m
m	mass flow rate	kg/hr
P	pressure	kN/m^2
r	radius	m
t	temperature	K or $^{\circ}C$
t	temperature difference	K or $^{\circ}C$
V	velocity	m/s
W	heat input	W
α	Orientation	degree
β	coefficient of thermal expansion	$1/^{\circ}C$
σ	surface tension	N/m
ρ	density	kg/m^3
λ	latent heat	J/kg
μ	dynamic viscosity	Ns/m^2
ν	kinematic viscosity	m^2/s

Dimensionless Modulu

Gr	Grash of number	$\frac{gd^3 \beta \Delta t}{\nu^2}$
Pr	prandtl number	$\frac{C\mu}{k}$
Np	pressure number	$\frac{g \sigma \rho_L}{p^2 gc}$
Nu	nusselt number	$\frac{hD_i}{k}$
Re	Reynolds number	$\frac{Dv}{\nu}$
St	stanton number	$\frac{h}{CG}$

Subscripts

i	inside
o	outside
l	liquid
v	vapour
w	wall

CHAPTER-1

INTRODUCTION

In recent years with the advancement in technology it has become increasingly important to develop methods for the efficient transportation of thermal energy from one location to another as the conventionally known methods do not satisfy the present day needs. Previously it used to be done by the transportation of vapour from source to sink accompanied with evaporation at the source end and the condensation at the sink end. But this mode of heat transfer has the limitation of either requiring the use of pump for the return of the liquid from the sink to the source or limiting its application to those places where the liquid may return by gravity from sink to source. Heat pipe, a recent innovation, removes all these limitations.

In heat pipe, thermal energy is absorbed at one end by the liquid and the vapour, thus formed by evaporation, travels to the other end through adiabatic section. Here the vapour gets condensed and the heat of condensation is transferred to an external sink. The condensate returns to the evaporation section by the capillary action developed in the wick which is an integral part of the heat pipe and extends throughout its length.

Although heat pipe is a new concept for the transportation of thermal energy, many research investigators have studied its various aspects related to its operational limits and the effect of operating parameters like heat input, orientation and the physico-thermal properties of the working fluids. But still there are certain ramifications which need further investigations.

These considerations have led to design and develop a heat pipe and to study it with the following objectives :

1. To conduct experiments for obtaining the temperature profile along the length of heat pipe over a wide range of operating parameters.

2. To determine the performance of the heat pipe and to obtain the effect of operating parameters on it.

CHAPTER - 2

LITERATURE REVIEW

Heat pipe is a noble device for the transportation of thermal energy from the source to the sink at a small temperature gradient without using either a pump or force of gravity for the return of the condensate from sink to the source. This concept was first of all put forward by R.S. Gaugler (1) in 1942. He developed it for the refrigeration systems in which the heat was to be absorbed at a point above the condensing place without expending upon the liquid any additional work for the return of the liquid to the evaporator. He suggested capillary structures for the return of the condensate and proposed various geometrical configurations for the capillary structures. This method could not become popular and its potentiality remained concealed because at that time other conventional methods satisfied the need. Later on in 1963, Grover et al (2) developed a device indentical to that in the Gaugler's patent and coined the term 'Heat Pipe' to describe it. They realised its immense applicability as a highly efficient heat conducting device. Since then many investigators have studied its various aspects namely the characteristics of the working fluids, wicks, thermal performance and the effect of operating parameters on the working of heat pipe. The important ones have been discussed in the following sections:

2.1 Working fluids

A wide varity of fluids ranging from cryogenic to liquid metals have been employed by various researchers. Liquid metals have been used in high temperature studies where as common liquids like water and alcohols for low and moderate temperature studies. However, in the intermediate temperature range from 200 to 350°C no proper working fluids have been reported as yet, although Deverall (3) has suggested the use of mercury with small amounts of titanium and manganese as the suitable working fluid for this temperature range.

Many workers have studied various working fluids in the Heat pipe studies and have concluded that the relative merits of various working fluids within a particular temperature range can be established by comparing the values of a dimensional fluid properly group for each fluid. This property group has been referred by different workers as the fluid property group, dimensional liquid parameter, liquid transport factor, capillary pumping parameter or figure of merit. It has the dimension of heat flux and is given by the following equation :

$$N = \frac{\rho_L \sigma_L \lambda}{\mu_l} \quad \ldots\ldots\ldots \qquad (2.1)$$

It is a direct measure of the effectiveness of a substance as a working fluid in a heat pipe. Table 2.1 gives the merit number of water for the temperature range of 20 - 200°C.

Table 2.1 Merit number of water as a function of temperature

Temperature, °C	Merit number, $N \times 10^{-8}$ kw/m^2
20	1.8
40	2.55
60	3.26
80	3.90
100	4.55
120	4.97
140	5.02
160	5.16
180	5.08
200	4.72

The choice of a particular fluid depends on its specific applications, however a few general guidelines are used for the selection of the working fluid. For high temperature high heat flux heat pipes the liquid metals are superior to nonmetallic liquids due to their vapour pressure characteristics, high surface tension and latent heat. The suitability of cryogenic fluids for low temperature heat pipe applications has not been confirmed so far.

2.2 Wick

A wide verity of wicks have been successfully used in heat pipes. The first wick used by Grover et al (2) was made of several layers of line mesh screen. Neal (3) rolled the screens on a mandril and upon insertion into the pipe removed the mandril. The screen was held against the pipe wall by its own resilience but he found that the resilience varied from screen to screen and so the performance of the pipe was not reproducible.

Deverall and Kemme (4) forced a steel ball through a heat pipe after the screen layers had been inserted to achieve the good contact between the wick and the wall. However, no attempt was made to check the reproducibility of data. Kemme (5) made rigid screen wick by the following procedure : Several layers of stainless steel screen were wrapped around a copper tube. The structure was placed into another copper tube and drawn through a die to comress the screen layers. Copper was removed chemically. The screen tube was heated to 1000°C in a vacuum oven to bond the structure. Finally, the baked rigid screen tube was inserted into the heat pipe. This proved to be an effective wick with reproducible qualities.

McKinney (6) used a coiled spring to hold a screen wick firmly aga-inst the heat pipe wall. Katzoff (7) constructed wicks in which a single layer of screen is metallically bonded to the wall. The bonding was affected by pressing the screen against the plate with a pressure of 15 Psi while backing them at 1100°C for two hours in a vacuum oven.

Several workers have employed textile fabrics for making wicks. Haskin (4) used a rayon cloth as wick for a nitrogen heat pipe. The cloth was held firmly against the heat pipe wall by sliding together two halves of a slotted diagonally cut retaining tube. Shlosinger et al (8) used quartz fiber cloth as a wick. The cloth was pressed against the wall with the springs but it could not been bonded with the pipe wall. Therefore, this type of heat pipe did not give good performance. It has been found that ordinary rubber cement produced acceptable bonds for temperature upto 50^{o}C if the rubber was allowed to cure and become tacky before the wick was pressed against the wall. At high temperatures silicon rubber failed because low molecular weight silicon compounds were released in the curing process and effectively waterproofed the wick. Thermo setting and Thermoplastic sheets of polyster resins and polyethylene type heat sealable film materials provided good bonding.

Some investigators have used porous metals as potential heat pipe wicks. Neal (4) used a sintered copper fiber wick but it could not be bonded to the pipe wall and so poor results were obtained. Porous metal wicks are extremely difficult to machine and normal cutting techniques tend to close the surface pores along the cut. The use of the filler material is not recommended because it is difficult to completely remove the filler, after cutting, which changes the wetting characteristics of the porous material. A technique to avoid the maching of porous metals completely has been developed. This entails the application of a mixture of particular matter, binder and solvent to a surface. As the solvent evaporates the surface tension of the fluid draws the particles together, compacting them yet leaving open pores. This technique can be applied to geometrically complex surfaces. Composite wicks have received the most attention as it has been found that the use of an integrated type of wick makes the structure to be very stable and pore size can be controlled easily. Kemme (5) made such a wick of saveral layers of screen of different mesh sizes with the finer screens installed on the inside to provide cappillary pumping forces and coarse screen located in the annulus between the fine screen and the wall to serve as the flow passage.

Several researchers experimented on heat pipe to measure capillary equilibrium levels in various wicks. Ferrell and his co-workers (9) measured the falling equilibrium height of water in packed beds consisting of the stainless steel particles (40 to 100 mesh) and glass beads (80 to 100 mesh) and obtained the equilibrium height to be a function of particle diameter. Phillips and Hinderman (10) measured the maximum capillary pressure for a 200 mesh screen of stainless steel, bronze and nickel using water, methane and benzene respectively. In addition several metal foams and felts were tested with these fluids.

For the screens capillary pressure ranged from 0.12 to 0.36 Psi and for the porous metals from 0.02 to 0.13 Psi. Katzoff(7) measured the lift capability of six screens and found the values of the minimum effective meniscus radius ranging between 0.75-0.9 times the spacing of the wires in the screen. Ernst (4) re-examined Katzoff's data and found that the effective mensiscus radius can be expressed by (d+di) where d is the mesh opening half width and di is the radius of the wire in the mesh. Ginwala et al. (4) examined a very large number of wicking materials ranging from cellular types to refractory products and observed the maximum rise height with silica vitreous fibers and filter papers while acceptable heights were observed in viscous rayon.

2.3 Compatability of Components

The choice of suitable materials for heat pipe construction is a vary important step in the design of heat pipe. Improper selection of components results in a gradual appearance of noncondensable gases. In the case of high temperature heat pipes improper material selection may accelerate corrosion and the desolution of wick structure. Grover et al (2) were the first to encounter and describe the generation of non-condensable gases. Andeen et al.(4) tested a water brass heat pipe and experienced severe problems with non-condensable gases. Schwartz (11) also noticed non-condensable gases in several water stainless steel heat pipes and found that the gas was composed of over 97% hydrogen which was formed as a result of a chemical reaction between the iron in the stainless steel and water. He suggested that the generation of non-condensable gases can be avoided either by choosing a heat pipe whose metal component range below hydrogen in the electromotive series or if the metals have an electro chemical potential above hydrogen, by using a non reacting fluid other than water. Conway and Kelley(12) also experienced noncondensable gases in water stainless steel heat pipe. Grover et al (13) recommended that the condenser cap be fabricated out of palladium allowing hydrogen to diffuse to the outside while retaining the working fluids. Kemme (4) has reported the successful operation of water stainless steel heat pipe for over 3000 hours without accumulation of non-condensable gas. In this case the stainless steel tube and the screen were first degreased in acetone and then bright dipped to guarantee clean surface which were subsequently degased at 600°C in a highvacuum oven. Many others have used different cleaning and treatment techniques to avoid any combination for which a possible chemical reaction exists and could lead to the generation of non-condensable gas. For high temperature heat pipes solubility of one metal in another, diffusion effects and the formation of possible intermetallic compounds should be considered.

2.4 Operating Characteristics

In early investigation very little more than the successful operation of the heat pipe was reported. After the work of Grover(2) Bainton (4) reported the successful operation of two sodium stainless steel heat pipes. Bowman and Crain (7) operated a water copper heat pipe at near ambient temperatures.

Several investigators have experimentally determined the wicking limit of heat pipe as a function of vapour temperature or geometric parameters. Bohdansky et al (14) measured the maximum possible heat flow in N_a . heat pipe in the temperature range from 500 to 800C. The pipe was 50 cm long and had a two cm inner diameter. The capillary system consisted of 85 groves of rectangular cross section with a width of 0.4 mm and a depth of 0.46 mm. The pipe was heated with an rf.coil and cooled through a variable resistance helium thermal bridge with cooling water on the other end. The pipe inclination was also varied to change the lift height between the evaporator and the condenser. Upon each variation in orientation the power input was increased until a hot spot was found at the far end of the evaporator indicating that the wick was no longer capable to supply sufficient fluid to this part of evaporator. They also obtained the effect of the lift height on the maximum heat transfer and found that for a constant lift height occurence of the maximum heat flow is due to the decrease in surface tension with increase in temperature.

Neal (4) confirmed the results of Bohdansky et al in a water stainless steel heat pipe fitted with four layers of 105 mesh screen. Cosgrove et al (15) investigated two water brass heat pipes in which the wick structures consisted of packed monel beads which were held in an anulus between a retaining screen and the wall. It was found that for a given particle diameter the maximum heat transfer decreased with increasing elevation and for a given pipe inclination the maximum heat transfer increases with decreasing particle diameter. This is due to the increased capillary pressure resulted from the smaller pore sizes. Further, the results of these investigators suggested that the capillary limiting curve depends on the pipe orientation, the geometry of the heat pipe and on the characteristic of the wick structure.

Anand et al (16) tested a water stainless steel heat pipe which had a 100 mesh stainless steel screen wick and correlated their experimental datas of boiling heat transfer by the following expression :

$$St = 0.0051\ (Pr)^{0.6}(N_p)^{0.2}(Re)^{1.43} \quad \ldots \quad .. (2.2)$$

Marto and Mosteller (4) studied the problem of wick boiling using a so-called everted heat pipe. In this pipe the vapour space was enclosed in an anulus between an interior tube and a confining envelope. The wick was of four layers of 100 mesh stainless steel screen attached to the outer side of the inner pipe. Heat addition and removal was done using a resistance heater and a tap water cooling system both installed within the inner tube. The authors concluded that wick boiling can exist in a heat pipe with no detrimental effect on its operation. Further, it was also found that for a given heat flux the superheat decreased as the absolute pressure increased. Many other investigators have studied boiling in heat pipes using sintered stainless steel screen as wick. Phillips et al. (10) measured the heat flux through a composite wick of nickel foam and stainless steel screen using water as a working fluid. The fluid was supplied through an artery and moved by capalliary forces. For a low value of T conduction was the mode of heat transfer. The maximum heat flux decreased with decreasing chamber pressure, due to the increase size of the vapour bubble formed during nucleate boiling at decreased pressure causing a premature burnout due to vapour blockage in the wick. Therefore, they concluded that the proper venting of the vapour was necessary if the full capabilities of the capillary supply system were to be utilised.

Kemmy (5) investigated the sonic limit using several different liquid metals as working fluids. The heat pipe was heated by an induction coil and cooled through a gas gap with a water calorimeter. Different mixtures of argon and helium in the gap varied the heat pipe temperature at a constant heat input or heat input variations at a constant heat pipe temperature. The heat flow was increased in steps and at a steady state the heat flow and the wall temperatures were measured. In the case of sodium heat pipe the evaporator exit temperature followed the sonic curve untill it reached temp. of 560°C. For temperatures lower than 560°C the flow in the condenser section consisted of continuum flow at the entrance and free molecule flow at the far end of the condenser. As the heat flow increased the entire condenser region was in the continuum flow regime and once this occured the heat removal area of the system remained fixed, so that a further increase in heat input resulted in a large temperature size at the evaporator exit and the vapour velocity became subsonic. Further experiments showed the occurance of the supersonic velocities at the condenser entrance. This has proved that the sonic limiting curve is highly dependent on the working fluid and at the pressure and the temperature at which the heat pipe is operating.

Dzakowic et al (17) also obtained the dependency of the sonic limit on the selection of the working fluid and operating condition of the heat pipe and also on pipe geometry. Sonic limit is not the only factor which contributes to start up problems of heat pipes. Ernest et al. (18) found that the methods of orienting the heat pipe during start up had a significant effect on its final operating condition. However for height difference of less than 4.4 inches between evaporation and the condenser no effect depending on pipe orientation was found. Once the pumping limit was reached, however, the temperature drop was greatly influenced by the method used to attain the elevation diffeence. McSweeney (19) measured the temperature in the vapour space of a sodium heat pipe during the transient and study state periods, and observed that the temperature oscillated even at steady state condition when the heat removal was highly concentrated by localised to calorimeter cooling. However no oscillations were observed and the vapour temperature remained nearly uniform throughout the vapour space when the cooling was effected by free convection and radiation. The oscillating behaviour may be due to the non-linear wick characteristic or the presence of non-condensable gases. Neal (4) and others have also studied the partly frozen heat pipes and observed that even a moderate heat input of only 50W caused wick dryout and subsequent overheating in the evaporator section before the entire pipe could begin to operate in its normal mode. They used an auxillary pipe to enhance the thawing of the primary heat pipe without local over heating and to reduce the transient period. Deverall et al. (20) also investigated the start up behaviour of a water heat pipe which was initially frozen over its entire length. Further, they have found that there is no degration of the water stainless heat pipe in a zero gravity fluid. In further tests it has been found that sinusoidal and random vibration improved the heat pipe performance by wetting the wick and forcing the liquid into all parts of the wick structure. Haskin (4) measured the total radial temperature drop in the evaporator and condenser in a low temperature nitrogen heat pipe and observed that for low heat loads (less than 36 W) the temperature drop in the condenser was larger than in the evaporator. For larger heat loads the temperature gradient in the evaporator became greater due to the partial drying of the wick and to the formation of a superheated vapour film on the inner metal tube surface. Schwartz (11) with a water stainless steel heat pipe found the temperature drop across the wall and wick in the evaporator to be higher than in the condenser and concluded that a higher condenser temperature drop is not the rule but the relation between the condenser and evaporator temperature drops depends on the geometry and the nature of the working fluid. McKinney (6) conducted test on a series of water heat pipes in a moderate temperature range upto 400^{O}F and found that the magnitude of the radial Reynolds number had little or no effect on heat pipe operation.

CHAPTER - 3

EXPERIMENTAL INVESTIGATIONS

An experimental set up as shown schematically in Fig 3.1 and photographically in Fig 3.2 was designed, fabricated and assembled for conducting experiments on the performance of heat pipe. The following sections discuss the main considerations which were taken during the raising of the set-up and its various components :

3.1 Design Considerations

In order to obtain reliable and reproducible data, following designs considerations for the experimental set-up were taken :

1) Supply of coolant at a constant volumetric flow rate. This was ensured by supplying the coolant through a constant over-head tank and measuring, its volumetric flow rate by means of an home-made rotameter.

2) Removal of noncondensables from the heat pipe. This was done by evacuating the system by means of a vacuum pump and recording the system pressure inside the heat pipe with the help of calibrated vacuum gauges. Further, the value of film heat transfer coefficient at the coolant side was made high by installing a swirling chamber around the condensing section.

3) Reduction of the heat loss from the system to the surrounding through attachements. For this the main attachements were mounted at the condenser side only and the number of fittings were also kept minimum to reduce the chances for leakages through them.

4) Fixing of the wick inside the heat pipe so that it may remain tightly attached to the inside surface of the heat pipe.

5) Mounting of the thermocouples to measure the bulk temperature of the vapour core. This was accomplished by mounting copper-constantan thermocouples on a stainless steel wire of 1 mm diameter at the positions shown in Fig 3.5. The assembly was then placed in the central position of the heat pipe. To keep it in the position, six special types of spring-spacers were used. Further, in order to measure the temperature in the wick a thermocouple was placed inside the wick in the evaporator section.

6) Orientation of the heat pipe. To place the heat pipe at various angles of inclination from the horizontal a pivot was provided in the centre of the gravity of the heat pipe and its inclination was measured by a graduated disc as shown in Fig 3.1

3.2 Experimental Set-up:

The experimental set-up has been depicted schematically in Fig 3.1. It consisted of the heat pipe, the constant head coolant supply line through rotameter, regulated and stabilised power supply system to the heater, a pivot for placing the heat pipe at various orientations with respect to the horizontal and the temperature measuring device. The constructional details of these components have been discussed in the following sections :

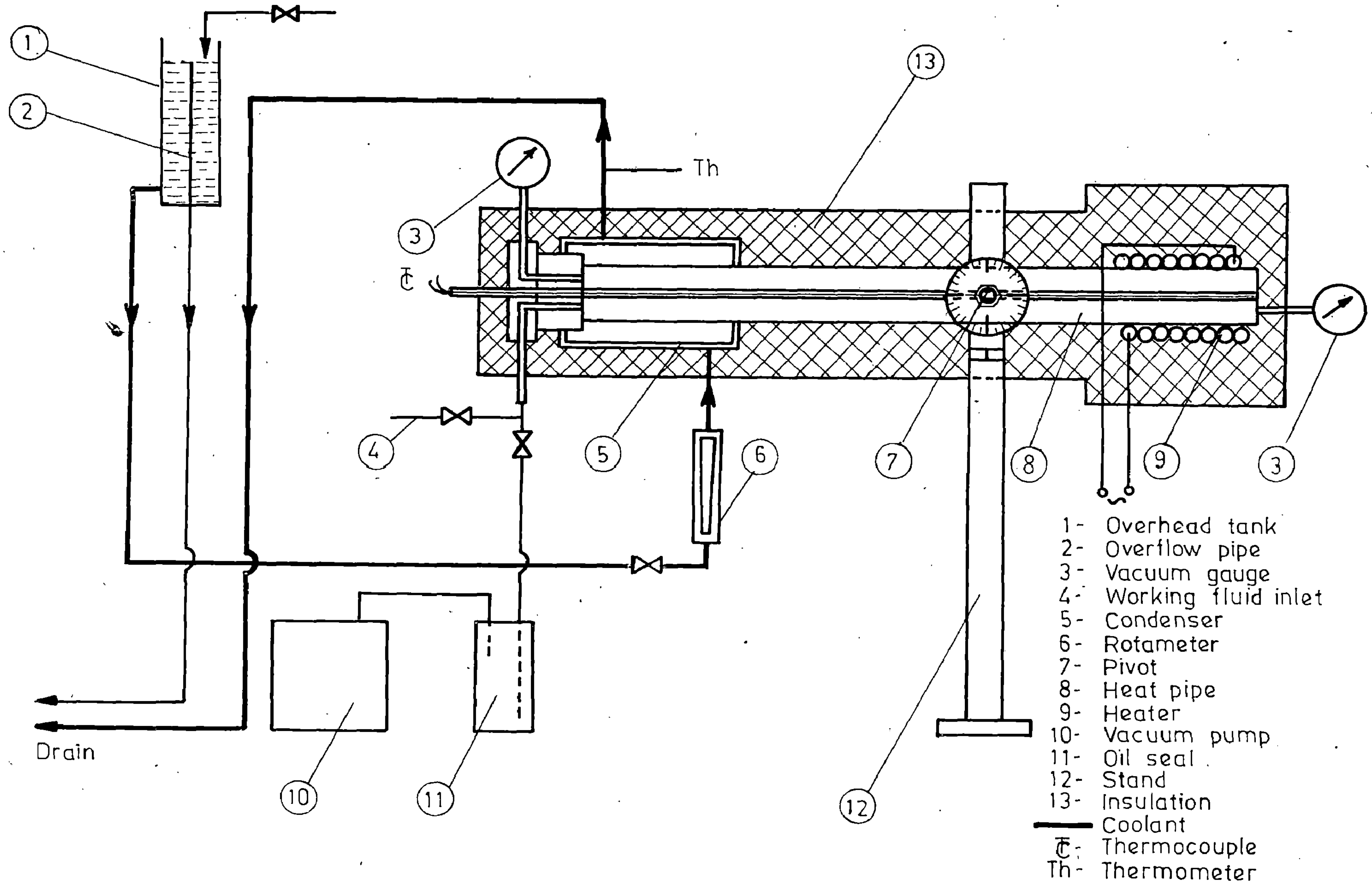

Fig 3.1 Schematic diagram of experimental set-up

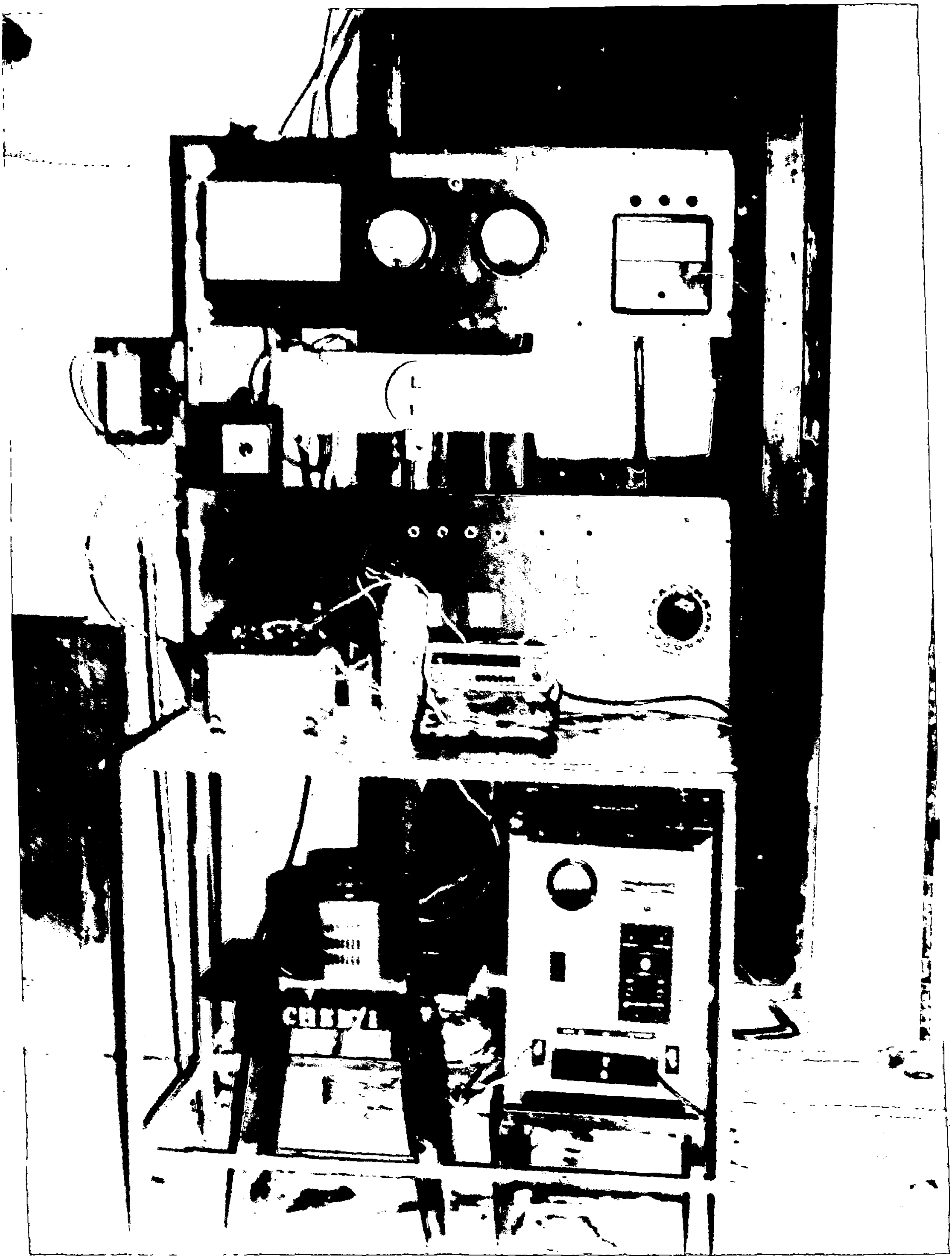

Fig 3.2 Photographic view of the experimental set-up

3.2.1 The heat pipe Assembly

The details of the heat pipe assembly have been shown in Fig 3.3. It consisted of a stainless steel straight pipe having outside diameter 31 mm and inside diameter 26 mm. One end of the pipe was provided with a circular disc having holes of 3 mm diameter on its periphery and then by a stainless steel plug of 5 mm thickness. The disc transmitted pressure to the vacuum gauge which was fitted at the plug end. It also helped in keeping the thermocouple assembly in the central position. At the plugged end an home-made electric heater was placed on the outer surface of the pipe. It was made by wrapping a coil of nichrome wire (24 SWG) on the outer surface of the pipe upto a distance of 150 mm from the plugged end. Mica sheet and Asbestos rope provided electrical insulation between the pipe and the heater. The two ends of the heater were connected to a stabilized power supply. The other end of the pipe was connected, with a detchable condenser. The condenser was a swirling chamber. This was essential to produce the high turbulence in the coolant so as to get high heat transfer coefficient on the coolant side. The condensing section was of 100 mm length and had flanges for coupling the condenser with the adiabatic zone. The condenser section outlet was plugged and the thermocouple assembly was taken out through the plug by means of compression fittings. The condenser end also had the provisions for mounting the vacuum gauge and the working fluid inlet valve.

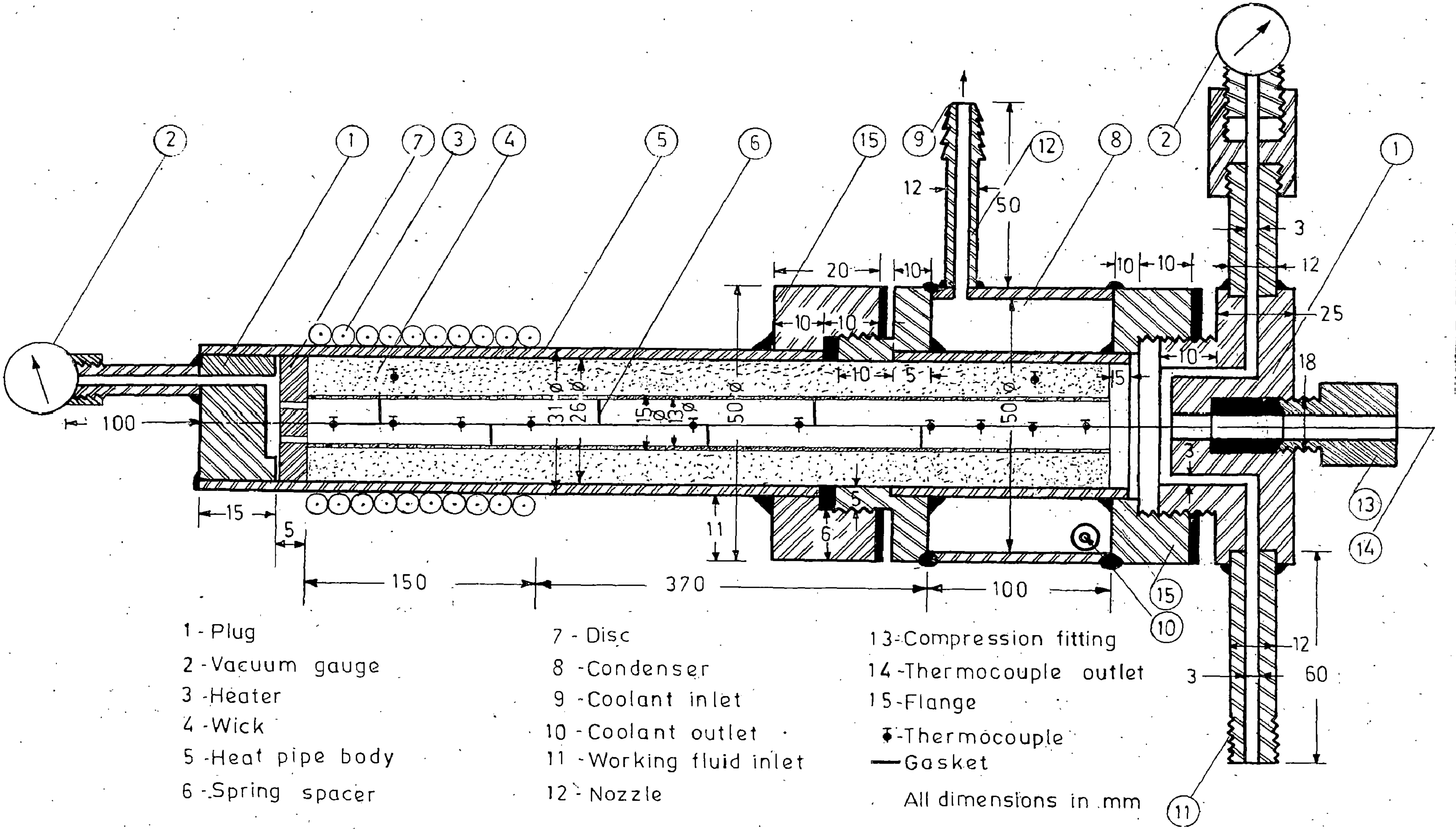

Fig.3.3 Details of the heat pipe assembly

Following subsections discusses the constructional details of various components :

3.2.2 The Wick

Wick was one of the most important components in the heat pipe, so sufficient care and precautions were taken while preparing and installing it in the pipe. Textile (cotton cloth) was used as the material for the preparation of wick. It was made by wrapping white cotton cloth over a stainless steel tube of 15 mm diameter, having 1 mm thickness and a length of 620 mm. (The length of the wick was made equal to that of the combined length of evaporator, adiabatic and condenser sections of the heat pipe). This tube was perforated on both ends upto the distances covering evaporator and condenser sections of the heat pipe. After wrapping several layers of cotton cloth tightly upon the tube, the wick matrix was introduced into the heat pipe body in such a way so that it may get tightly fitted in the pipe. The tube supporting the wick also serves the purpose of a separator between the vapour cover and the wick. As a matter of fact, it is difficult to have a complete adiabatic condition in the section between the evaporator and the condenser due to the subcooling of the vapour. This is due to the transfer of energy either between the liquid in the wick and the vapour moving towards condensing sections or between the condensed vapour on the wick and the liquid inside the wick. The placing of the tube separator between the wick and the core prevents the condensation of the vapor at the towards wick and also the entrainment since vapour in the core and liquid in the wick do not come in the

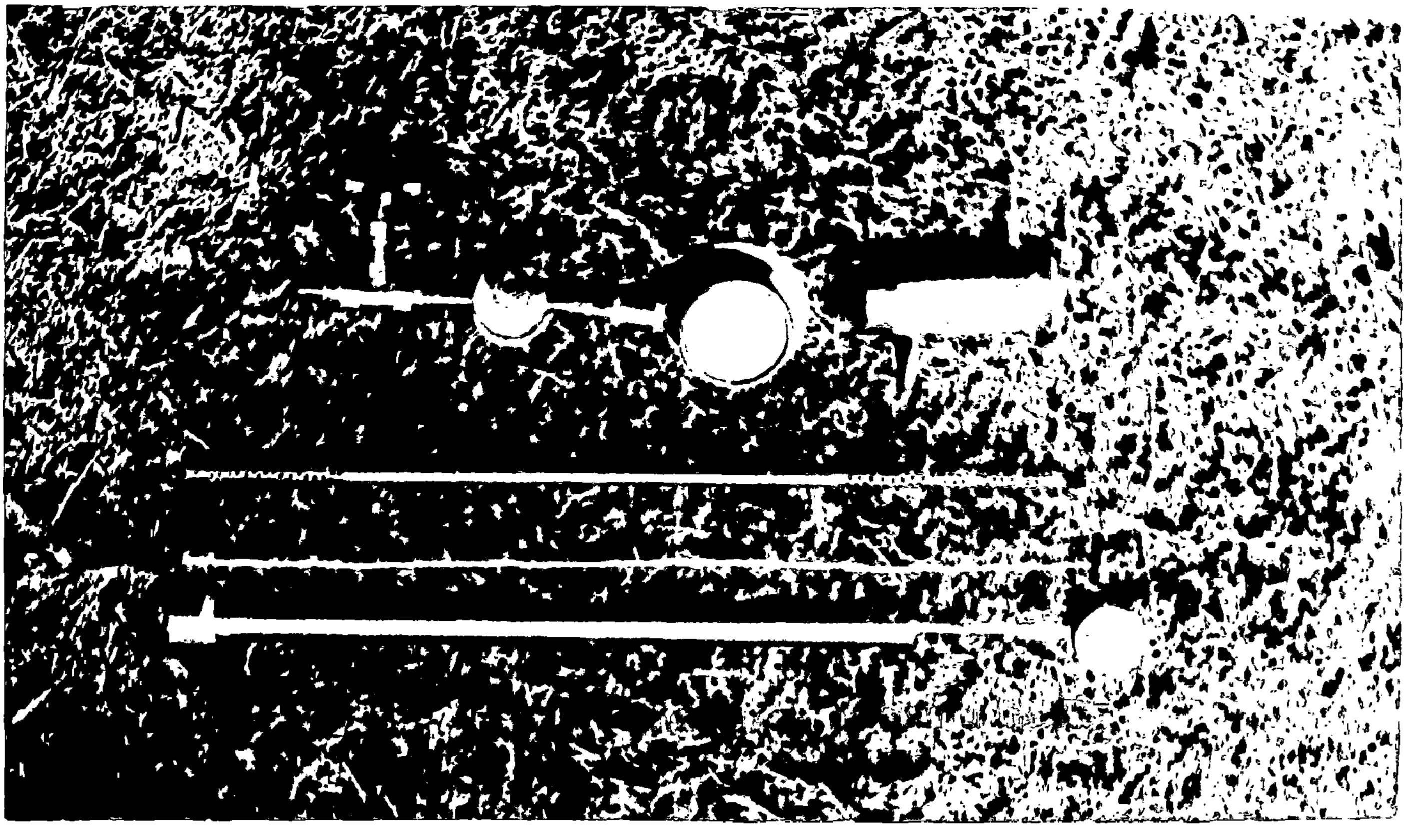

Fig 3.4 (a) Photographic view of heat pipe components

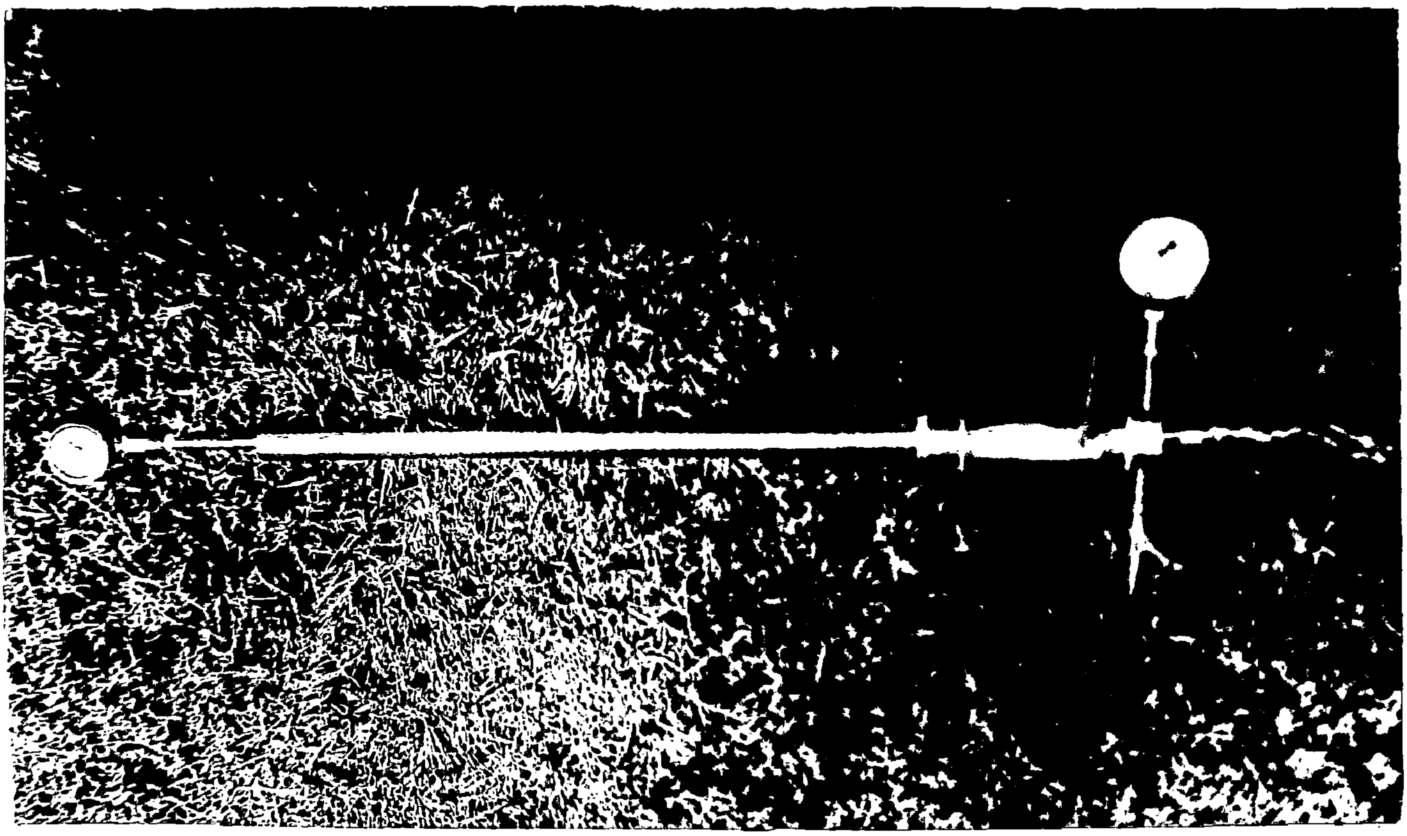

Fig 3.4 (b) Photographic view of heat pipe assembly

direct contact. After the installation of the wick, the heat pipe assembly was completely insulated by glass wool and a covering of asbestos and 85% magnesia powder to reduce the heat losses to the surrounding environment.

3.2.3 Coolant supply system

A perspex jar having a capacity of 5 litres was used as a constant overhead tank for supplying the coolant (water) at a constant volumetric rate of flow which was measured with the help of an home-made rotameter. It was made up out of perspex sheet of 250 mm thickness and had a glass ball as its float. The rotameter measured the flow rate ranging from 2 c.c. to 300 c.c. per minute. Its calibration curve is given in Fig A.1 of Appendix A.

3.2.4 Power Supply System

The heater was energized by means of a contant voltage stablized alternate current. This was regulated by an auto-transformer and measured by calibrated wattmeter supplied by M/s Nippon Electrical Instruments Company Bombay. It had a least count of 5 watts over range of operation of 0 to 300 W.

3.2.5 Evacuation System

The non-condensables (air) from the heat pipe was removed by evacuating it by means of a vacuum pump, connected with a surge tank. The vacuum pump was supplied by M/s International Telephone and Telegraph Corporation, U.S.A. It was of 1/8 H.P. having 1850 rpm. The pressure inside the heat pipe was measured with the help of calibrated vacuum gauges.

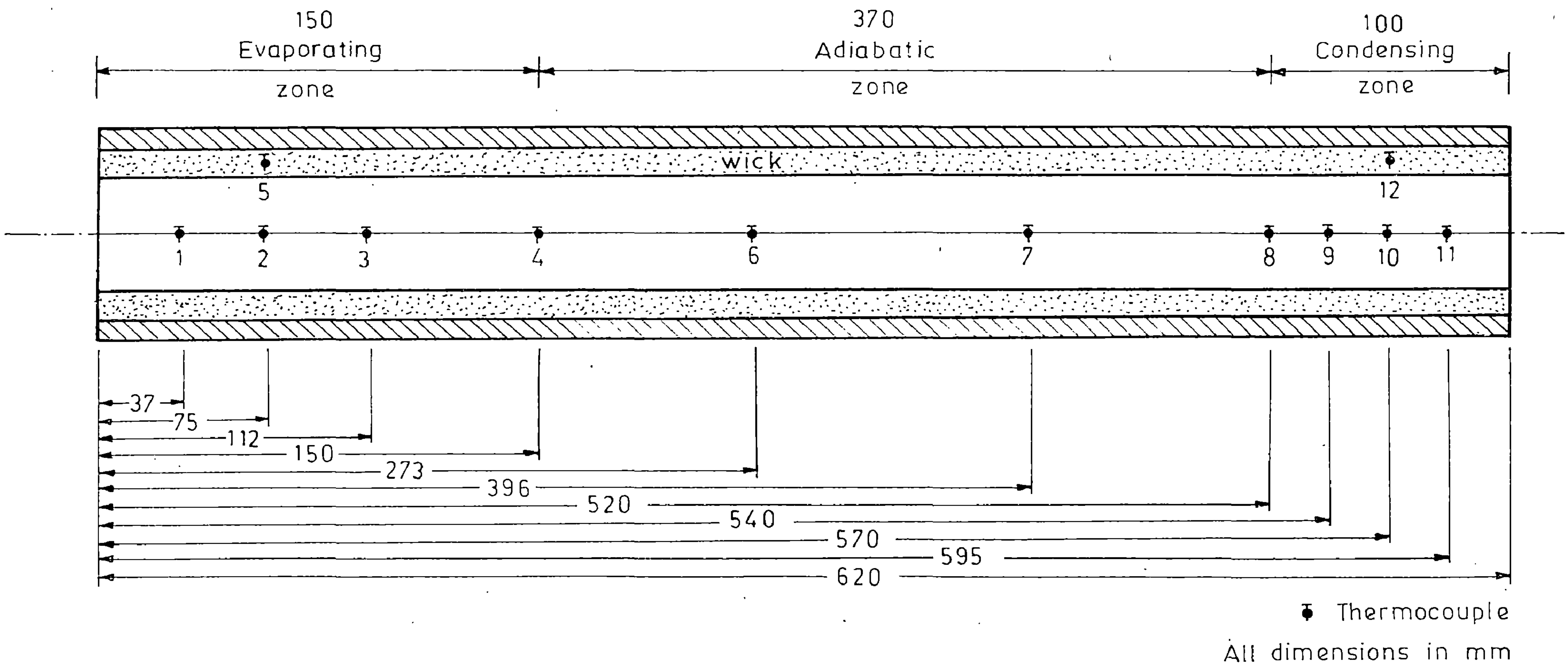

Fig.3.5 Mounted positions of thermocouples

3.2.6 Tilting Device

To change the orientation of the heat pipe a pivot was mounted at the centre of gravity of the heat pipe and its inclination with respect to the horizontal axis was read on a circular graduated disc attached to the pivot.

3.2.7 Temperature Measuring Device

The coolant inlet and outlet bulk temperatures were measured by means of a mercury-in-glass thermometer having a least count of 0.1°C. The temperatures in the wick and in the vapour core of evaporator, adiabatic and condenser sections of the heat pipe were measured by calibrated copper constantan thermocouples (24 gauge). The thermocouples for measuring the temperature in the core were mounted on a stainless steel wire of 1 mm diameter and were held in the centre by fixing several special type of spring-spacers on the wire. The disc provided at the evaporator end also helped in keeping it in central position. After fixing the thermo-couples assembly all the thermocouples were taken out through a plug provided at the end of the condensing section. Compression fittings did not allow any mechanical leakage to take place along the thermocouple wires. All the thermocouples were connected through a cold junction to a Digital Multimeter. The cold junction was kept in a melting ice bath to obtain a reference temperature of 0°C. The e.m.f. of all the thermocouples was measured by a Digital Multimeter supplied by M/s Keithley Instruments Inc, Ohio, U.S.A. Its accuracy for various ranges of operations is is given in Table 3.1

Table 3.1 Accuracy of DMM for various ranges of operation.

Range mv	Maximum Reading mv	Accuracy ± (% digits)
200	199.99	0.5% + 15d
2	1.9999	0.5% + 15d
20	19.999	0.5% + 15 d
200	199.99	0.5% + 15d
1000	1000.0	0.5% + 15d

****

C H A P T E R - 4

EXPERIMENTAL PROCEDURE

The experimenta set up was assembled as shown in Fig 3.1. It was tested against any mechanical and electrical leakages. All the thermocouples were tested for their continuity and were connected to Digital Multimeter through cold junction and a 12-point selector switch. Before conducting the experiments the whole system was cleaned for any foreign matter that may remain within the wick and other components of heat pipe and may reduce the capability of the wick.

4.1 Operating Procedure

First of all, the heat pipe assembly was oriented in the horizontal position and the vacuum pump was switched on to evacuate the system. Then the liquid inlet valve was opened and a measured quantity of the working fluid (distilled water) was allowed to enter the heat pipe. The coolant (water) was introduced in the jacket located at the condensing section through the rotameter from the over-head tank.

For the successful operation of the heat pipe it is essential that it should be highly evacuated as noncondensableseffect the heat transfer rate significantly. Therefore, the system was evacuated by switching on the vacuum pump. After this it was completely sealed. Electric power was switched on and a stabilised regulated and measured wattage was supplied to the heater.

The temperatures at the inlet and outlet of the coolant were measured by mercury-in-glass thermometer. The readings of the thermocouples installed in the vapour core and in the wick were taken at regular intervals. The thermocouples at the evaporator side began to show higher temperature that of others. For this quasi-steady state data were taken and are given in Appendix B. After a continuous operation of 10 hours the readings of all thermocouples, coolant temperature and coolant flow rate become steady. At this condition of steady state thermocouple readings, water flow rate, coolant temperature and the supplied wattage were recorded. The reproducibility of experimental data were checked by conducting a few runs at different times. These were conducted under the same operating conditions and the data were found to be reproducible.

Heat input was increased in steps from lower value to higher value and the experimental data were taken. Similar experiments were conducted for various values of coolant flow rate. The orientations of the heat pipe with respect to the horizontal axis was also varied and a series of experiment runs were conducted in the same manner as has been outlined above. Orientation of the heat pipe has been taken with respect to the horizontal axis. The quantity of the working fluid was also an operating parameter and hence its amount was varied in the heat pipe and the experimental data were conducted. Distilled water was used as the working fluid. The following table given the range of operating variables:

Table 4.1 Range of operating variables

Working fluid quantity, c.c.	Heat input, W	Coolant flow rate, cc/min.	Orientation
130	40,50,60, 70,80	111.25 149.20 169.60 191.00	0-10°
150	40,50,60, 70,80	111 25 149.20 169.60 191.00	0-10°
1[illegible]	4[illegible]50,60, 70,80	111.25 149.20 169.60 191.00	0-10°

The amount of heat output at the condenser end was calculated by the flow rate and the temperature rise in the condenser. The temperature of the insulation and that of the surrounding air was measured and the heat loss to the surroundings by free- convection was calculated by using the method shown in Appendix C- Sample Calculations. It may be mentioned that the temperature of the air surrounding the heat pipe did not vary much (18 to 20°C) for all the experimental runs of this investigation. However, the temperature of the insulation exposed to the surrounding air in adiabatic section was from 27 to 34°C and at the evaporator section from 26 to 30°C. The values of heat inputs, heat output at the condenser end and the heat convected out to the surrounding air through insulation for selected runs are given in Table 4.2 From this table it is seen that the unaccounted losses are only upto 5%.

Table 4.2 Heat balance around the heat pipe

Sl. No.	Heat input, W	Heat output at condenser end, W	Heat loss to the surroundings, W	Unaccounted loss %
	Working fluid quantity		150 c.c.	
	Orientation		5°	
	Coolant flow rate		111.25 c.c./min.	
1.	40	20.8	17.4	4.5
2.	50	27	20.74	3.7
3.	60	33.6	23.8	4.3
4.	70	40.6	25.97	4.9
5.	80	48	27.5	5.6
		Orientation - horizontal		
6.	40	25	13.4	4
7.	50	32	15.4	5.2
8.	60	39	18.12	4.8
9.	70	46.55	20.23	4.6
10.	80	54	22.72	4.1
		Orientation 10°		
11.	40	23.2	14.85	4.8
12.	50	29.75	18.15	4.2
13.	60	36.9	21.00	3.5
14.	70	44.1	22.1	3.4
15.	80	52	24.4	4.5

CHAPTER - 5

RESULTS AND DISCUSSION

Experimental data were conducted for the study of the performance of heat pipe under the conditions of varying heat inputs, coolant flow rates, working fluid quantities and inclinations with respect to horizontal axis. The data are given in Appendix B.

The salient results obtained from the experimental data are discussed in the following sections:

5.1 Limitations of Experimentation

The experiments were carried out for various values of heat inputs. Its higher value was fixed by the temperature of the wick and the lower value by the quantity of heat removed at the condenser section. These were determined by conducting series of experiments for various values of heat inputs. The present experimental facility could not be evacuated to a very high degree.

5.2 Temperature profile along Heat Pipe Length

From the experimental data of Appendix B the temperature profile along the length of heat pipe was obtained for the transient and steady state conditions which are discussed as follows:

Figure 5.1 represents the variation of temperature along the length of the heat pipe at various intervals of time of operation.

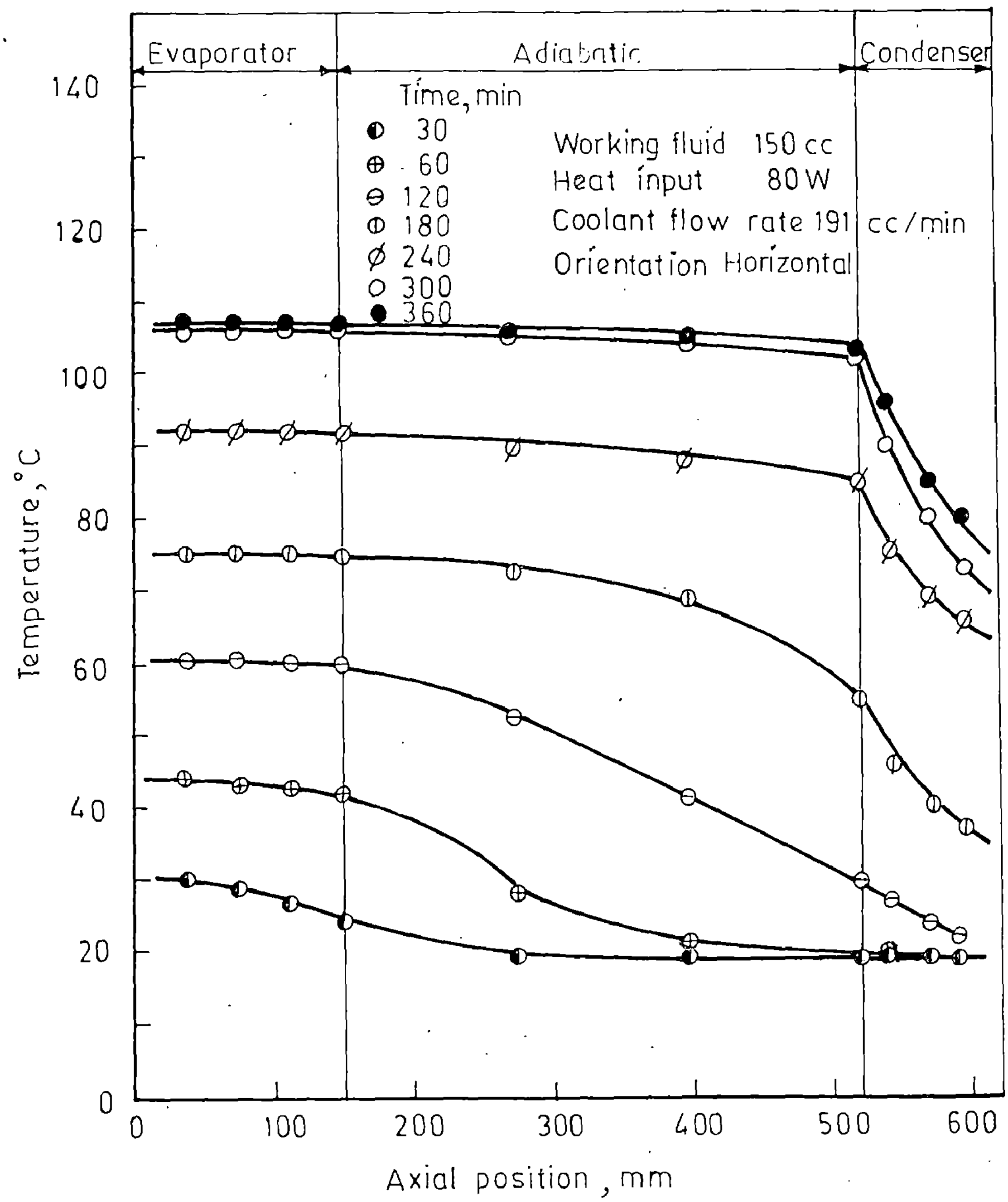

Fig 5.1 Transient temperature profiles along the length of heat pipe

It is for the working fluid quantity 150 c.c., heat input 80 W, coolant flow rate 111.25 c.c./min. and for horizontal position of the heat pipe. This shows the following characteristics:

1. At a given time of operation, the temperature in the evaporator section is higher than that of in the adiabatic and condenser sections. However, after a large time of operation the temperature in a part of the adiabatic section becomes equal to that of in the evaporator section. Further, the temperature drops sharply in the condenser section. This trend retains undisturbed till the condition of steady state is attained.

2. As the time of operation increases the temperature in all the sections of the heat pipe - evaporator, adiabatic and condenser increases and ultimately the temperature in the evaporator section reaches to its maximum value corresponding to the vapour pressure in the evaporator.

These observations are consistant and can be explained by the fact that as heat is supplied in evaporator, the temperature of the liquid rises and the vapour is formed whereas the liquid present in other sections of the heat pipe remains cold. Therefore, the temperature in the evaporator is higher than that of in other sections. Initially the vapours are small in quantity and low in pressure hence they loose their heat only in preheating the liquid present in the adiabatic and further in condenser section. After sometime the temperature of the liquid present in the adiabatic section becomes equal to its saturation temperature. At this

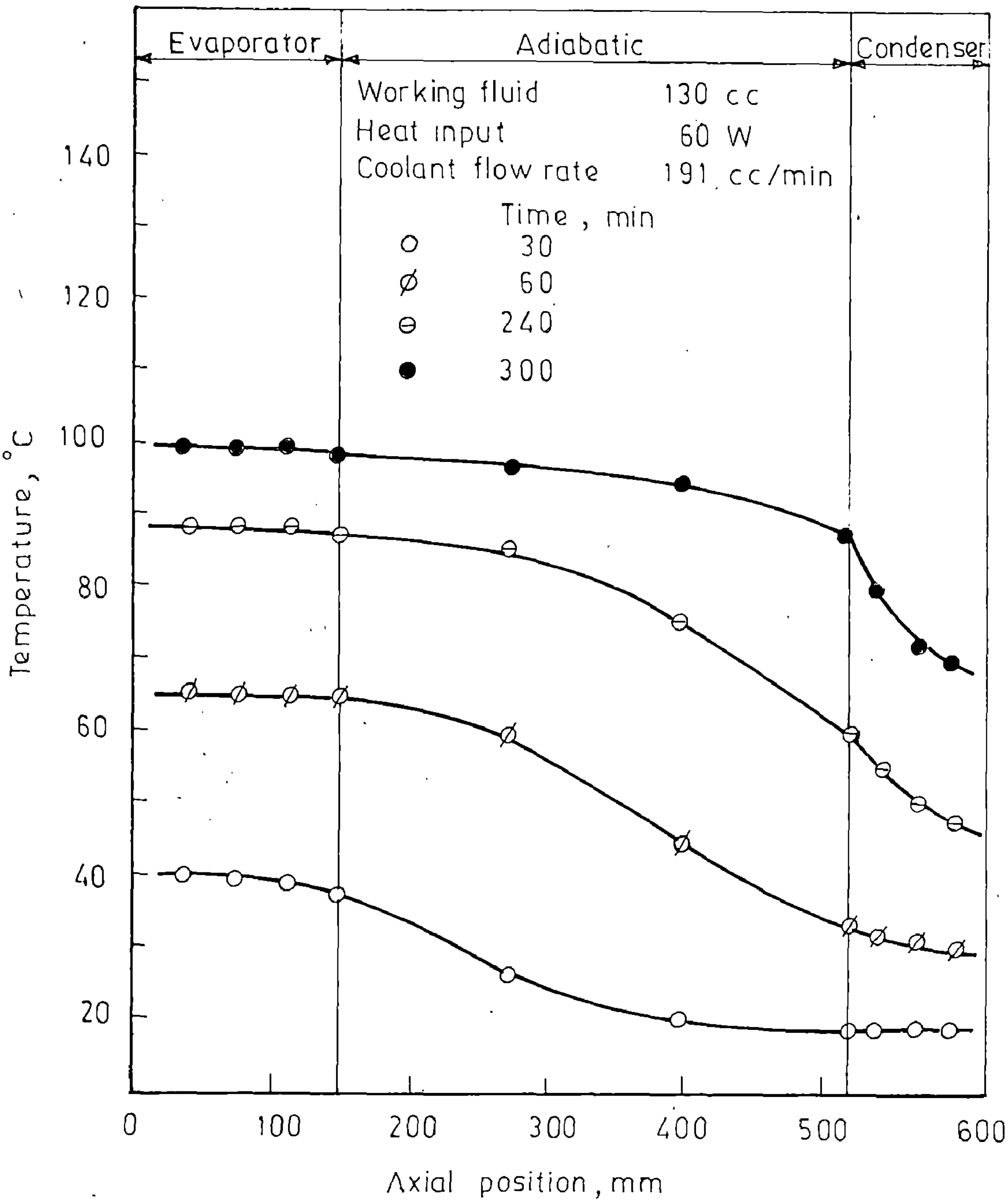

Fig 5.2 Transient temperature profiles along the length of heat pipe

condition the vapour does not exchange heat appreciably with the liquid in the adiabatic section and gets rapidly cooled in the condenser. Thus the temperature in the adiabatic section becomes equal to that of the evaporator section. In the condenser section the condensation of the vapour takes place and the pressure drops sharply. This makes the temperature in the condenser section to drop rapidly.

Figure 5.2 is a similar plot of the temperature profile along the length of heat pipe for the working fluid (distilled water) quantity of 130 c.c., heat input of 60 W, coolant flow rate 191 c.c. per minute and for the horizontal position of the heat pipe.

5.3 Effect of Coolant Flow Rate and Heat Input on Heat Pipe Performance

The performance of the heat pipe has been studied under the varying conditions of coolant flow rate, heat inputs, working fluid (distilled water) quantities and for various orientation of the heat pipe. The following section discusses the effect of the variables on the temperature profile along the length of heat pipe and on the performance of the heat pipe :

Figure 5.3 has been drawn to show the effect of coolant flow rate on the temperature profile along the length of the heat pipe for the working fluid (distilled water) quantity 150 c.c., heat input 80 W and for horizontal orientation. This plot has two distinct curves - the upper one is for the lower coolant flow rate (111.25 c.c/min.) and the lower one for high coolant flow

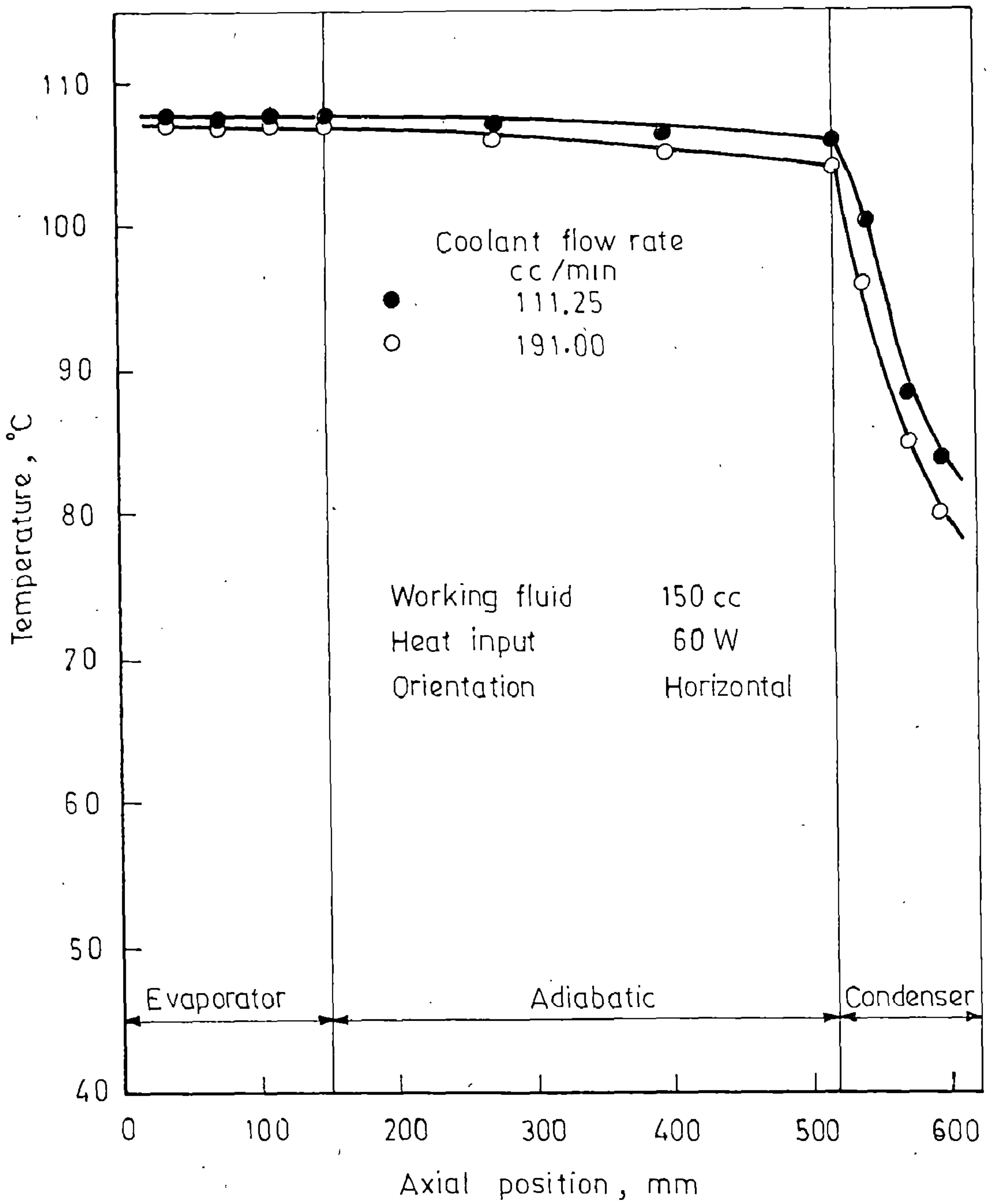

Fig. 5.3 Temperature profile along the length of heat pipe with coolant flow rate as a parameter

rate (191 c.c./min). This decrease in temperature due to the increase in coolant flow rate can be explained as follows: An increase in coolant flow rate increases the turbulence which, inturn, decreases the resistance to heat transfer on the coolant side and so the overall resistance. This allows more heat to be taken out from the condenser which, in turn, decreases the pressure and temperature in the condenser section. Subsequently, the pressure and temperature in the evaporator decreases and thus the temperature along the heat pipe decreases.

In figure 5.4 temperature variation along the length of heat pipe for the range of heat input from 40 to 80 W has been shown. This plot indicates that as the heat input is increased, the temperature in all the sections of the heat pipe increases. However, the increase in temperature is not in proportion to the increase in heat inputs. This is due to the reason that as the heat input is increased, more amount of vapour is formed. As the rate of condensation on the condensing side does not increase appreciably so the pressure in the heat pipe increases and reaches to steady pressure which, in turn, increases the temperature in the heat pipe.

Performance of the heat pipe defined by the heat picked-up by the coolant at the end to the heat input was calculated for all the experimental data as shown in Appendix C -Sample Calculations.

Figures 5.5 to 5.7 show the performance of the heat pipe as a function of the heat input with coolant flow rate as a parameter. These plots are for $0^{o}, 5^{o}$ and 10^{o} orientations respectively. From these curves the following points are observed:

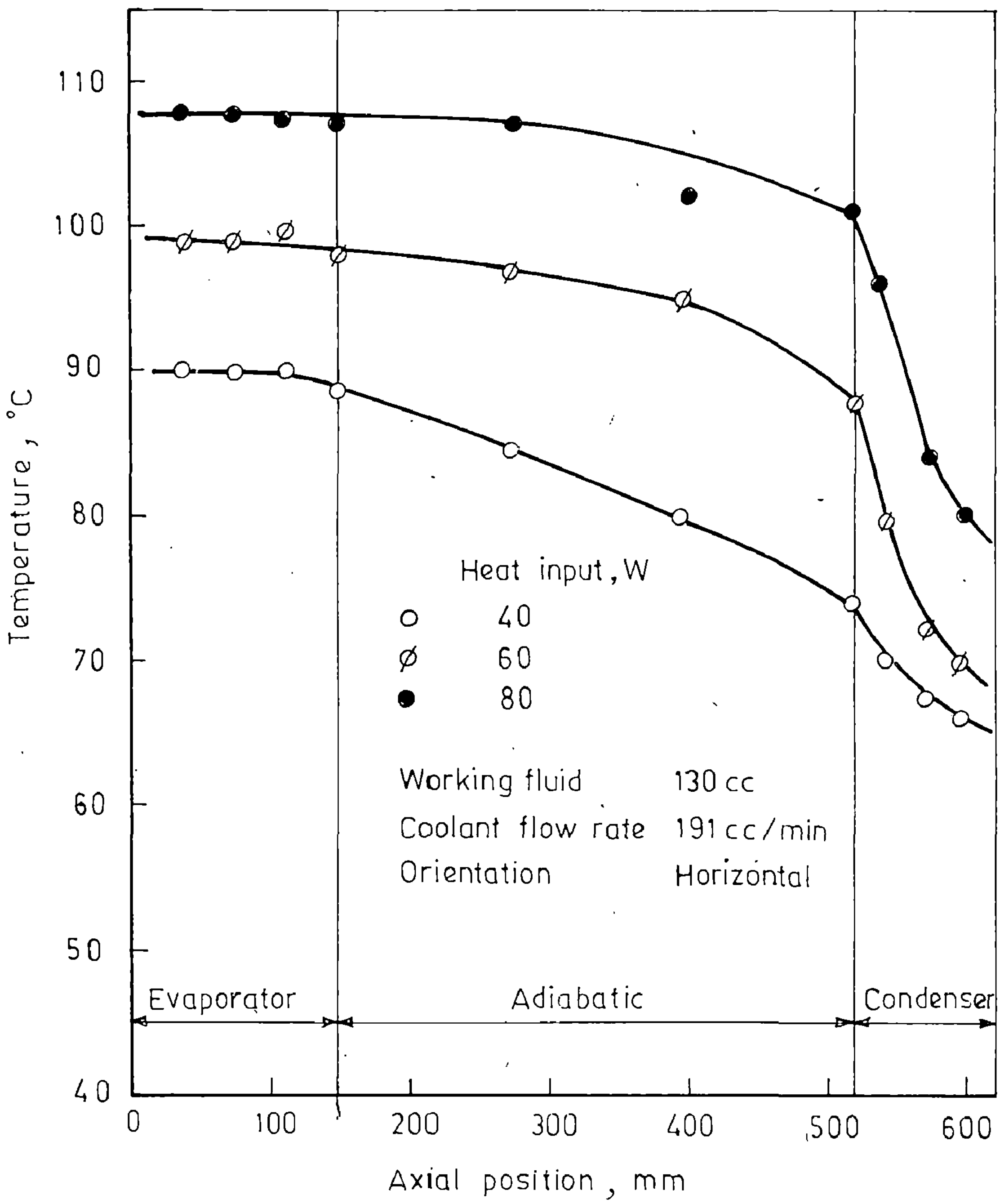

Fig 5.4 Temperature profile along the length of heat pipe with heat input as a parameter

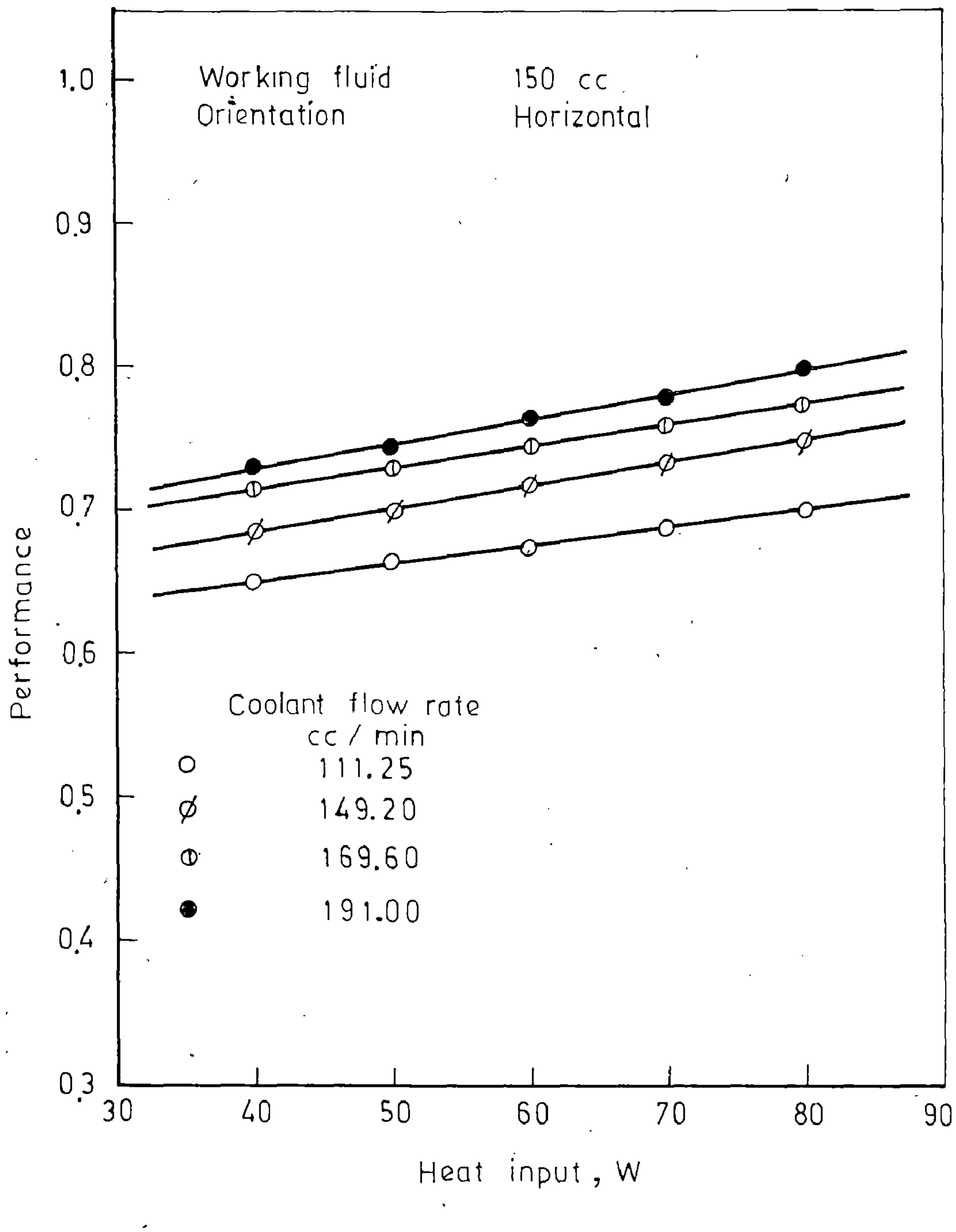

Fig 5.5 Plot of heat input vs performance with coolant flow rate as a parameter

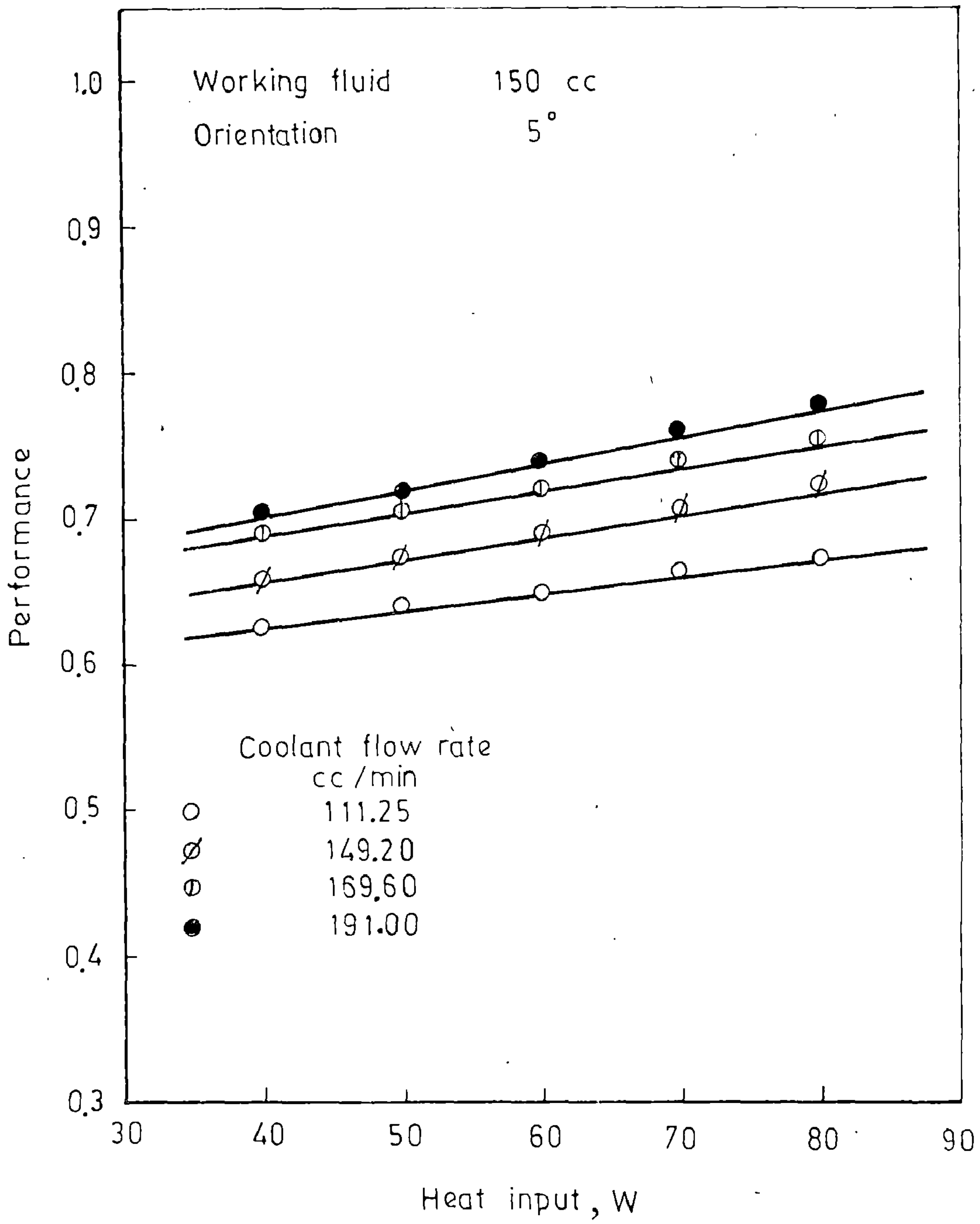

Fig 5.6 Plot of heat input vs performance with coolant flow rate as a parameter

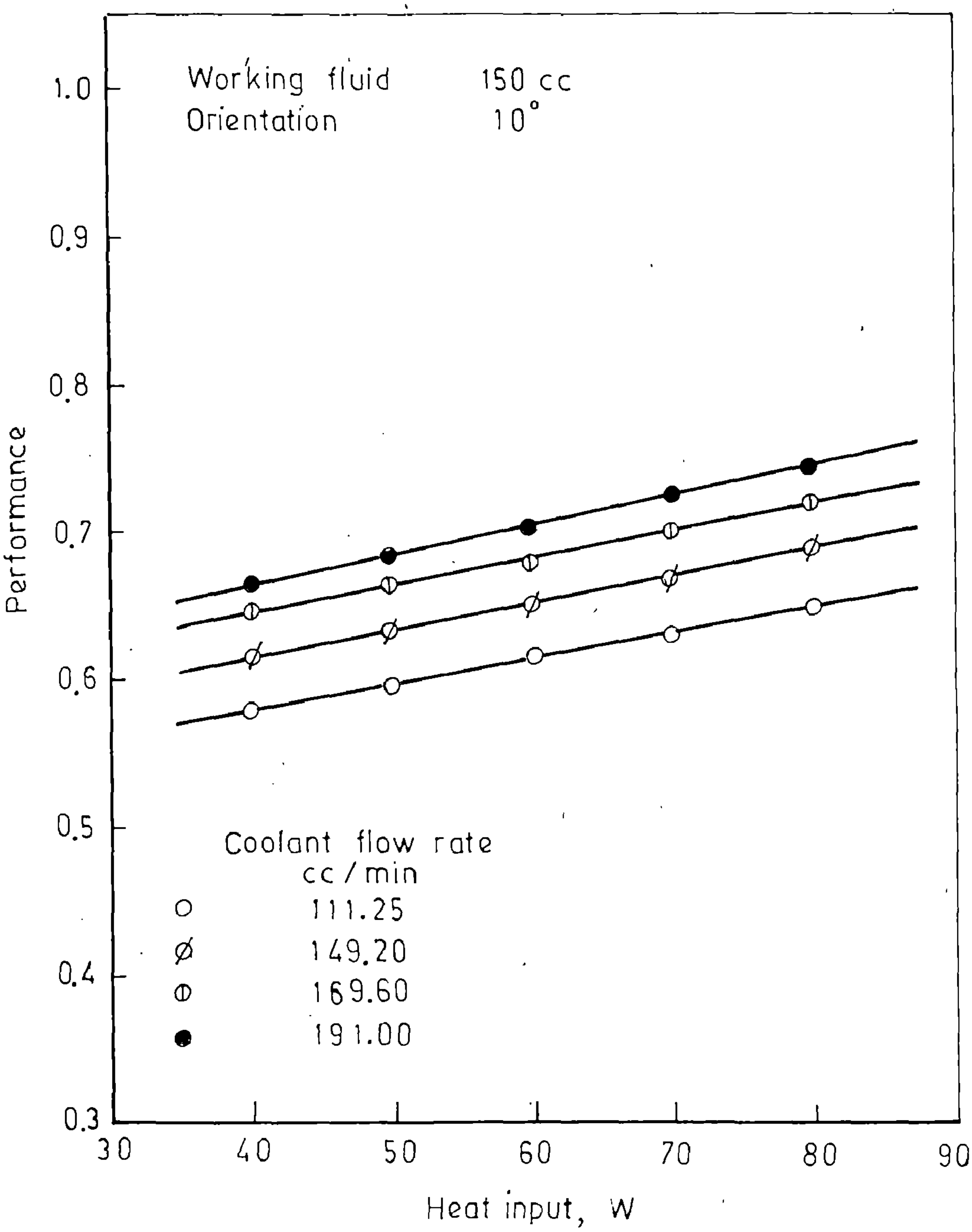

Fig 5.7 Plot of heat input vs performance with coolant flow rate as a parameter

1. The performance of the heat pipe increases linearly with an increase in heat input.
2. An increase in coolant flow rate increases the performance of the heat pipe.

As explained earlier an increase in coolant flow rate decreases the resistance in the path of heat flow on coolant side of the condenser which, in turn, increases the amount of heat picked up by the coolant and so the performance of the heat pipe, An increase in heat input increases the temperature in the all sections of the heat pipe and therefore more amount of heat is picked up by the coolant.

5.4 Effect of Orientation on Heat Pipe Performance

Figure 5.8 is a typical plot of temperature profile along the length of heat pipe for the horizontal and 10° orientation. This is for the working fluid quantity of 130 c.c., heat input 60W and for coolant flow rate of 191.0 c.c./min. It can be seen from this plot that as the orientation of heat pipe (evaporator above the condenser) is increased the temperature in the evaporator section becomes higher and in the condenser section lower. This particular behaviour of the curve can be explained as follows: As a matter of fact, any tilt of the heat pipe placing the condenser below the evaporator reduces the amount of the condensate returned to the evaporator by the capillary action of the wick and the vapour generated in the evaporator section becomes superheated. These vapours on way to the condenser exchanges its heat appreciably with

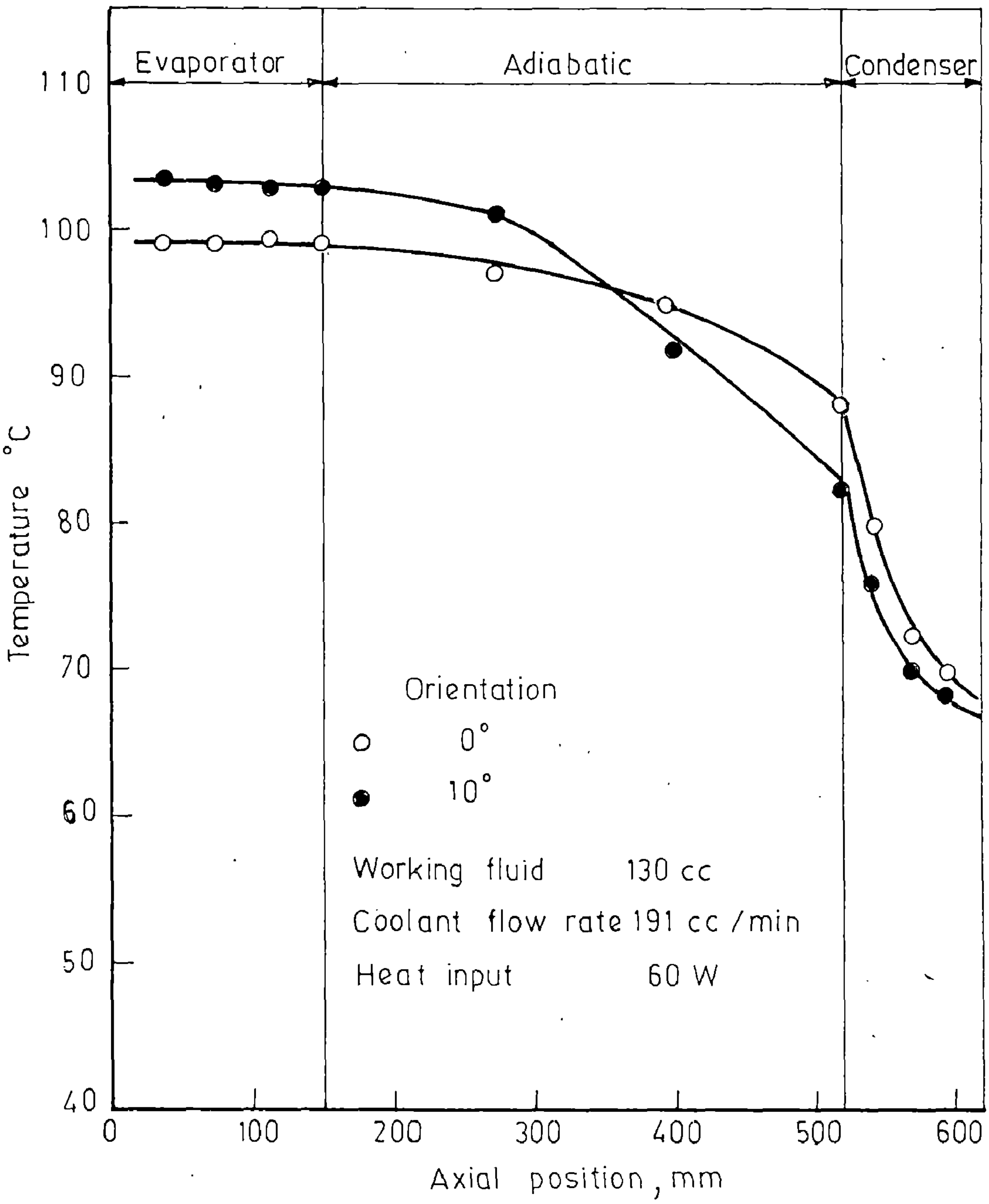

Fig 5.8 Variation of temperature along the length of heat pipe as a function of its orientation

the condensate present in the wick in the adiabatic section and thus the vapour temperature decreases significantly and further in the condenser section.

To show the effect of orientation of the heat pipe on its performance plots were prepared for various values of heat inputs and coolant flow rates. Figure 5.9 is one of such plots. This plot indicates that the performance of the heat pipe is a function of the heat pipe orientation. It decreases as the heat pipe is tilted more towards the vertical position keeping condenser below the evaporator. This variation is due to the decrease in the amount of the condensate returned to the evaporation and the formation of liquid pool at the condenser end. This will add to the resistance and thus the heat picked up by the coolant decrrases which in turn decreases the performance of the heat pipe.

5.5 Effect of Working Fluid Quantity on Temperature Profile and Performance of the Heat Pipe

In order to demonstrate the effect of working fluid (distilled water) quantity on the temperature profile of the heat pipe, figure 5.10 has been drawn. This plot has three curves each representing a particular amount of the working fluid. This plot shows that for the heat pipe containing 130 c.c. working fluid the temperature in the evaporator section is higher than that of the curves for 150 c.c. and 170 c.c. working fluids. However its value in the condenser section is lower than that of for other two curves. The temperature profile for 170 c.c. working fluid quantity in evaporator and condenser sections lies between the curves for 130 cc. and 150 c.c. This phenomena can be explained as follows :

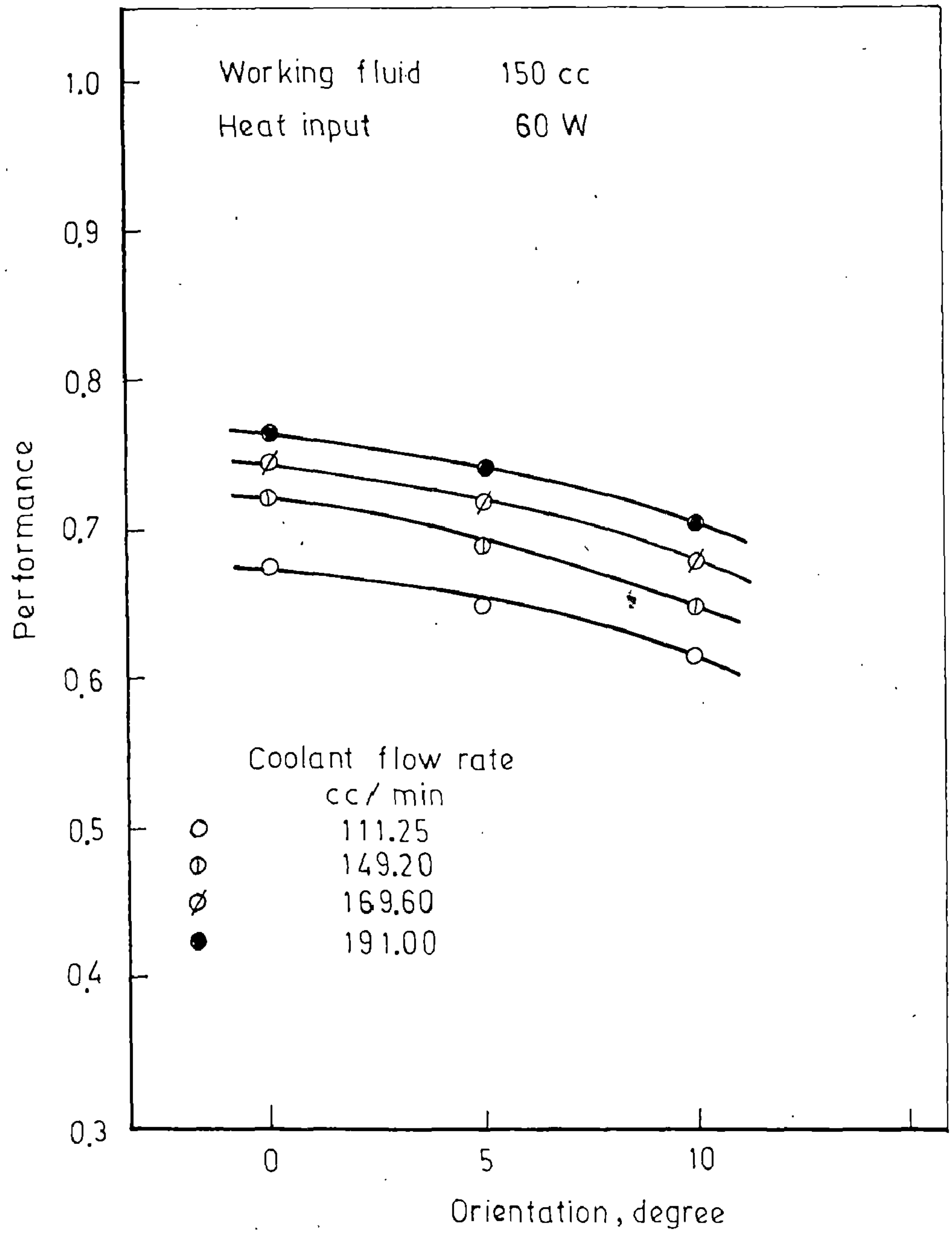

Fig 5.9 Effect of orientation of heat pipe on its performance as a function of coolant flow rate

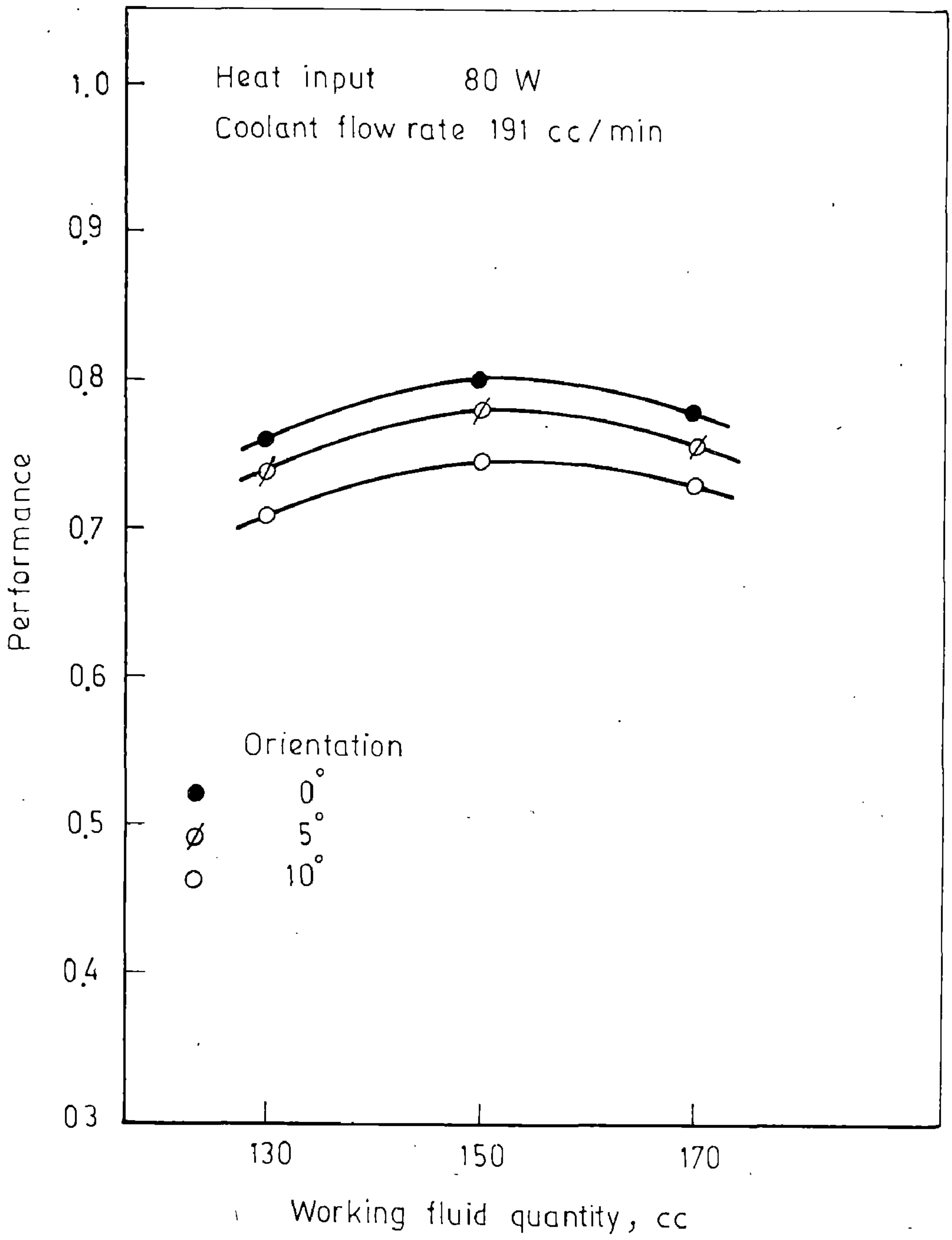

Fig 5.11 Plot of working fluid quantity vs performance as a function of heat pipe orientation

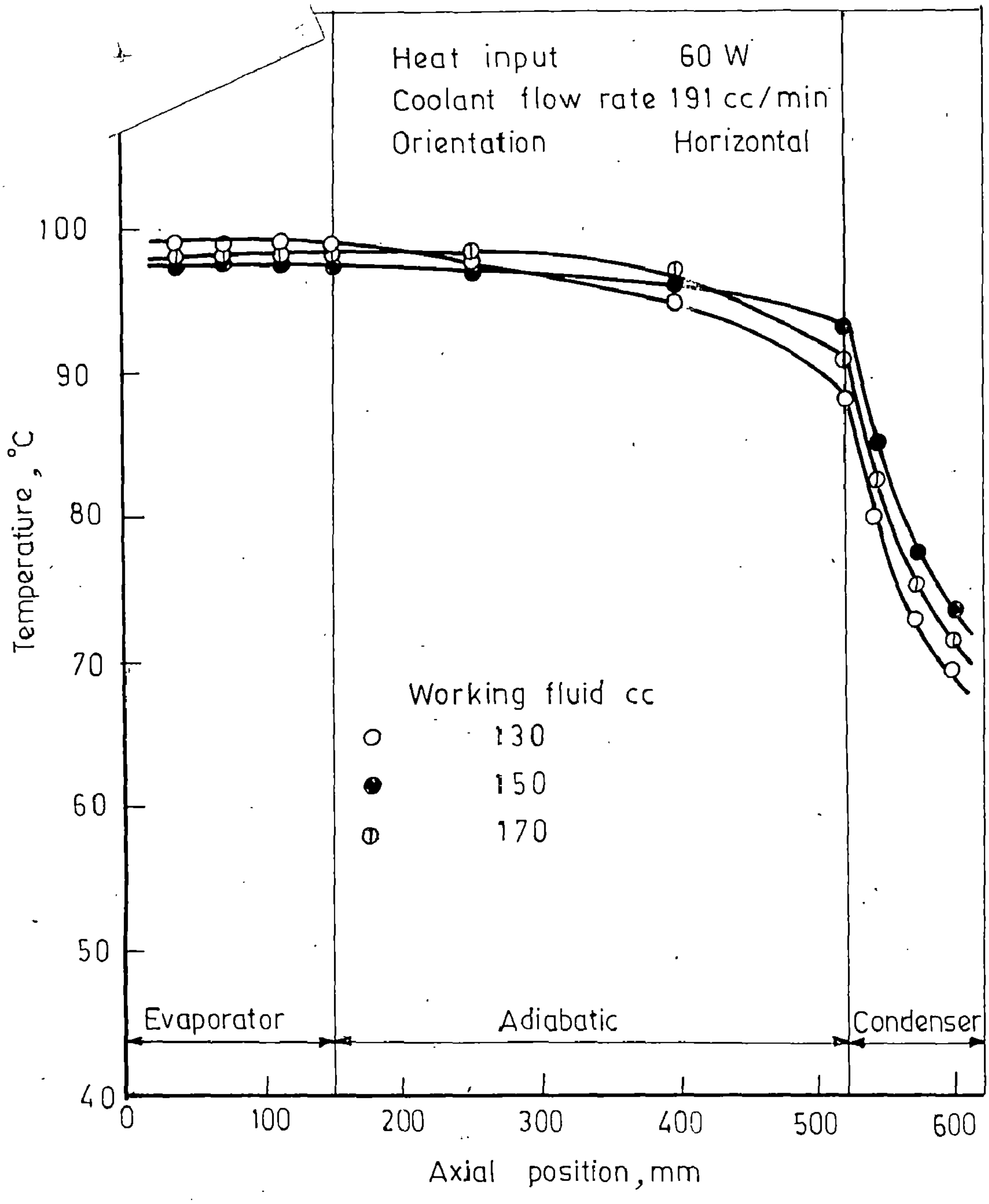

Fig 5.10 Effect of working fluid quantity on the temperature in heat pipe

Insufficient quantity of working fluid fails to supply sufficient liquid to evaporator section when the evaporation and the capillary pumping ability of the wick are more than the working fluid present in the heat pipe. This creats a condition in which the wick in the evaporator section starves and thus superheated vapours are produced. It gives away the superheat while passing through the adiabatic section and condenses in the condenser section at a lower temperature. This observation is quite clear for the case of 130 c.c. working fluid quantity.

When the working fluid quantity is increased to meet the evaporation demand within the capillary pumping ability of the wick, evaporation of the liquid produces saturated vapour in large quantity and thus the evaporator temperature decreases and condenser temperature increases. In such cases a high performance of heat pipe is observed. The performance of heat pipe for three different quantities of working fluids i.e. 130 c.c., 150 c.c. and 170 c.c. are ploted in figure 5.11. It shows that performance is poor in the case of working fluid quantity 170 c.c. than that of in the 150 c.c. This can be explained as follows: When the working fluid quantity increases than a certain optimal value which is a function of wick pumping capability, the performance of heat pipe decreases. The excess liquid present in the heat pipe gets accumulated in the condenser zone and creats a barrier in the way of heat transfer This decreases the out flowing of heat from the condenser and hence the performance.

CHAPTER - 6

CONCLUSIONS AND RECOMMENDATIONS

The main conclusions emerging out from the present investigation are :

1. The temperature in the evaporator section remains almost uniform but it decreases sharply in the condenser section during transient and steady state operations of the heat pipe.
2. Heat pipe performance is enhanced by the increase in coolant flow rates and the heat inputs.
3. Tilting of the heat pipe (evaporator above condenser) decreases the performance of the heat pipe.
4. An increase in the working fluid quantity changes the heat output at the condenser section.

As a result of the present investigation, the following points emerge for future research work:

1. To obtain the generalized effect of the parameter experiments should be conducted for various working fluids.
2. In order to investigate the wicking limit, experiments should be conducted with various wicks of differing materials and sizes such as stainless steel screen, sintered, grooved etc.
3. A high degree of vacuum in the heat pipe will enhance its performance. Therefore, it is recommended that experiments should be carried out under the condition of negative pressure of high order.

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APPENDIX - A

CALIBRATION OF INSTRUMENTS

The measuring instruments - rotameter, Vacuum gauge and the thermocouples were calibrated by using the methods given below:

A.1 Calibration of Rotameter

The home-made rotameter was used to measure the volumetric flow rate of the coolant (water). It was calibrated by using the simple method of measuring the amount of water flowing through it per unit time. The calibration curve of rotameter has been shown in Fig. A.1.

A.2 Calibration of Thermocouples

Twelve numbers of copper-constantan thermocouple (24 gauge) have been used for measuring the temperatures in the heat pipe. Before mounting them to the positions of Fig 3.5. They were calibrated at the boiling point of distilled water and at several other temperatures using a constant temperature bath and measuring the temperature by a thermometer of high accuracy. It was found that thermocouples numbering 1 to 6 show a temperature 3.5^{o}C more than that of thermometer. Thermocouples numbering from 7 to 12 also registered 1.6^{o}C temperature higher than indicated by the thermometer.

A.3 Calibration of Vacuum Gauge

Vacuum gauges were calibrated by using a simple U-tube mercury manometer. The results of the calibration for the vacuum gauges has been shown in Figures A.2 and A.3.

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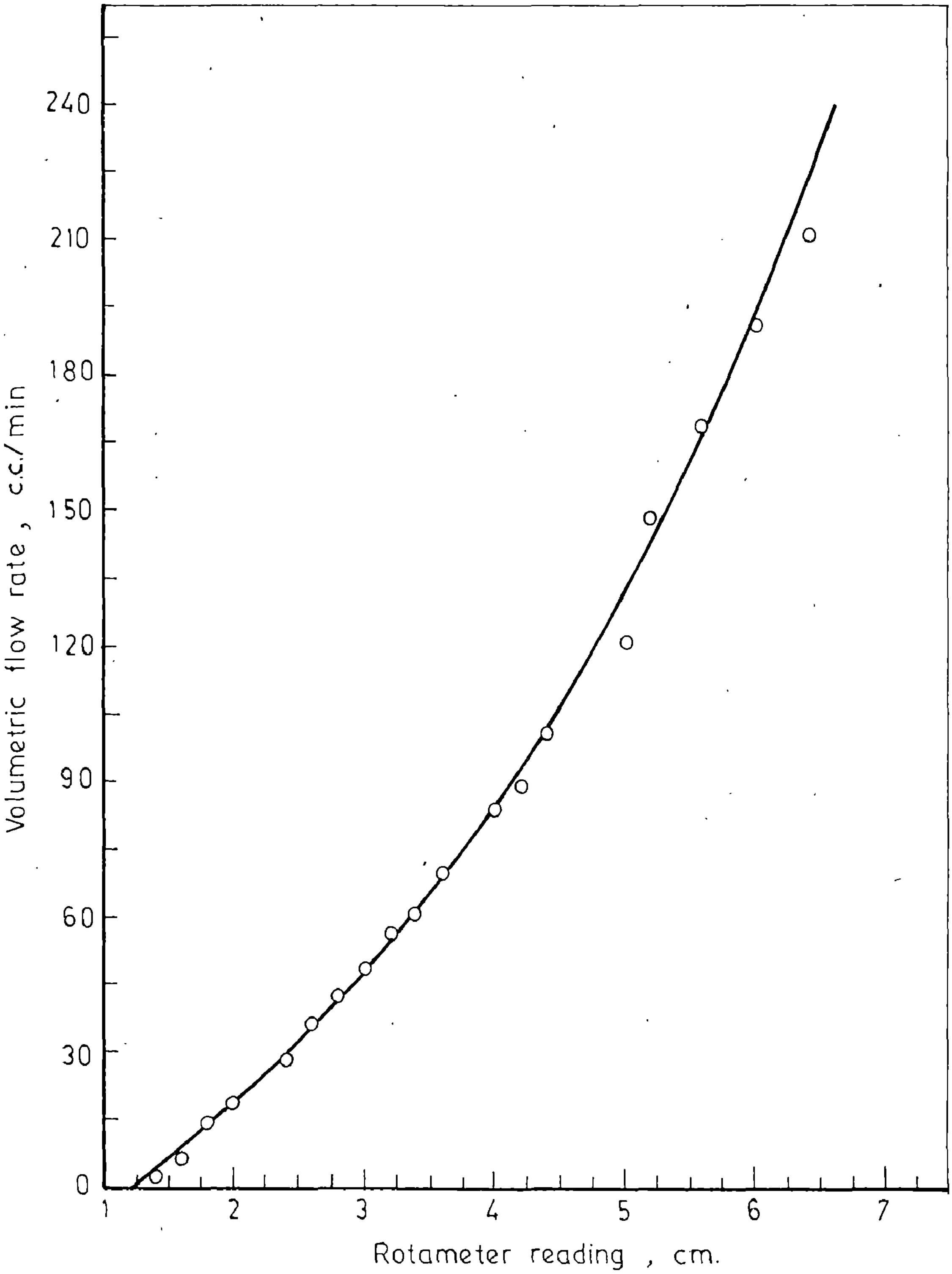

Fig A.1 Calibration curve of rotameter

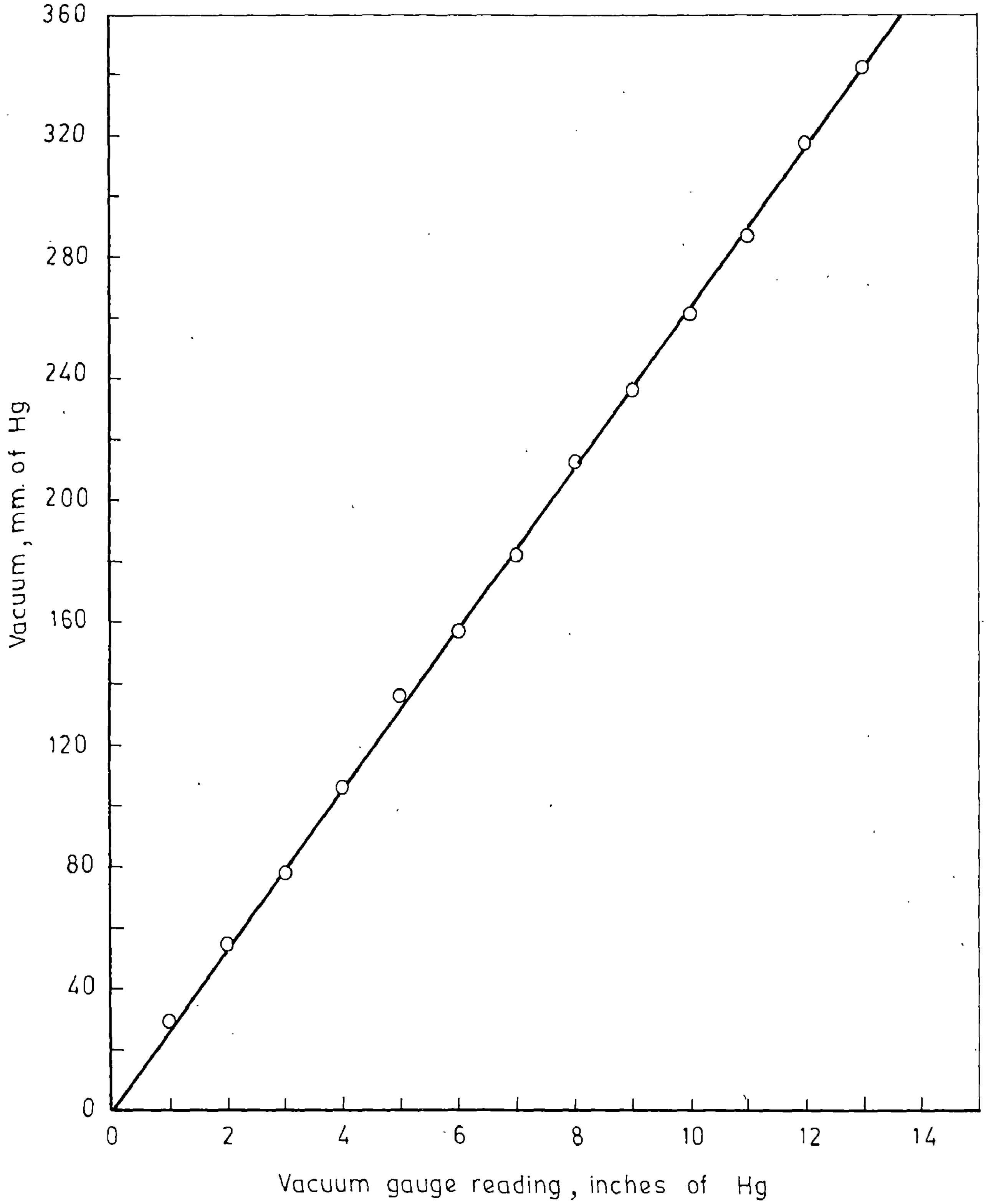

Fig A.2 Calibration curve of vacuum gauge I

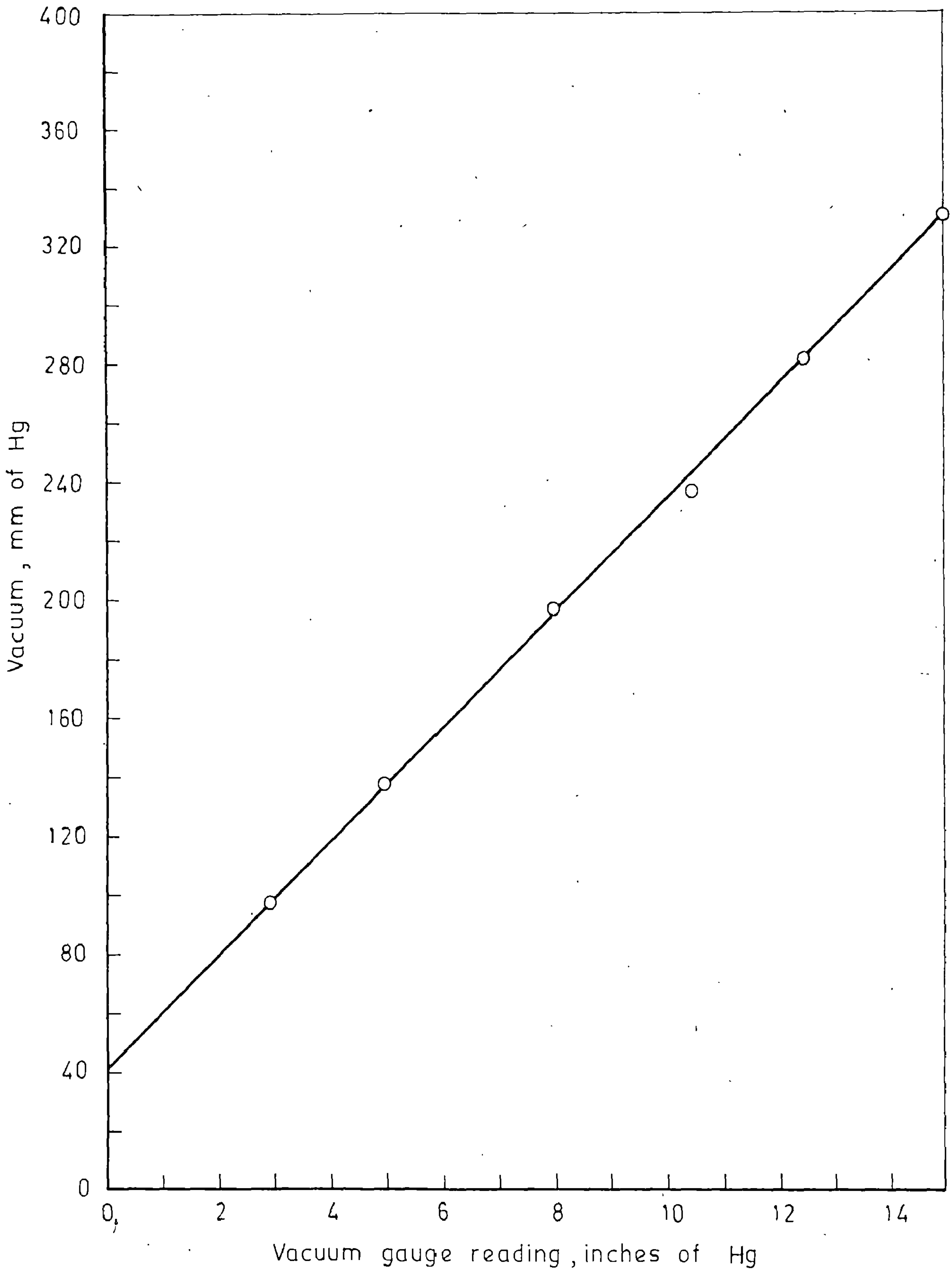

Fig A.3 Calibration curve of vacuum gauge II

APPENDIX - B

EXPERIMENTAL DATA

Table B.1 Experimental data for the transient temperature profile along the length of heat pipe.

Run No.	Time, minute	Coolant flow rate, cc/min.	Temperature, °C — Evaporation Zone — Vapour Core				Wick		Adiabatic Zone		Condenser Zone.		Wick		Coolant inlet temp., °C	Coolant outlet temp., °C
i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
		Working fluid 150 cc.														
		Orientation horizontal														
		Heat input 80 W														
1	30	191	30	29	27	24.5	31.0	19.5	19.5	19.5	19.5	19.5	19.5	19.5	18.5	18.5
2	60	191	44	43	42.5	42.0	45.0	28.5	22.1	19.5	19.5	19.5	19.5	19.5	18.5	18.5
3	120	191	60.5	60	59.9	59.0	61.5	53.0	42.0	30.0	28.5	24.5	22.5	20.4	18.6	18.8
4	180	191	75	74.9	74.5	74.2	76.0	72.9	69.2	55.1	46.1	40.0	37.1	33.2	18.5	19.5
5	240	191	92	91.8	91.8	91.5	93.0	90.1	88.2	85.1	75.9	69.2	66.1	63.2	18.5	21.3
6	300	191	106	105.9	105.9	105.9	107.0	105.1	104.8	100.1	90.1	82.0	72.8	71.6	18.6	22.5
7	360	191	106	105.9	105.9	105.9	107.0	105.2	105.0	104.1	95.5	85.2	80.1	78.0	18.6	23.4
		working fluid 130 cc														
		orientation horizontal														
		heat input 60W														
8	30	191	40	39.5	39.0	37.1	41.0	26.1	20.0	19.1	19.1	19.1	19.1	19.1	18.5	1855
9	60	191	66	65	64.1	64.0	67.0	59.1	45.1	33.1	32.1	30.2	30.0	26.7	18.5	19.5
10	240	191	88.5	88.0	87.8	87.0	89.5	85.1	74.9	60.2	55.1	50.0	48.1	45.2	18.6	20.5
11	300	191	99.5	99.2	99.3	98.0	100.5	97.1	95.0	88.1	80.0	72.2	70.0	67.5	18.6	21.8

Table B.2 Experimental data for the study of performance and temperature profile along the length of the heat pipe

Run No.	Heat input, watts.	Coolant Flow rate, cc/min.	Temperature, oC: Evaporator Zone: Vapour		Core		Wick	Adiabatic zone: Vapour	Core	Condenser Zone: Vapour		Core	Wick	Coolant inlet temp, oC		Coolant outlet temp, oC
i.	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12.	iv	v
			Working fluid quantity 130 c.c. Orientation horizontal													
1	40	111.25	91.2	91.1	91.0	90.9	92.3	88.6	83.8	78.8	75.8	71.0	69.0	67.0	18.5	21.5
2	40	149.2	91.0	90.8	90.7	89.7	91.1	86.9	81.9	76.0	72.9	69.8	67.8	66.1	1855	20.9
3	40	169.6	90.5	90.3	90.3	89.0	91.6	85.0	80.6	74.7	70.6	68.6	66.7	64.9	18.5	20.7
4	40	191.0	90.0	89.8	89.9	88.5	91.1	84.5	80.1	74.0	70.0	67.5	66.0	64.1	18.5	20.5
5	50	111.25	96.1	96.0	95.9	95.8	97.1	95.2	90.7	90.2	81.0	73.9	71.5	66.4	18.6	22.5
6	50	149.2	95.0	94.9	94.8	94.7	96.0	94.1	89.6	88.4	79.4	71.5	69.7	65.1	18.6	21.7
7	50	169.6	94.5	94.4	94.3	94.2	95.5	93.6	89.1	87.4	78.0	70.4	68.8	65.6	18.7	21.5
8	50	191.0	94.2	94.3	94.3	94.2	95.2	93.3	88.8	86.9	77.5	69.9	68.0	65.9	18.6	21.2
9	60	111.25	101.5	101.4	101.3	101.2	102.5	99.6	96.4	89.9	82.0	75.9	74.0	70.0	18.5	23.3
10	60	148.25	100.2	100.1	100.1	100.0	101.2	98.3	95.8	88.7	80.9	74.0	72.0	69.0	18.5	22.3
11	60	169.6	99.8	99.5	99.5	98.4	100.7	97.5	95.3	88.3	80.4	72.9	70.8	68.1	18.5	22.0
12	60	191.0	99.5	99.0	99.2	98.0	100.4	97.0	95.0	88.0	80.0	72 5	70.3	67.5	18.6	21.8
13	70	111.25	106.5	106.4	106.4	106.3	107.5	105.5	100.1	99.1	95.1	83.2	79.2	76.2	18.5	24.3
14	70	149.2	105.4	105.3	105.1	105.0	106.4	104.4	99.0	98.0	94.1	82.1	78.1	75.1	18.5	23.1
15	70	169.6	104.8	104.7	104.6	104.5	105.8	103.8	98.4	97.4	93.5	81.5	77.5	74.6	18.6	22.8
16	70	191.0	104.5	104.4	104.4	104.2	105.5	103.5	98.1	97.1	93.2	81.2	77.2	74.3	18.6	22.5

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
17	80	111.25	110.1	110.0	109.9	109.8	111.1	109.1	104.0	103.4	98.1	86.0	82.3	78.8	18.6	25.3
18	80	149.2	109.0	108.9	108.8	108.6	110.0	108.1	102.9	102.3	97.0	84.9	81.2	77.7	18.7	24.1
19	80	169.6	108.5	108.4	108.4	108.3	109.5	107.6	102.4	101.8	96.5	84.4	80.7	77.2	18.5	23.4
20	80	191.0	108.2	108.1	108.1	108.0	109.2	107.3	102.1	101.5	96.2	84.1	80.4	76.9	18.6	23.2

working fluid quantity - 130 c.c.

orientation 5°

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
21	40	111.25	92.7	92.6	92.5	92.4	93.7	90.1	82.8	77.8	74.7	69.8	67.8	65.2	18.6	21.5
22	40	149.2	91.6	91.5	91.5	91.4	92.6	89.0	81.7	76.7	73.6	68.7	66.7	64.1	18.5	20.8
23	40	169.6	91.1	91.0	91.0	90.90	90.89	88.5	81.2	76.2	72.9	68.2	66.2	63.6	18.7	20.9
24	40	191.0	90.8	90.7	90.6	90.5	90.59	88.2	80.9	75.9	72.6	67.9	65.9	63.3	18.5	20.5
25	50	111.25	97.6	97.5	97.4	97.3	98.6	96.7	89.2	88.7	79.5	72.4	70.0	64.9	18.5	22.2
26	50	149.2	96.5	96.4	96.4	96.2	97.5	95.6	88.1	87.6	78.4	71.3	69.1	63.8	18.5	21.5
27	50	169.6	96.0	95.9	95.8	95.7	97.0	95.1	87.6	87.1	77.9	70.8	68.6	63.5	18.5	21.2
28	50	191.0	95.7	95.6	95.6	95.3	96.7	94.8	87.3	86.3	77.6	70.5	68.3	63.2	18.5	21.0
29	60	111.25	103.1	103	102.9	102.8	104 .1	101.1	95.0	88.4	80.5	74.4	72.5	68.5	18.6	23.2
30	60	149.2	102.0	101.9	101.8	101.7	103.0	100.0	93.9	87.3	79.4	73.3	71.4	67.4	18.6	22.3
31	60	169.6	101.5	101.4	101.3	101.1	102.5	99.5	93.4	86.8	78.9	72.8	70.9	66.8	18.6	22.0
32	60	191.0	101.2	101.1	101.0	100.9	102.2	99.2	93.1	86.5	78.6	72.5	70.6	66.5	18.6	21.7
33	70	111.25	108.1	108.0	107.9	107.8	109.1	107.0	98.6	97.6	93.6	81.7	77.7	74.7	18.5	24.0
34	70	149.2	107.0	106.9	106.8	106.7	108.0	105 .9	97.5	96.5	92.5	80.6	76.6	73.6	18.5	23.0
35	70	169.6	106.4	106.3	106.3	106.2	107.4	105 .3	96.9	95.9	91.9	80.0	76.0	73.1	18.5	22.6
36	70	191.6	106.1	106.0	106.0	105.9	107.1	105 .0	96.6	95.6	91.6	79.4	75.7	72.8	18.6	22.4

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
157	80	111.25	110.1	110.0	109.9	109.8	111.1	109.1	104.0	103.5	98.0	86.1	82.4	78.4	18.6	25.3
158	80	149.2	109.1	109.0	108.9	108.8	110.1	108.0	102.8	102.2	97.1	84.9	81.3	77.3	18.6	24.0
159	80	169.6	108.6	108.5	108.5	108.4	109.5	107.5	102.3	101.7	97.6	84.3	80.7	76.7	18.5	23.4
160	80	191.0	108.3	108.2	108.2	108.1	109.2	107.2	102.1	101.5	97.3	83.9	80.2	76.2	18.5	23.0

working fluid quantity 170 cc

orientation 10°

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
161	40	111.25	92.8	92.7	92.6	92.5	93.8	91.8	82.5	82.0	81.6	69.3	66.6	63.6	18.5	21.3
162	40	149.2	91.7	91.6	91.5	91.4	92.7	90.7	81.4	80.9	80.5	68.2	65.5	62.5	18.6	20.9
163	40	169.6	91.2	91.1	91.0	90.0	92.2	90.2	80.9	80.4	80.0	67.7	65.0	62.0	18.5	20.6
164	40	191.0	90.9	90.8	90.8	90.7	91.9	89.9	80.6	80.1	79.7	67.4	64.7	61.7	18.5	20.4
165	50	111.25	98.3	98.2	98.2	98.1	99.3	97.4	88.2	88.1	85.3	75.5	71.5	68.6	18.5	22.2
166	50	149.2	97.2	97.1	97.0	97.0	98.2	96.3	87.1	87.0	84.2	74.4	70.4	67.5	18.6	21.5
167	50	169.6	96.7	96.6	96.4	96.3	97.5	95.8	86.6	86.5	83.7	73.9	69.6	67.0	18.5	21.2
168	50	191.0	96.4	96.3	96.2	96.1	97.2	95.5	86.3	86.2	83.4	73.6	69.6	65.7	18.5	21.0
169	60	111.25	103.4	103.3	103.1	103.0	104.4	102.5	93.4	93.0	89.3	79.6	75.3	73.0	18.6	23.1
170	60	149.2	102.3	102.2	102.1	102.0	103.1	101.4	92.3	91.9	88.2	78.5	74.2	71.9	18.5	22.2
171	60	169.6	101.8	101.7	101.7	101.5	102.6	100.9	91.8	91.4	87.7	78.0	73.7	71.4	18.6	21.9
172	60	191.0	101.5	101.4	101.4	101.2	102.3	100.7	91.5	91.0	87.3	77.6	73.3	71.1	18.5	21.6
173	70	111.25	109.1	109.0	108.8	108.7	110.1	107.7	98.6	98.0	93.0	81.7	77.4	74.2	18.5	24.0
174	70	149.2	108.0	107.9	107.8	107.7	109.0	106.0	97.5	96.9	91.9	80.6	76.3	73.1	18.5	22.9
175	70	169.6	107.4	107.3	107.3	107.2	108.4	106.0	96.9	96.3	91.3	80.0	75.7	72.5	18.5	22.5
176	70	191.0	107.1	107.0	106.9	106.8	108.1	105.7	96.6	96.0	91.1	78.7	75.4	72.2	18.5	22.2

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
177	80	111.25	112.2	112.1	112.0	111.9	113.2	111.1	102.0	101.4	95.9	84.0	80.3	76.3	18.5	24.9
178	80	149.2	111.1	111.0	110.9	110.8	112.1	110.0	100.9	100.3	94.8	82.9	79.2	75.2	18.6	23.7
179	80	169.6	110.5	110.4	110.4	110.3	111.5	109.4	100.3	99.7	94.2	82.3	78.6	74.6	18.6	23.3
180	80	191.0	110.2	110.1	109.9	109.8	111.2	109.1	100.0	99.3	93.8	82.0	78.3	74.3	18.5	22.9

APPENDIX - C

SAMPLE CALCULATIONS

C.1 Determination of the Heat picked up by the Coolant

Run No. 20 of Table B.2 of Appendix -B has been selected to demonstrate the calculation procedure.

Following are experimental data corresponding to this run:

Heat in put	=	80 W
Coolant flow rate	=	191 cc/min.
Coolant inlet temperature	=	18.6 $^{\circ}$C
Coolant outlet temperature	=	23.2 $^{\circ}$C

Heat picked up by the coolant = (191x60)x1x(23.2-18.6)

= 52716 Cal

= 61.31 W

C.1.1 Calculation of Performance

Performance of the heat pipe is calculated by the following procedure :

$$\text{Performance} = \frac{\text{Heat picked up by the coolant}}{\text{Heat input to the evaporator}}$$

$$= \frac{61.31}{80} = 0.766$$

C.2 Calculation of the Heat Loss from the Outer Surface of Heat Pipe

Length of evaporator section with insulation	=	.34 m
Length of adiabatic section with insulation	=	0.37 m
Diameter of the adiabatic section with insulation	=	0.15 m
Equivalent Diameter of the evaporator section with insulation	=	0.30 m
Surface temperature of the adiabatic section with insulation	=	27°C
Surface temperature of evaporator section with insulation	=	28°C
Ambient temperature of the surrounding	=	18.5°C
Mean temperature of the adiabatic section	=	(27+18.5)/2 = 22.75°C
Mean temperature of the evaporator section	=	(28+18.5)/2 = 23.25°C

Air properties corresponding to [illegible] 22.75°C are as follows :

$k = 0.224$ KCal/mhr°C; $= 1.517 \times 10^{-5}$ cm²/sec, Pr = 0.702

$= 1.111 \times 10^{-3}$ 1/°C

The value of Gr is obtained :

$$Gr = \frac{9.81 \times (0.15)^3 \times 1.11 \times 10^{-3} \times (27-18.5)}{(1.517 \times 10^{-5})^2} = 2.7 \times 10^6$$

$$Gr \times Pr = 2.7 \times 10^6 \times 0.702 = 1.89 \times 10^6$$

The value of constant C and n are obtained from (21)

$C = 0.54$; $n = 0.25$

$Nu = 0.54\ (1.89 \times 10^{6})^{0.25} = 20$

$h = \frac{20 \times 0.0224}{0.15} = 2.99\ \text{KCal/hr.m}^2.^{\circ}\text{C}$

Heat loss through adiabatic section to the surroundings

$= 2.99 \times \pi \times 0.15 \times 0.37 \times (27-18.5)$

$= 4.43$ KCal/hr

$= 5.15$ W

The value of the heat transfer coefficient and the amount of the heat lost to the surroundings from the evaporator section were obtained in the similar manner and were found to be 2.97 KCal/ hr.m^2.$^{\circ}$C and 10.2 W respectively.

Total heat loss to the surroundings $= 5.15 + 10.2$

$= 15.35$ W

Heat unaccounted $= 80-(61.31 + 15.35)$

$= 3.34$ W

Heat unaccounted $= 4.175$ %

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i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
37	80	111.25	112.1	112.0	111.9	111.8	113.1	111.1	102.0	101.4	96.1	84	80.3	76.8	18.5	24.[illegible]
38	80	149.2	111.0	110.9	110.8	110.7	112.0	110.1	100.9	100.3	95.1	83.9	79.2	75.7	18.6	23.8
39	80	169.6	110.4	110.3	110.3	110.1	111.4	109.5	100.3	99.4	94.5	83.3	78.6	75.1	18.5	23.3
40	80	191.0	110.1	110.0	110.0	109.9	111.3	109.2	100.0	99.1	94.2	83.0	78.3	74.8	18.6	23.0

working fluid quantity 130 c.c.
orientation 10°

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
41	40	111.25	100.0	99.9	99.8	99.7	101.0	98.7	87.2	86.6	77.1	70.2	67.9	63.1	18.6	22.1
42	40	149.2	93.7	93.6	93.6	93.4	94.7	91.0	79.6	74.6	71.5	66.6	64.7	62.1	18.5	20.7
43	40	169.6	93.2	93.1	93.0	93.0	94.2	90.5	79.1	74.1	71.0	66.1	64.1	61.6	18.5	20.5
44	40	191.0	93.0	92.9	92.8	92.7	94.0	90.3	78.9	73.9	70.8	65.9	63.8	61.4	18.5	20.2
45	50	111.25	100.0	99.9	99.8	99.7	101.0	98.7	87.2	86.6	77.1	70.2	67.9	63.1	18.6	22.1
46	50	149.2	98.9	98.8	98.7	98.6	99.9	97.6	86.1	85.5	76.0	69.1	66.8	62.0	18.6	21.4
47	50	169.6	98.4	98.3	98.2	98.1	99.5	97.1	85.6	85.0	75.5	68.6	66.3	61.5	18.5	21.1
48	50	191.0	98.1	98.0	97.9	97.8	89.2	96.8	85.3	84.7	75.2	68.3	66.0	61.2	18.5	20.4
49	60	111.25	105.2	105.1	105.0	105.0	106.3	103.1	93.0	86.4	78.5	72.3	70.4	66.3	18.5	22.8
50	60	149.2	104.1	104.0	103.9	103.8	105.2	102.0	91.9	84.3	77.4	71.2	69.3	65.2	1[illegible].6	22.1
51	60	169.6	103.5	103.4	103.3	103.2	104.6	101.4	91.3	83.7	76.8	70.6	68.7	64.6	18.5	21.7
52	60	191.0	103.2	103.1	103.0	103.0	104.3	101.1	91.2	82.5	76.0	70.3	68.5	64.3	18.5	21.5
53	70	111.25	110.2	110.1	110.0	110.0	111.3	109.0	96.5	95.7	91.7	79.8	75.6	72.5	18.6	23.8
54	70	149.2	109.1	109.0	109.0	108.9	110.2	107.9	95.4	94.6	90.6	78.7	74.5	71.4	18.5	22.7
55	70	169.2	108.5	108.4	108.3	108.2	109.6	107.3	94.8	94.0	90.0	78.6	73.9	70.8	18.5	22.4
56	70	191.0	108.3	108.2	108.1	108.0	109.4	107.1	94.6	93.8	89.8	78.4	73.7	70.6	18.6	22.2

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
57	80	111.25	114.4	114.3	114.2	114.1	115.4	113.4	100.0	99.3	94.1	82.1	78.1	74.6	18.5	24.7
58	80	149.2	113.3	113.2	113.1	113.0	114.3	112.3	98.9	98.2	93.0	81.0	77.1	73.5	18.5	23.5
59	80	169.6	112.7	112.6	112.5	112.4	113.7	111.7	98.3	97.6	92.4	80.4	76.5	72.9	18.5	23.1
60	80	191.0	112.4	112.3	112.2	112.1	113.4	111.4	98.0	97.3	92.1	80.1	76.2	72.6	18.6	22.9

working fluid quantity 150 c.c.
orientation horizontal

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
61	40	111.25	88.2	88.1	88.0	87.9	89.2	87.4	86.8	86.3	85.8	74.8	70.8	67.8	18.5	21.8
62	40	149.2	87.2	87.1	87.0	86.9	88.1	86.3	85.7	85.2	84.8	73.7	69.7	66.8	18.5	21.1
63	40	169.6	86.9	86.6	86.5	86.4	87.6	85.8	85.2	84.7	84.3	73.2	69.2	66.3	18.6	21.0
64	40	191.0	86.4	86.3	86.2	86.1	87.3	85.4	84.8	81.4	84.0	83.1	69.0	66.0	18.5	20.7
65	50	111.25	94.0	93.8	93.7	93.6	95.0	93.1	92.8	92.3	90.4	79.8	75.8	72.9	18.5	22.8
66	50	149.2	93.1	93.0	92.9	92.8	94.1	92.1	91.7	91.3	89.4	78.7	75.0	71.8	18.6	22.0
67	50	169.6	92.6	92.5	92.3	92.2	93.6	91.6	91.2	90.8	88.9	78.5	74.5	71.30	18.5	21.6
68	50	191.0	92.3	92.2	92.2	92.1	93.1	91.3	90.9	90.5	88.6	70.3	74.2	71.0	18.5	21.3
69	60	111.25	99.1	99.0	98.1	98.8	100.1	98.3	97.8	97.3	93.4	83.7	79.6	76.7	18.6	23.8
70	60	149.2	98.1	98.0	97.9	97.8	99.1	97.3	96.7	96.2	92.3	82.6	78.5	75.5	18.5	22.6
71	60	169.6	97.6	97.5	97.4	97.3	98.6	96.8	96.2	95.7	91.8	82.1	78.0	75.0	18.5	22.3
72	60	191.0	97.3	97.2	97.1	97.0	98.3	96.5	96.0	95.5	91.6	81.9	77.8	74.8	18.5	21.9
73	70	111.25	104.2	104.1	104.0	103.9	105.2	103.4	102.8	102.1	97.0	85.7	81.5	78.4	18.5	24.7
74	70	149.2	103.1	103.0	102.9	102.8	104.1	102.4	101.8	101.1	96.0	84.7	80.5	77.3	18.5	23.4
75	70	169.6	102.7	102.6	102.5	102.4	103.7	102.0	101.4	100.7	95.6	84.3	80.1	77.0	18.5	23.0
76	70	191.0	102.5	102.4	102.4	102.3	103.5	101.8	101.2	100.5	95.4	84.2	79.9	76.8	18.6	22.7

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
77	80	111.25	108.0	107.5	107.3	107.5	109.0	107.0	106.5	106.0	100.5	88.5	84.0	81.0	18.5	25.7
78	80	149.2	107.0	106.9	106.7	106.5	108.4	106.1	105.9	105.1	99.4	87.4	81.8	80.5	18.5	24.3
79	80	169.6	106.5	106.4	106.2	106.0	107.9	105.8	105.5	104.9	97.1	86.0	79.1	78.5	18.6	23.8
80	80	191.0	106.0	105.8	105.2	105.3	107.0	105.1	105.0	104.0	96.0	85.0	80.0	78.0	18.6	23.4
						working fluid quantity 150 c.c. orientation 50										
81	40	111.25	89.6	89.5	89.3	89.2	90.6	88.7	85.8	85.0	84.5	73.5	69.5	66.5	18.5	21.7
82	40	149.2	88.6	88.5	88.3	88.2	89.6	87.6	87.0	84.9	83.4	72.4	68.4	65.4	18.6	22.1
83	40	169.6	88.1	88.0	88.0	87.5	89.1	87.1	86.5	84.4	82.9	71.9	67.8	64.9	18.5	20.8
84	40	191.0	87.9	87.8	87.6	87.5	88.9	86.8	86.2	84.1	82.6	71.6	67.5	64.6	18.6	20.7
85	50	111.25	95.4	95.3	95.2	85.1	96.4	94.5	91.8	91.3	89.4	77.3	73.8	70.9	18.5	22.6
86	50	149.2	94.4	94.3	94.1	94.0	95.4	93.5	91.7	90.3	88.4	76.8	72.7	68.8	18.5	21.7
87	50	169.6	93.9	93.8	93.7	93.6	94.9	93.0	91.2	89.8	88.0	76.3	72.2	69.3	18.5	21.[illegible]
88	50	191.0	93.5	93.4	93.3	93.2	94.5	92.6	90.8	89.4	87.6	76.0	71.8	68.9	18.5	21.2
89	60	111.25	110.4	100.3	100.2	100 .1	101.4	99.4	96.8	95.3	91.2	82.2	78.1	75.1	18.6	23.6
90	60	149.2	99.3	99 2	99.2	99.0	100.3	98.3	95.7	94.2	90.1	81.1	77.0	74.0	18.6	22.6
91	60	169.6	98.8	98.7	98.7	98.5	99.8	97.8	95.2	93.7	89.6	80.6	76.5	73.5	18.6	22.2
92	60	191.0	98.5	98.4	98.4	98.2	99.5	97.5	94.9	93.4	89.3	80.3	76.2	73.2	18.5	21.8
93	70	111.25	105.6	105.5	105.4	105.3	106.6	104.8	101.4	100.4	96.0	84.3	[illegible]	77.0	18.7	24.7
94	70	149.2	104.6	104.5	104.5	104.4	105.6	103.7	100.7	99.0	95.0	83.2	79.1	75.9	18.5	23.2
95	70	169.6	104.1	104.0	103.9	103.8	105.1	103.2	100.2	98.5	94.5	82.7	78.6	75.4	18.6	23.0
96	70	191.0	103.9	103.7	103.6	103.5	104.9	103.0	99.9	98.2	94.2	82.4	78.3	75.1	18.7	22.7

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
97	80	111.25	109.1	108.6	108.4	108.4	110.1	107.5	105.5	105.0	98.5	86.4	83.5	79.5	18.5	25.4
98	80	149.2	108.0	107.5	107.3	107.3	109.0	106.4	104.4	103.9	97.4	85..3	82.4	78.4	18.5	24.1
99	80	169.6	107.6	107.1	106.9	106.9	108.6	106.0	104.0	103.5	97.0	84.9	82.1	78.3	18.6	23.7
100	80	191.0	107.3	106.8	106.6	106.6	108.3	105.7	103.7	103.2	96.7	84. 6	8188	78.0	18.5	23.2
					working fluid quantity orientation				150 c.c. 10°							
101	40	111.25	91.6	91.5	91.4	91.3	92.6	90.7	83.8	83.0	82.5	71.5	67.5	64.5	18.6	21.6
102	40	149.2	90.6	90.5	90.4	90.3	91.6	89.6	82.6	81.9	81.4	70.4	66.4	63.4	18.5	20.9
103	40	169.6	90.1	90.0	89.9	89.8	91.1	89.1	82.2	81.4	80.9	69.5	65.9	62.9	18.5	20.7
104	40	191.0	89.3	89.7	89.6	89. 5	90.8	88.8	81.9	81.3	80.6	69.2	65.6	62.6	18.5	20.5
105	50	111.25	97.3	97 .2	97.1	97.0	98.3	96.5	93.8	93.3	91.4	69.8	75.8	72.9	18.5	22.3
106	50	149.2	96.2	96.1	96.0	95.9	97.2	95.4	92.7	92.1	90.3	78.7	74.7	71.8	18.6	21.6
107	50	169.6	95.7	95.6	95.5	95.4	96.7	94.9	92.2	91.6	89.8	78.2	74.2	71.3	18.5	21.3
108	50	191.0	95.4	95.3	95.2	95.1	96.4	94.6	91.9	91.3	89.5	77.9	73.9	71.0	18.5	21.1
109	60	111.25	102.5	102.4	102.3	102.2	103.5	101. 4	94.8	93.3	89.2	80.2	76.1	73.0	18.6	23.3
110	60	149.2	101.4	101.3	101.2	101.1	102.4	100. 3	93.7	92.2	88.1	79.1	75.0	72.0	18.5	22.2
111	60	169.6	100.9	100.8	100.7	100.6	101.9	99.8	93.2	91.7	87.6	78.6	74.5	71.5	18.6	22.0
112	60	191.0	100.7	100.6	100.5	100.4	101.7	98.7	93.0	91.5	87.4	78.4	74.3	71.3	18.5	21.7
113	70	111.25	107.6	107.5	107.4	107.3	108.6	106.8	99.8	98.1	94.0	82.3	78.2	75.0	18.5	24.2
114	70	149.2	106.5	106.4	106.3	106.3	107.5	105.7	98.7	97.0	93.0	81.2	77.1	74.1	18.5	23.0
115	70	169.6	105.9	105.8	105.7	105.7	106.9	105.1	98.1	96.4	92.4	80.6	76.5	73.5	18.5	22.6
116	70	191.0	105.6	105.5	105.4	105.4	106.5	104.8	97.8	96.1	92.1	80.3	76.2	73.2	18.5	22.3

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
117	80	111.25	110.6	110.5	110.4	110.3	111.6	109.0	104.0	103.5	97.0	84.9	82.0	78.0	18.6	25.3
118	80	149.2	109.6	109.5	109.4	109.3	110.6	108.0	103.0	102.4	96.0	83.8	81.0	77.0	18.5	23.8
119	80	169.6	109.1	109.0	108.9	108.7	110.1	107.5	102.5	101.9	95.5	83.3	80.5	76.5	18.6	23.5
120	80	191.0	108.7	108.7	108.6	108.5	109.8	107.2	102.2	101.6	95.2	83.0	80.2	76.2	18.6	23.1

working fluid quantity 170 c.c.
orientation horizontal

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
121	40	111.25	89.2	89.1	89.0	88.9	90.3	88.6	85.8	85.3	84.8	73.5	69.5	65.8	18.6	21.8
122	40	149.2	88.1	88.0	88.0	87.9	89.2	87.5	84.7	84.3	83.8	72.4	68.7	65.7	18.5	21.0
123	40	169.6	87.6	87.5	87.4	87.3	88.0	87.0	84.2	83.8	83.5	72.0	66.3	65.3	18.6	20.9
124	40	191.0	87.3	87.2	87.2	87.1	88.4	86.7	83.9	83.9	83.2	71.7	68.0	64.9	18.5	20.6
125	50	11.25	95.1	95.0	94.9	94.8	96.1	94.2	91.7	91.2	89.3	78.7	74.7	71.8	18.5	22.6
126	50	149.2	94.0	93.9	93.8	93.7	95.0	93.1	90.6	90.0	88.1	67.5	73.4	78.5	18.5	21.7
127	50	169.6	93.5	93.4	93.4	93.3	94.7	92.7	90.2	89.6	87.7	76.1	73.0	68.1	18.5	21.4
128	50	191.0	93.3	93.3	93.2	93.1	94.5	92.6	90.0	89.3	87.5	75.9	72.8	67.9	18.6	21.3
129	60	111.25	100.2	100.1	100.1	100.0	101.2	99.4	96.6	96.1	92.3	82.6	78.5	76.5	18.6	23.6
130	60	149.2	99.0	98.9	98.8	98.7	100.1	98.4	95.5	95.3	91.2	81.5	77.4	75.4	18.5	22.5
131	60	169.6	98.6	98.5	98.3	98.3	99.8	98.1	95.2	95.0	90.9	81.2	77.1	75.0	18.5	22.1
132	60	191.0	98.4	98.3	98.1	98.1	99.6	97.9	95.0	94.5	90.7	81.0	76.8	74.1	18.6	21.9
133	70	111.25	105.5	105.4	105.4	105.3	106.6	104.7	101. 6	101.0	96.0	84.7	80.4	77.2	18.6	24.6
134	70	149.2	104.4	104.3	104.2	104.1	105.5	103.6	100.5	99.9	94.8	83.6	79.3	76.1	18.5	23.2
135	70	169.6	103.9	103.8	103.8	103.7	105.0	103.1	100.0	99.4	94.3	83.1	78.5	75.6	18.6	22.9
136	70	191.0	103.6	103.5	103.2	103.1	104.7	102.8	99.7	99.1	94.0	82.8	78.1	75.3	18.6	22.6

i	ii	iii	1	2	3	4	5	6	7	8	9	10	11	12	iv	v
137	80	111.25	109.1	109.0	108.9	108.7	110.1	108.1	105.0	104.5	99.0	87.1	83.5	80.0	18.5	25.4
138	80	149.2	108.1	108.0	107.8	107.6	109.1	107.0	104.1	103.4	98.0	86.0	82.4	79.1	18.6	24.2
139	80	169.6	107.5	107.4	107.2	107.0	108.5	106.4	103.5	102.8	97.4	85.4	81.8	78.5	18.6	23.7
140	80	191.0	107.2	107.2	107.1	107.0	108.2	106.2	103.2	102.5	97.1	85.1	81.5	78.3	18.6	23.3

working fluid quantity 170 cc

orientation 5°

141	40	111.25	90.7	90.6	90.5	90.4	91.7	89.7	84.6	84.1	83.6	71.3	768.6	65.6	18.7	21.7
142	40	149.2	89.6	89.5	89.4	89.2	90.5	88.5	83.5	83.0	82.5	70.2	67.4	64.5	18.5	20.9
143	40	169.6	89.0	88.9	88.8	88.7	89.9	87.9	82.8	82.4	81.9	69.6	66.8	63.9	18.6	20.8
144	40	191.0	88.8	88.6	88.5	88.4	89.7	87.2	82.6	82.2	81.7	69.4	66.6	63.5	18.6	20.7
145	50	111.25	96.2	96.1	96.1	96.0	97.2	95.3	90.2	90.0	87.1	77.5	73.5	70.6	18.5	22.4
146	50	149.2	95.0	94.9	94.8	94.7	96.1	94.2	89.1	89.0	86.0	76.4	72.4	69.5	18.6	21.7
147	50	169.6	94.5	94.4	94.4	94.2	95.6	93.7	88.6	88.5	85.5	75.9	71.9	69.0	18.5	21.4
148	50	191.0	94.2	94.1	94.0	93.9	95.3	93.4	88.3	88.2	85.2	75.5	71.5	68.6	18.5	21.1
149	60	111.25	101.3	101.2	101.1	101.0	102.3	100.5	95.4	95.0	91.3	81.6	77.3	75.0	18.6	23.4
150	60	149.2	100.2	100.1	100.0	100.0	101.2	99.4	94.3	94.0	90.1	80.3	76.1	73.8	18.5	22.3
151	60	169.6	99.7	99.6	99.6	99.5	100.7	98.9	93.8	93.5	89.6	79.8	75.6	73.3	18.6	22.1
152	60	191.0	99.3	99.2	99.1	99.0	100.3	98.5	93.4	93.1	89.2	79.4	75.2	72.9	18.5	21.7
153	70	111.25	107.0	106.9	106.8	106.7	108.0	105.7	100.6	100.0	95.0	83.7	79.4	76.2	18.5	24.2
154	70	149.2	106.1	106.0	106.0	105.9	107.9	104.6	99.5	98.9	93.9	82.6	78.2	75.1	18.6	23.2
155	70	169.6	105.6	105.5	105.4	105.2	107.4	104.1	99.0	98.4	93.4	82.1	77.7	74.6	18.6	22.8
156	70	191.0	105.3	105.2	105.1	105.0	107.1	103.8	98.7	98.1	93.1	81.8	77.4	74.3	18.5	22.4