FABRICATION, TESTING AND ANALYSIS OF THERMOSYPHON HEAT PIPE HEAT EXCHANGER

A Project Report

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BONAFIDE CERTIFICATE

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ABSTRACT

Energy is an important input for development. The need for energy is increasing day by day. The present energy situations are characterized by high rate of growth of energy consumption and increasing dependence on finite sources of energy. To break away from the past trends that are not sustainable and to build on a future of hope and strength, the most reliable strategy is "Energy Saving and Conservation". Energy conservation is now faced with the challenge of applying the latest technology for facilities and improvements, which can be justified on its own merits.

The need for maximization of heat recovery requires better technology than the present one. The convection mode of heat transfer will be effective than the conduction mode of heat transfer. Heat pipes works on the principle of convection. There is liquid-vapor equilibrium inside the heat pipe. When the heat is supplied to the evaporator, this equilibrium breaks down as the working fluid evaporates. The generated vapor is at a higher pressure than the liquid and it travels to the condenser section through the vapor space provided. Vapor condenses giving away its latent heat of vaporization to the heat sink. Then the condensed fluid returns back to the evaporator section by means of gravity. The cycle repeats and the heat is continuously transported from evaporator to condenser in the form of latent heat of vaporization.

Heat is given as input to the evaporator end and is rejected at the condenser end with minimal losses. The middle region is called adiabatic region and there is no change in temperature throughout the length. When the evaporator end is connected to the heat source and the condenser unit is linked to the heat

more preferable method for heat recovery than the solid type heat exchangers. More over heat exchanger with heat pipe units possess many advantages such as high heat recovery effectiveness, high compactness, no moving parts, light weight, relative economy, no external power requirements, pressure tightness, complete separation of hot and cold fluids and high reliability.

In this project "Fabrication, testing and analysis of thermosyphon heat pipe heat exchanger", experimental and theoretical research has been carried out to investigate the thermal performance of water to air thermosyphon heat exchanger. The material used for heat pipe is copper. Glycol is used as heat recovering medium inside the pipe. Among the many independently controllable process parameters affecting the thermal performance of HPHE, Heat input (Q), Water temperature (Tw) and Air velocity (Va) are selected as factors to carry out the experimental works. The water to air thermosyphon heat exchanger has been constructed and tested in a test rig under steady state conditions. The experiment was carried out using DOE technique. A correlation is developed for the effectiveness of heat pipe heat exchanger in terms of heat input, water temperature and velocity of air. The developed correlation is helpful in analyzing the performance of the heat pipe heat exchanger. Optimization is done using SYSTAT software and the optimum operating parameters are obtained.

ஆய்வு சுருக்கம்

அறிவியல் வளர்ச்சிக்கு மிகவும் முக்கியமான முதலீடு ஆற்றல் ஆகும். இவ்வாற்றலின் தேவையானது நாளுக்கு நாள் அதிகரித்துக் கொண்டே வருகிறது. எனவே ஆற்றலை காப்பாற்றுவது மற்றும் பாதுகாப்பது முக்கியமான ஒன்றாகும். தற்போதைய சூழ்நிலையில் ஆற்றலை பாதுகாப்பது என்பது மிகவும் சவாலாக அமைந்துள்ளது. ஆற்றல் என்பது அணைத்து துறைகளிலும் பயன்படுத்தப்பட்டு வருகிறது. அவ்வாறு பயன்படுத்தப்படும் ஆற்றலில் பல்வேறு துறைகள் உள்ளன. அதில் முக்கியமான ஒன்று வெப்ப ஆற்றலாகும். இத்துறையில் வெப்பத்தை அதிகம் வீண் செய்யாமல் திரும்ப அடைவதற்கு ஒரு புதிய முறை அவசியமாகிறது.

இந்த ஆய்வில் "தெர்மோசிபான்" வெப்ப குழாய் வெப்ப மாற்றதை பற்றிய உருவாக்குதல், சோதனை செய்தல் மற்றும் பகுப்பாய்வு ஆகிய செயல்முறைகளை பற்றி விவரிக்கிறது. நீரிலிருந்து வாயுவிற்கான தெர்மோசிபான் வெப்பமாற்றத்தில் அதன் வெப்ப செயல்திறனை சோதனை முறை மற்றும் விஞ்ஞான தத்துவ முறையின் மூலம் கண்டறியப்பட்டு ஆராயப்பட்டுள்ளது.

இதில் பயன்படுத்தப்படும் வெப்பகுழாயானது காப்பர் உலோகத்தினால் ஆனதாகும். வெப்பகுழாயில் "கிளைகால்" வெப்பத்தை திரும்ப அடைவதற்கான ஒரு பொருளாய் பயன்படுத்தப்படுகிறது. வெப்ப குழாய் வெப்ப மாற்றத்தின் செயல்பாட்டு திறனை கட்டுபடுத்தக்கூடிய செயல் அளபுருக்கள் பல இருந்தாலும் தனிபட்ட முறையில் அவற்றை கட்டுபடுத்த வெப்ப உள்ளீடு, நீரின் வெப்பநிலை மற்றும் வாயுவின் திசை வேகம் ஆகியவை இச்சோதனை முறைக்கு முக்கியமாக எடுத்துக்கொள்ளப்படுகிறது. நீரிலிருந்து வாயுவிற்கான வெப்ப குழாய் வெப்ப மாற்றம் மிக குறைந்த நிலைப்பு தன்மையில் சோதனைக்கு உட்படுத்தப்படுகிறது. இச்சோதனையில் "டிசைன் ஆப் எக்ஸ்பிரிமெண்ட்" என்ற நுணக்கமுறைக்கு உட்படுத்தப்படுகிறது. இதில் வெப்ப உள்ளீடு, நீரின் வெப்பநிலை மற்றும் வாயுவின் திசைவேகம் ஆகிய மூன்றையும் ஒன்றோடொன்று பொருத்தப்பட்டு வெப்பகுழாய் வெப்ப மாற்றத்தின் "எபக்டிவ்னெஸ்" கண்டறியப்பட்டு அதன் செயல்திறனை பகுப்பாய்வு செய்ய உதவுகிறது. "சிஸ்டேட்" என்ற மென்பொருளை பயன்படுத்தி உகப்பாக்கம் செய்யபடும்போது வெப்பகுழாய் வெப்ப மாற்றத்தின் உகப்பு நிலை அளபுருக்கள் கண்டறியப்படுகிறது.

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NOMENCLATURE

Symbol	**Definition**
HPHE	Heat pipe heat exchanger
DOE	Design of Experiments
ε	Effectiveness
Tw	Water temperature
Te	Evaporator temperature
Tc	Condenser temperature
Q	Heat input
Va	Velocity of air

INTRODUCTION

CHAPTER 1

INTRODUCTION

1.1 CURRENT TREND

The huge demand in energy of this revolutionary world calls for various new sources of energy as the existing fossils are depleting. Hence various ways for new sources are been analyzed day to day. But instead of new ones, converting the waste into useful could act as another source. This is called recovery from waste. The energy emitted into the atmosphere can be converted into useful by recovering called waste heat recovery. At present there are various systems that could serve for waste heat recovery. Commercially available systems are based on the mode of conduction. But due to the losses in this system, it requires for higher technology that recovers more heat from the heat rejecting systems. As convection is more efficient than conduction, it is possible to recover more heat with the help of fluids instead of solids. Since radiation requires no medium for heat transfer only convection could be the better possible mode than conduction. Hence the present trend is going for heat recovery through convection heat transfer.

1.2 PROJECT IMPORTANCE

The heat pipe is one such equipment which is used in thermal applications. They can transfer heat from one point to the other with least loss which helps in increasing the heat transfer efficiency. Once the heat is transferred, it can be used for other process which is secondary in nature. Though the processes are secondary in nature they show a notable increase in the efficiency of the overall system by using waste heat instead of fresh energy. Thus the application of heat pipes is to recover the waste heat and use it for improving the efficiency of the system.

1.3 SCOPE OF THE PROJECT

We arrived at a solution of heat pipe heat exchanger to recover the waste heat more efficiently than the available conventional type heat exchanger. This heat pipe is made up of copper pipes. The fluid for convection is used as glycol. Though there are a number of heat pipes available for cooling purpose, our aim is to recover the heat from waste heat sources. Hence the convection mode of heat transfer could be better than the conduction mode. Cheaper metals like aluminium, stainless steel and others could be used instead of copper. At present heat pipes are available for cooling applications only. For example, cooling of chips in computers using miniature heat pipes, cooling of aircraft fins with the help of leading edge heat pipes. So in near future heat pipe will have wide scope for heat recovery. Heat pipe heat exchanger will be a better unit to recover the waste heat. We can vary the heat transfer rate of the heat pipe by varying the working fluids, so that they can be used for various operating temperatures. Similarly the length and cross section of the heat pipe can be varied for increasing the heat recovery rate.

1.4 OUTLINE OF THE PROJECT REPORT

This project report is organized into following ten chapters which describes the purpose of the project.

Chapter 1: Introduction
Chapter 2: Line of attack
Chapter 3: Literature survey
Chapter 4: Overview about heat pipe heat exchangers
Chapter 5: Design of Experiments
Chapter 6: Experimentation
Chapter 7: Methodology
Chapter 8: Optimization of heat pipe heat exchanger
Chapter 9: Results and Discussion
Chapter10: Conclusion

Chapter 1: Introduction presents the introduction of this project work with its importance, scope of the project work and an outline of the project report.

Chapter 2: Problem chosen states the problem chosen for this project work. It describes the nature of problem giving the details of present situation of the problem and the technique to be adopted to solve the problem.

Chapter 3: Literature survey reveals the relevant work done earlier related to the problem identified and the approach adopted to solve the problem. It gives the description of literature reviewed from various research papers published in international and national journals, proceedings of various conferences, etc. and books.

Chapter 4: Overview about heat pipe heat exchangers describes about the basics of heat pipe and its classifications along with its advantages and applications. It also explains about the working principle and the considerations that to be adopted while manufacturing the heat pipes.

Chapter 5: Design of Experiments deals in detail about what is meant by design of experiments, the need, its approach that is design process along with its advantages.

Chapter 6: Experimentation describes/ the experimental procedure adopted in this project work. It describes in detail about the experimental set up and equipments used.

Chapter 7: Methodology discusses about the experimental design procedure, identification of factors and responses and their limits. It also discusses about the development of design matrix and how the experiments were conducted and finally it discusses about the evaluation of regression coefficients and development of mathematical model.

Chapter 8: Optimization of heat pipe heat exchanger deals with design optimization of heat pipe which includes an introduction about the software

Chapter 9: Results and Discussion analyses the result obtained from the experiment. It gives the comparison of the actual and theoretical results. It also provides various interactive effects among the input parameters on effectiveness.

Chapter 10: Conclusion concludes with providing a brief summary about the work done in this project work. It also provides with a derived mathematical model from the experiments conducted along with the optimal parameters needed for improving the thermal performance.

LINE OF ATTACK

CHAPTER 2

LINE OF ATTACK

According to the law of conservation of energy "energy can neither be created nor be destroyed, but it can be transform to one form to another". Hence it is necessary to conserve the energy. In the present days the energy consumption is not proportional to that of the energy generation; hence energy conservation plays a vital role in the present days.

Apart from the energy conservation, the important factor that needs concentration is that of the pollution. Due to the increase of pollution in the industrial sector there are two main by-factors that are being emitted to the surrounding environment, and one among them is that of the heat. In the present days most of heat energy from the industries is being dissipated to the surroundings.

The method of extracting heat from the process in which useless heat is rejected from one system to another system is called heat recovery. . Heat recovery is an energy saving process in which cost of a industrial unit or any other system that uses this technique is reduced. This recovered heat is used back by the same system or different system. The recover of the heat energy can be done by means of a heat pipe heat exchanger. Here in this project an attempt has been made to study the optimum performance of a thermosyphon heat pipe heat exchanger by means of selecting the appropriate parameters. And finally the optimum parameter is been selected accordingly by means of a suitable optimizing technique.

LITERATURE SURVEY

CHAPTER 3

LITERATURE SURVEY

The following papers are studied as a reference in order to have a basic idea as well as a deep overview of heat pipe heat exchangers. I have gone through the existing technologies and the problems which are in need of new solution and they motivated me to fabricate, test and analyze thermosyphon heat pipe heat exchanger.

Noie (2006) investigated the thermal performance of an air-to-air thermosyphon heat exchanger using ε-NTU method. Experimental and theoretical research has been carried out to investigate the thermal performance of the heat exchanger. Many factors affect the thermal performance of thermosyphon heat exchangers including velocity and temperature of input air, type and filling ratio of working fluid, and pipe material. The air-to-air thermosyphon heat exchanger has been designed, constructed and tested in a test rig under steady state conditions. The lengths of both the evaporator and condenser sections of the heat exchanger were 600mm and its central adiabatic section had a length of 100mm. Several experiments were carried out under different operating conditions by varying the parameters in order to determine and investigate their effect on the thermal performance of the thermosyphon heat exchanger. The overall effectiveness of the thermosyphon heat exchanger obtained from experiments varied between 37% and 65%. The experimental results showed the minimum effectiveness of the thermosyphon took place at $C_h=C_c$. Therefore, equal value of air face velocities in evaporator and condenser sections should be avoided. For constant velocities the effectiveness increased up to nearly 150^0C and then remained constant. The agreement between the experimental results with theoretical predictions was good and became better as the velocity increases.

Xiao Huang, et al., (2006), designed and fabricated a hybrid bi-model wick structure for heat pipe application using combinations of Cu mesh, Cu powder and Ni powder. The objective is to simultaneously enhance performance in capillary pumping, permeability and evaporative heat transfer. Utilizing substrates with large pores and sintered powders, a highly integrated bi-model wick structure was created with small pores lining the walls of the large pores. Micro structural studies were conducted and found that sintering had occurred in a controlled manner, forming initial bonding while maintaining enough pores in the structure. Tests of heat pipes containing the bi-model wick structure in various configurations revealed increases in effective thermal conductivity by as much as 400% as compared to base line heat pipes containing monolithic wick materials such as copper mesh. By varying the fine pore distribution, further improvements in effective thermal conductivity and maximum heat input were achieved. Since the thermal conductivities of heat pipes changes drastically over a range of operating temperatures and heat input values, it is important that the comparison of heat pipe performance and the selection of wick structure are based on the required service temperature and heat input.

Feng Yang, et al., (2003), studied the feasibility of using heat pipe heat exchangers for heating automobile using exhaust gas and developed the calculation method. Simple experiments are carried out to examine the performance of the heat exchanger. The experimental results indicate the benefit of exhaust gas heating, are in good agreement with numerical results. Author has concluded that heat transferred by the heat exchanger will increase with the rise of gas temperature.

Noie, et al., (2000), made a research on the theory, design and construction of heat pipes, especially their use in heat pipe heat exchangers for energy recovery, reduction of air pollution and environmental conservation. A heat pipe heat exchanger has been designed and constructed for heat recovery in hospital and laboratories, where the air must be changed up to 40 times per hour. In this research, the characteristic design and heat transfer limitations of single heat pipes for three types of wick and three working fluids have been investigated, initially inserting the wick, creating the vacuum, injecting the fluid and installation have also been carried out. After obtaining the appropriate flux, the air-to-air heat pipe heat exchanger was designed, constructed and tested under low temperature operating conditions, using methanol as the working fluid. The heat transfer rate to the evaporator section of a single heat pipe obtained from the developed computer simulation was very close to the experimental results for the constructed heat pipe. The examination of the heat transfer limits for three working fluids (acetone, water and methanol) showed that the minimum heat transfer is well above the required heat transfer rate. With reference to the experimental results obtained, the efficiency and effectiveness of HPHE can be increased by using finned pipes, increasing the number of rows, complete insulation of the test rig and perfect sealing of pipes.

OVERVIEW ABOUT HEAT PIPE HEAT EXCHANGERS

CHAPTER 4

OVERVIEW ABOUT HEAT PIPE HEAT EXCHANGERS

4.1 INTRODUCTION

The introduction of the heat pipe was first conceived by Gaugler (1944) of the general motors corporation in the U.S. Patent No.2350348. Gaugler, who was working on refrigeration problems at that time, envisioned a device which would evaporate a liquid at a point above the place where condensation would occur without requiring any additional work to move the liquid to the higher elevation. His device consisted of a closed tube in which the liquid would absorb heat one location causing the liquid to evaporate. The vapor would then travel down the length of the tube where it would recondense and release its latent heat. It would then travel back up to a higher point; Gaugler suggested the use of a capillary structure consisting of sintered iron wick. A refrigeration unit proposed by Gaugler used a heat pipe to transfer the heat from the interior of a compartment to a pan of crushed ice below. However, his idea was not used by general motors for the refrigeration problem.

4.2 HEAT PIPE BASICS

A heat pipe is a device that efficiently transports heat from its one end to the other. It utilizes the latent heat of the vaporized working fluid instead of the sensible heat. As a result, the effective thermal conductivity may be several orders of magnitudes higher than that of the good solid conductors. Figure 4.1 shows a schematic of a heat pipe operation. Heat input at the evaporator vaporizes the working fluid and this vapor travels to the condenser section. Here the latent heat is rejected via condensation. The vapor of the working fluid condenses and the condensate returns to the evaporator by means of gravity. A heat pipe consists of a sealed container and a small amount of working fluid that is just sufficient to saturate and it is in equilibrium with its own vapor.

The operating pressure inside the heat pipe is the vapor pressure of its working fluid. The length of the heat pipe can be divided into 3 parts viz. evaporator section, adiabatic section and condenser section. Space for the vapor travel is provided inside the container. Fins may be attached to the evaporator and the condenser portion to increase heat transfer rate depending upon the application.

4.3 TYPES OF HEAT PIPES

- Two-phase closed thermosyphon.
- Capillary-driven heat pipe
- Annular heat pipe
- Flat-plate heat pipe
- Rotating heat pipe
- Leading edge heat pipe
- Gas-loaded heat pipe
- Capillary pumped loop heat pipe
- Monogroove heat pipe

4.4 OPERATING PRINCIPLE OF TWO-PHASE CLOSED THERMOSYPHON HEAT PIPE

A heat pipe operates on a closed two phase cycle. Figure 4.1 shows a schematic of a typical heat pipe operation. As previously mentioned, there is liquid-vapor equilibrium inside the heat pipe. When the heat is supplied to the evaporator, this equilibrium breaks down as the working fluid evaporates. The generated vapor is at a higher pressure than the liquid and it travels to the condenser section through the vapor space provided. Vapor condenses giving away its latent heat of vaporization to the heat sink. Then the condensed fluid is return back to the evaporator section by means of gravity. The cycle repeats and the heat is continuously transported from evaporator to condenser in the form of latent heat of vaporization.

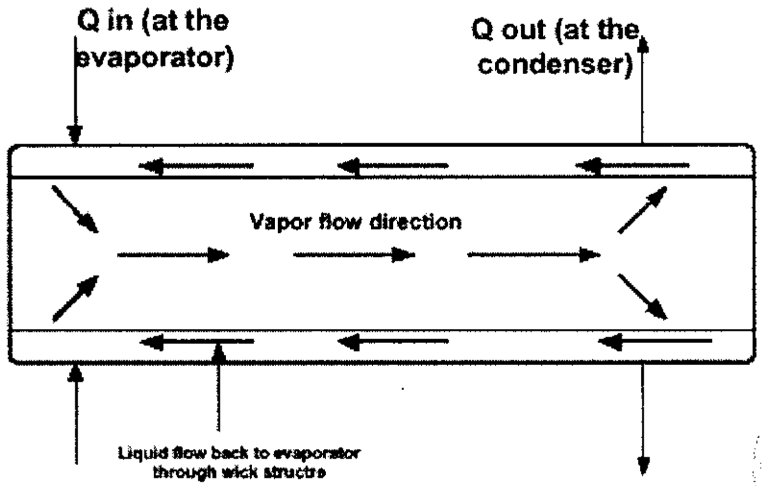


Figure 4.1 Schematic of a Typical Heat Pipe

4.5 HEAT PIPE HEAT EXCHANGERS

Increases in the cost of energy have promoted new methods of conserving energy in industrial applications. Due to their high heat transfer capabilities with no external power requirements, heat pipes are being used in heat exchangers for various applications. In the power industry, heat pipe heat exchangers are used as primary air heaters on new and retrofit boilers. The major advantages of heat pipe heat exchangers compared to conventional heat exchangers are that they are nearly isothermal and can be cheaper then conventional tubular heat exchanger because they are smaller and can be shipped in a small number of modules. Heat pipe heat exchangers can serve as compact waste heat recovery systems which require no power, low pressure drop and are easy to install on existing lines. Heat pipe heat exchangers can be categorized into gas-gas, gas-liquid and liquid-liquid type heat units. Among these three, gas-gas heat pipe exchanger consists of a group of externally finned heat pipes, which reclaim waste heat (Groveret al., 1964; Hassan and Accensi, 1973; Holmes and field, 1986; Ivanovskiiet al., 1982). These units eliminate cross-contamination due to the solid wall between the hot and cold gas streams. Also, the heat pipe design is totally reversible (heat can be transferred in either direction). Gas-gas energy recovery units typically fall into recovery of excess process heat for space heating (moderate temperature), and recovery of waste heat from high temperature exhaust streams for reuse in the process (preheating of combustion air, for example). The units for these applications, but many commercial models are now available utilizing this heat pipe design.

Gas-liquid heat pipe exchangers are less commonly available than gas-gas models due to the fact that the present design of waste heat boilers is very efficient. In the past, exhaust heat from boilers was simply dispersed to atmosphere.

Recently, Faghri (1993a) invented an innovative design for a centrifugal heat pipe vapor absorption heat pump. The heat pipes in this heat pump system are disk-shaped with one face partially or completely being the evaporator and the opposite face partially or completely being the condenser (Faghri, 1994). The wick is designed such that the centrifugal force aids in the delivery of the vapor-absorption heat pump by increasing the heat pumping capacity that can be packaged in a given value, resulting in a more efficient and compact vapor-absorption heat pump system.

4.6 HEAT EXCHANGER CLASSIFICATION

In general, heat exchangers can be classified as either regenerators or re-cooperators. In a regenerative heat exchanger, heat is alternately removed from the high-temperature fluid and transferred to low-temperature fluid. The energy transfer which occurs in this type of heat exchanger is dependent on the physical properties of the fluids and heat transfer surface as well as the flow situation of the two fluids. A common type of regenerative heat exchanger is known as the rotary regenerator, which alternately exposes a metal surface to the high and low-temperature fluid streams. While the surfaces are in the high-temperature stream, they absorb heat through conduction into the metallic structure. Then, when the surface is moved into the cold stream, heat is rejected from the metal surface. Rotary regenerators have been used for air-heating applications and flue-gas reheating. An example of a fixed regenerative heat exchanger is the packed porous bed where the high and low- temperature fluids alternately flow through a porous releases the heat to the low-temperature stream as the two fluids cycle through the heat exchanger. While regenerative type heat exchangers often have an efficiency advantage over recuperative types, heat exchangers such as the rotary regenerator require an auxiliary power supply to operate, and are prone to leakage problems between the high- and low-temperature fluids.

In recuperative heat exchangers, the high- and low- temperature fluids do not come into direct contact with each other, but are separated by a solid wall. This type of heat exchanger operates by transferring heat from the high-temperature fluid, through a wall, and into the low-temperature fluid. In which the high- and low-temperature fluids are ducted past each other, separated by a solid wall. Heat is transferred from the high- to low-temperature fluid stream by conduction through the solid wall.

4.7 ADVANTAGES OF HEAT PIPE HEAT EXCHANGERS

A rotary regenerator, plate type, and heat pipe heat exchanger which were designed to operate in the same heat recovery application are compared These three systems were designed to operate with the same high- and low-temperature mass flow rates and physical properties. Implicit to the comparison is the fact that the same that recovery will not be achieved by all three systems. In this table, efficiency is a measure of the heat exchanger performance for the given operating condition, defined as the ratio of the heat transferred by the real heat exchanger to the heat transferred by a heat exchanger performance accounting for size, defined as the ratio of thermal conductance to the volume of the heat exchanger, and the heat-transfer/pressure drop ratio is a measure of the power required to force the high- and low- temperature gas streams through the heat exchanger (Klaschka, 1979).

Heat pipe heat exchangers immediately offer the greatest advantage in terms of size reduction. However, there are additional factors which tend to further encourage the use of heat pipe heat exchangers. Some of these are:

1. HPHE's have no moving parts or auxiliary power requirements, implying very high reliability

2. The high- and low-temperature fluid streams are completely isolated in a HPHE, eliminating cross contamination.

3. HPHE's can be designed to be completely reversible: i.e., eat can be transferred in either direction if required.

4. The rate of heat transferred in HPHE can be controlled by adjusting the tilt angle.

5. HPHE's are redundant in design. If one individual heat pipe fails, the heat exchanger is still operational.

6. HPHE's have the capability to operate as thermal transformers. By altering the relative the relative lengths of the evaporator and condenser sections the temperature at which heat is transferred can be controlled.

4.8 APPLICATIONS

Since that time, numerous applications have been found in many industries. Heat pipes have been applied in many ways since their introduction in1964. Depending on their intended use, heat pipes can operate over a temperature range from 4.0 to 3000K. In all cases, their applications can be divided into three main categories: separation of heat source and sink, temperature equalization, and temperature control. Due to their extremely high thermal conductivity, heat pipes can efficiently transport heat from a concentrated source to a remotely mounted sink. This property can enable dense packing of electronics, for example, without undue regard for heat sink space requirements. Another benefits of the high thermal conductivity if the ability to provide an accurate method of temperature equalization. For example, a heat pipe mounted between two opposing faces of an orbiting platform will enable both faces to maintain constant and equal temperatures, thus minimizing thermal stresses. The temperature control is a result of the capability of heat pipes to transport large quantities of heat very rapidly. This feature enables a source of varying flux to be kept at a constant temperature as long as the heat flux extremes are within the operating range of the heat pipe.

In the mid 1970s, HPHE began to be commercially produced. However, HPHE applications can be divided into three main categories:

1. Heat recovery in air conditioning devices
2. heat recovery from the processed exhaust stream to preheat air fro space heating
3. Heat recovery from the process exhaust stream for reuse in the process.

4.9 MANUFACTURING CONSIDERATIONS OF HEAT PIPES

The manufacture of heat pipes involves several procedures which are recommended to be strictly followed in order to achieve the highest quality possible. The three basic components of a heat pipe are:

1. The container
2. The working fluid
3. The wick or capillary structure

4.9.1 Container

The function of the container is to isolate the working fluid from the outside environment. It has to therefore be leak-proof, maintain the pressure differential across its walls, and enable transfer of heat to take place from and into the working fluid.

Selection of the container material depends on many factors. These are as follows:

- Compatibility (both with working fluid and external environment)
- Strength to weight ratio
- Thermal conductivity
- Ease of fabrication, including welding, machine ability and ductility
- Porosity
- Wettability

Most of the above are self-explanatory. A high strength to weight ratio is more important in spacecraft applications. The material should be non-porous to prevent the diffusion of vapor. A high thermal conductivity ensures minimum temperature drop between the heat source and the wick.

4.9.2 Working Fluid

A first consideration in the identification of a suitable working fluid is the operating vapor temperature range. Within the approximate temperature band, several possible working fluids may exist, and a variety of characteristics must be examined in order to determine the most acceptable of these fluids for the application considered. The prime requirements are:

- compatibility with wick and wall materials
- good thermal stability
- wettability of wick and wall materials
- vapor pressure not too high or low over the operating temperature range
- high latent heat
- high thermal conductivity
- low liquid and vapor viscosities
- high surface tension
- acceptable freezing or pour point

The selection of the working fluid must also be based on thermodynamic considerations which are concerned with the various limitations to heat flow occurring within the heat pipe like, viscous, sonic, capillary, entrainment and nucleate boiling levels.

In heat pipe design, a high value of surface tension is desirable in order to enable the heat pipe to operate against gravity and to generate a high capillary driving force. In addition to high surface tension, it is necessary for the working fluid to wet the wick and the container material i.e. contact angle should be zero or very small. The vapor pressure over the operating temperature range must be sufficiently great to avoid high vapor velocities, which tend to setup large temperature gradient and cause flow instabilities.

A high latent heat of vaporization is desirable in order to transfer large amounts of heat with minimum fluid flow, and hence to maintain low pressure drops within the heat pipe. The thermal conductivity of the working fluid should preferably be high in order to minimize the radial temperature gradient and to reduce the possibility of nucleate boiling at the wick or wall surface. The resistance to fluid flow will be minimized by choosing fluids with low values of vapor and liquid viscosities.

4.9.3 Wick or Capillary Structure

It is a porous structure made of materials like steel, aluminium, nickel or copper in various ranges of pore sizes. They are fabricated using metal foams, and more particularly felts, the latter being more frequently used. By varying the pressure on the felt during assembly, various pore sizes can be produced. By incorporating removable metal mandrels, an arterial structure can also be molded in the felt.

Fibrous materials, like ceramics, have also been used widely. They generally have smaller pores. The main disadvantage of ceramic fibres is that, they have little stiffness and usually require a continuous support by a metal mesh. Thus while the fibre itself may be chemically compatible with the working fluids, the supporting materials may cause problems. More recently, interest has turned to carbon fibers as a wick material. Carbon fibre filaments have many fine longitudinal grooves on their surface, have high capillary pressures and are chemically stable. A number of heat pipes that have been successfully constructed using carbon fibre wicks seem to show a greater heat transport capability.

The wick structure in a heat pipe facilitates liquid return to the evaporator from the condenser. Fig.4.2 shows various wick structures. The prime purpose of the wick is to generate capillary pressure to transport the working fluid from the condenser to the evaporator. It must also be able to distribute the liquid around the evaporator section to any area where heat is likely to be received by the heat pipe. Often these two functions require wicks of different forms. The selection of the to the properties of the working fluid. The most commonly used wick structure is a wrapped screen wick. At this point, we will define a parameter called 'Mesh Number' which is used to specify a particular wrapped screen wick. It is defined as the number of wires per linear inch, counted from the center of any wire to a point exactly one inch distant, including the fractional distance between wires thereof. For example a mesh number of 60 per inch can be interpreted as 60 × 60 mesh wires per inch. A mesh could be square or rectangular mesh. Obviously, higher mesh number represents a finer grid.

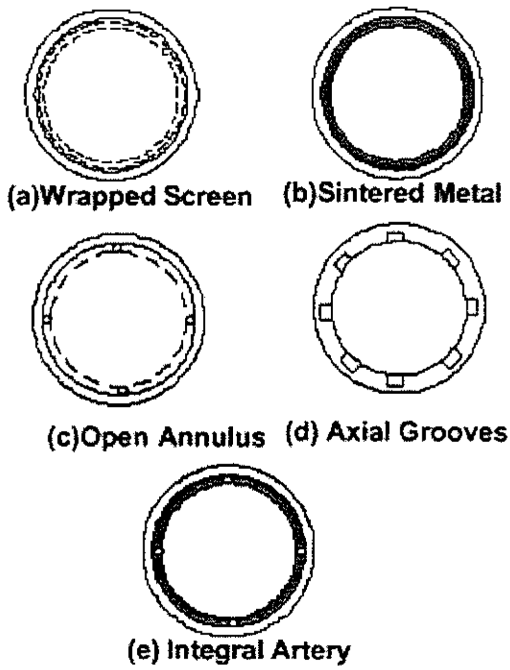


Figure 4.2 Various Wick Structures

The important requirements of a wick structure are listed below:

- Should be compatible with the wick and container material
- High latent heat
- High thermal conductivity
- High surface tension
- Low liquid and vapor viscosities
- Wettability of wick and wall materials

The maximum capillary head generated by a wick increases with decrease in pore size. The wick permeability increases with increasing pore size. Another feature of the wick, which must be optimized, is its thickness. The heat transport capability of the heat pipe is raised by increasing the wick thickness. The overall thermal resistance at the evaporator also depends on the conductivity of the working fluid in the wick. Other necessary properties of the wick are compatibility with the working fluid and wet ability.

4.10 HEAT PIPE COMPONENT CONSTRUCTION

There are certain commonly used steps to be considered while fabrication. Each of these steps is examined in the following text in detail.

4.10.1 Circular Cross – Section Heat Pipes

In most cases, the geometry of the heat pipes is cylindrical. Therefore, circular cross-section heat pipes are discussed in this section. Most of the information concerning the fabrication of cylindrical heat pipes is applicable to other geometry. A typical heat pipe consists of five components: the container, the wick, the end caps, the filler tube and the working fluid. There is also a multipoint thermocouple probe used to measure vapor temperature during performance testing of prototype heat pipes. The ends of the probe are supported by the end caps so that it does not contact the interiors of the pipe wall. During either brazing or welding, the design shown allows for the introduction of an inert gas i.e. argon, to be passed through the interior of the pipe to reduce oxidation of the wick and the pipe wall. The main body of the hat pipe container can be made from commercially available metallic pipes such as aluminium, copper, mild steel and stainless steel. For applications where the working temperature will be very high, expensive refractory materials such as titanium or tungsten can be used. For low temperature applications, copper and aluminum are the materials of choice, whereas stainless steel is preferable in most high temperature environments. Careful consideration must be given to the possible incompatibility of the materials of the wall, wick, end caps, brazing or welding material, and the working fluid. Problems with chemical reactions, such as the formation of alloys action between the different metallic parts must be taken into account. A full discussion concerning this topic is given by Brennan and Kroliczek (1979).

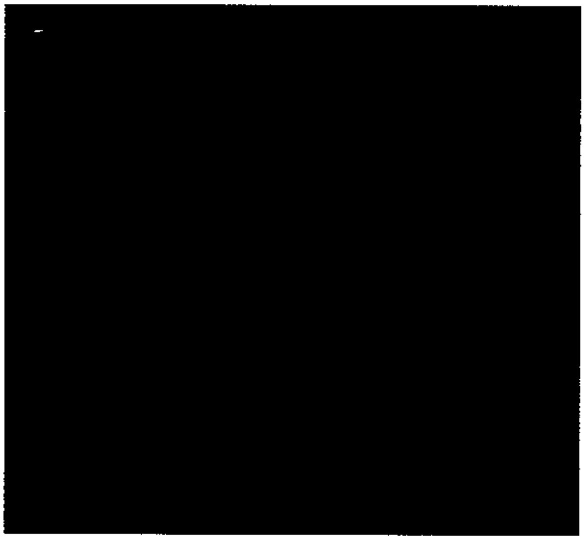
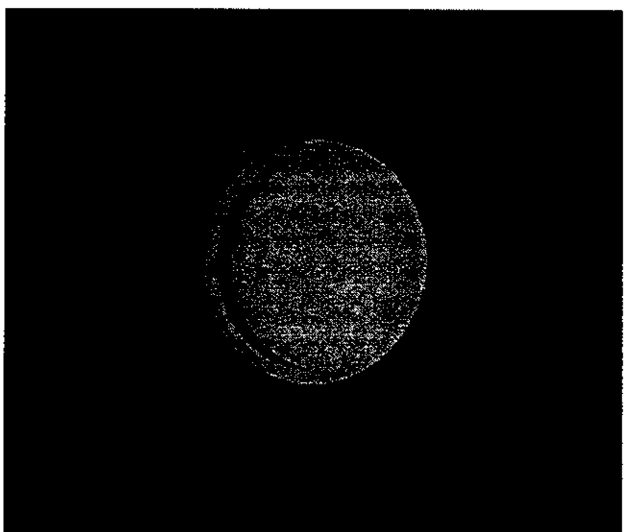


Figure 4.3 Heat Exchanger Model

4.10.2 End Caps

The end caps are designed to provide closure for the container and to provide for the fill tube and instrumentation. There are various end cap designs: butt joint, fillet joint, and internal or external lap joints as shown in figure. In designing an end cap, consideration must be given to the proper thickness ratio at the joint for welding and pressure retention to provide a rupture-proof container. End caps are usually machined with one end cap containing the fill tube.



Variable Parameters affecting the thermal performance of HPHE:

Surface temperature of heat pipe

- Outlet temperature of air
- Number of heat pipes
- Diameter of heat pipe
- Fin Density

Assumptions:

- Standard gravity assisted heat pipe. (Condenser placed above the evaporator)
- Steady state operation.
- Turbulent and incompressible vapor flow. (Starting assumption)

The following is a brief description of the method commonly used in fabricating a heat pipe:

1. Machine the heat pipe container including the pipe wall and end caps.

2. Clean the components of the heat pipe of solid particle, oils, and oxides.

3. Charge the heat pipe with the working fluid.

4. Assemble the heat pipe using brazing or welding techniques.

5. Leak-check the heat pipe container.

6. Fully instrument the heat pipe with thermocouples, heaters, anemometer, voltmeter, ammeter, etc (for performance testing).

DESIGN OF EXPERIMENTS

CHAPTER 5

DESIGN OF EXPERIMENTS

"Design of Experiments" refers to experimental methods used to quantify indeterminate measurements of factors and interactions between factors statistically through observance of forced changes made methodically as directed by mathematically systematic tables. A Design of Experiment (DOE) is a structured, organized method for determining the relationship between factors (Xs) affecting a process and the output of that process (Y).It is used for conducting and analyzing controlled tests to evaluate the factors that control the value of a parameter or group of parameters.

5.1 THE NEED FOR DESIGNED TESTS

- When theory is unknown or inadequate
- When the risk is high
- There are a lot of unknowns
- For new products
- When other people are not convinced

If we can understand the underlying mechanism inherent in a system and can formulate a model between design and response variables, then we may not need a designed test. But this is usually not the case. Using DOE results in empirical models being developed which are more than adequate as replacements for theoretical models.

When the risk of making incorrect product decisions is high we need DOE. For example, when making a change to a profitable product we usually want concrete evidence that the change is for the better. Using DOE is like taking out an insurance policy against making bad product decisions.

DOE is especially useful when making decisions involving a lot of unknowns. For example, when developing a new product there are usually a lot of unknowns about how best to design the product. DOE can turn unknowns into accurate estimates of the effects of variables. Many times people involved in product development need to be convinced that a certain direction is best. These people require hard evidence on which to base decisions. They are not willing go forward on the basis of product expert's recommendations. A properly designed test will convince the skeptics of the best course of action.

5.2 DESIGN AND RESPONSE PARAMETERS

Table 5.1 Terms and Synonyms of DOE

(1)	(2)
Design Variables	Response Variables
Controlled	Measured
Independent	Dependent
Factors	Characteristics
Input	Output
Recipe	Attributes
Knobs	Parameters

The terms in column (1) table 5.1 are synonyms as are the terms in column (2). Design variables are the variables we have control over. Response variables are the variables we can't control but can measure. Typically we want to achieve certain values of Response variables by manipulating the levels of Design variables. Examples of Design variables include weight, size, % ingredients, processing settings such as time and temperature. Examples of response variables include consumer acceptance measures, quality measures, purity, yield, cost, tensile strength. The distinction between design and response variables can be then it is best to chose one as a design variable and measure the other as a response variable.

5.3 THE IMPORTANCE OF DOE

Finagle's 2nd law: No matter what the experiment's result, there will always be some eager to:

- Misinterpret it
- Fake it
- Believe it supports his own pet theory

5.4. DESIGN OF EXPERIMENTS PROCESS

The DOE process is divided into three main phases, which encompass all experimentation approaches. The three phases are

(1) The planning phase,

(2) The conducting phase, and

(3) The analysis phase.

The planning phase is by far the most important phase for the experiment to provide the expected information. The planning phase is when factors and levels are selected and, therefore, is the most important stage of experimentation. Also, the correct selection of factors and levels is non-statistical in nature and is more dependent upon product and process expertise.

The second most important phase is the conducting phase, when test results are actually collected. If experiments are well planned and conducted, the analysis is actually much easier and more likely to yield positive information about factors and levels.

The analysis phase is when the positive or negative information concerning the selected factors and levels is generated based on the previous two phases. The analysis phase is least important in terms of whether the experiment will successfully yield positive results. This phase, however, is the most statistical in involvement of statistics, the analysis phase is typically the least understood by the product or process expert.

The major steps to complete an effective designed experiment are listed in the following text. The planning phase includes steps 1 through 9, the conducting phase is step 10, and the analysis phase includes steps 11 and 12.

1. State the problem(s) or area(s) of concern.
2. State the objective(s) of the experiment.
3. Select the Quality characteristic(s) and measurement system(s).
4. Select the factors that may influence the selected quality characteristics.
5. Identify limits of factors
6. Select levels for the factors.
7. Select the appropriate design
8. Select interactions that may influence the selected quality characteristics or go back to step 4 (iterative steps).
9. Assign factors to design and locate interactions.
10. Conduct tests described by trials in design.
11. Analyze and interpret results of the experimental trials.
12. Conduct confirmation experiment.

These steps are fundamentally the same regardless of whether one is designing a Taguchi-based experiment or a classical design. All designed experiments require that a certain number of combinations of factors and levels be tested to observe the results of those test conditions. Two or more passes through the process are often utilized; earlier rounds of experimentation provide a growth of knowledge and a basis for later rounds of experimentation.

5.5. RESPONSE SURFACE METHODOLOGY

Experimentation and making inferences are the twin features of general scientific methodology. Statistics as a scientific discipline is mainly designed to achieve these objectives. Planning of experiments is particularly very useful in deriving which inferences can be made in the best possible manner. The methodology for making inferences has three main aspects. First, it establishes methods for drawing inferences from observations when these are not exact but subject to variation, because inferences are not exact but probabilistic in nature. Second, it specifies methods for collection of data appropriately, so that assumptions for the application of appropriate statistical methods to them are satisfied.

5.6 ADVANTAGES OF DOE

1. DOE eliminates the 'confounding of effects' whereby the effects of design variables are mixed up. Confounding of effects means we can't correlate product changes with product characteristics.

2. DOE helps us handle experimental error. Any data point may contain bad data, i.e. is

    - Accurate to only +/-? %.
    - Experimental Error
    - The effects of variation in:
    - Raw Materials
    - Test Instruments
    - Machine Operators

3. DOE helps us determine the important variables that need to be controlled.

4. DOE helps us find the unimportant variables that may not need to be controlled.

5. DOE helps us measure interactions, which is very important.

EXPERIMENTATION

CHAPTER 6

EXPERIMENTATION

6.1 HEAT PIPE PERFORMANCE TESTING OBSERVATION:

After the successful processing, it is necessary to perform experiments to determine the thermal performance of a thermosyphon heat pipe heat exchanger (5 thermosyphons are arranged in a row). For this a special test rig was constructed and set up. The test rig consisted of

- Heat pipe heat exchanger
- Heating coil with adjusting knob
- Rheostat
- Voltmeter
- Ammeter
- Temperature sensor
- Blower
- Anemometer

Figure 6.1 Total Experimental Setup

The equipments are connected as per the requirements for experimentation. The setup was placed in the R&AC laboratory.The water in the evaporator section is heated using heating coil. The power of heating coil is adjusted using fine adjusting knob. The adjusting power Q is taken as one of the parameter. The heat pipe conducts the heat from evaporator section to the condenser section. The air is blown to the condenser section using blower with voltage control method. The rheostat is used for the purpose of varying the voltage which varies in turns the blower speed.

As per the design matrix the experiments were conducted. The three parameters are water temperature, heat input and the air velocity in condenser section. The first set of readings is taken with water bath maintained at particular temperature. At this temperature different set of readings are observed by adjusting the blower speed and corresponding temperature in the evaporator and condenser sections are measured, also noted the ambient temperature. In each stage of experiment voltmeter and ammeter readings are noted to calculate the heat input. Then repeat the experiment for different water temperature according to the design matrix. Finally by using the above readings, the effectiveness of heat pipe heat exchanger is calculated by using the equation

6.2 SPECIFICATION OF HEAT PIPE HEAT EXCHANGER

- Pipe Material =copper.
- Length of the pipe = 1500 mm.
- Length of evaporator section = 700 mm.
- Length of adiabatic section = 100 mm.
- Length of condenser section = 700 mm.
- Inner diameter of the pipe = 8 mm.
- Outer diameter of the pipe = 16 mm.
- Fluid used = Glycol
- Operating temperature = 40°c to 80°c
- Number of heat pipes = 5

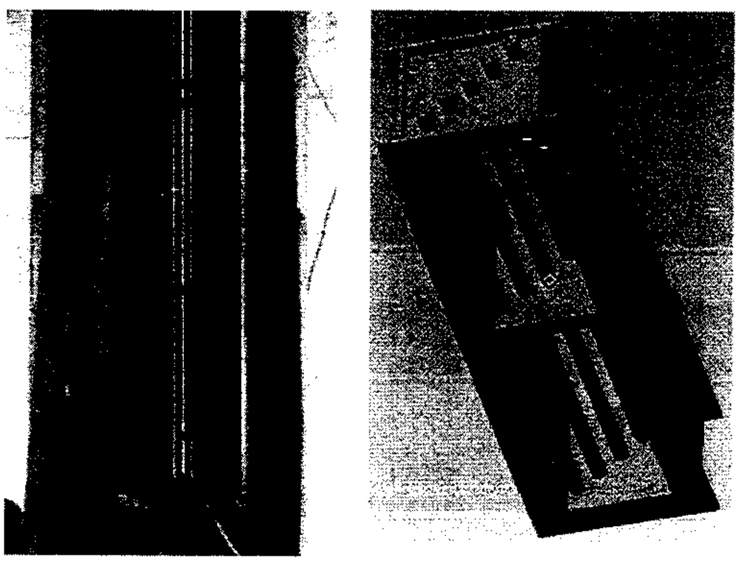


Figure 6.2 Arrangements of Heat Pipe Heat Exchanger

The specification of the heat pipe is shown above. The pipe material is made up of copper. The conductivity of this copper is 0.9. The length of the copper pipe is taken as 1500mm. From the measurements it is found that the pipe has an inner diameter of 8mm and the outer diameter is 16mm. The minimum operating

Glycol, B.P is 470 K. It is a colorless, orally toxic fluid and is miscible with water and ethanol.

Table 6.1 Experimental Results

S.NO	Q in W	Tw in ^{0}C	Va in m/s	Te in ^{0}C	Tc in ^{0}C
1	136	56	1.8	43.3	42.7
2	248	56	1.8	44.2	43.1
3	136	74	1.8	54.5	53.2
4	248	74	1.8	53.6	51.8
5	136	56	2	45.1	42.4
6	248	56	2	44.1	41.6
7	136	74	2	53.8	52.5
8	248	74	2	53.1	51.8
9	98	65	1.9	47.5	44.5
10	286	65	1.9	48.2	45
11	192	50	1.9	35.2	31.1
12	192	80	1.9	60.5	57.6
13	192	65	1.7	46.7	43.3
14	192	65	2.1	46.7	42.4
15	192	65	1.9	47.7	44.4
16	192	65	1.9	48.5	45.2
17	192	65	1.9	47.5	44.6
18	192	65	1.9	46.7	44.5
19	192	65	1.9	45.6	43.5
20	192	65	1.9	46.8	44.5

The table shows the various temperatures measured in the evaporator and condenser sections of the heat pipe according to the input given.

METHODOLOGY

CHAPTER 7

METHODOLOGY

7.1 EXPERIMENTAL DESIGN PROCEDURE

The experimental design procedure used for this study is briefly explained below.

7.1.1 Identification of Factors and Responses

Among the many independently controllable process parameters affecting the thermal performance of HPHE, Heat input (Q), Water temperature (Tw) and Air velocity (Va) are selected as factors to carry out the experimental works and the development of mathematical models. The chosen response was effectiveness of heat pipe heat exchanger.

7.1.2 Finding the limits of the process variables

For the three factors, the high and low values for each can be seen below in Table 7.1.

Table 7.1 Higher and Lower Limits of Process Variables

Factor	High Value	Low Value
Heat input (Q)	286	98
Water temperature (Tw)	80	50
Air velocity (Va)	2.1	1.7

The working ranges of all process variables selected had to be determined to fix their levels and to develop the design matrix. This is achieved with the assistance of trial runs carried out by varying one of the process variables while keeping the rest of them at constant value. A large number of trial runs have been conducted. In conducting the experiment, the upper limit of a factor was coded as +1.682 and the lower limit as −1.682, the coded values for intermediate values were

$$X_i = \frac{1.682(2X-(X_{max}+X_{min}))}{(X_{max} - X_{min})} \qquad \text{......................} \qquad (7.1)$$

Where X_i is the required coded value of a variable X, X is any value of the variable from X_{min} to X_{max}, X_{min} is the lower limit of the variable and X_{max} is the upper limit of the variable. The coded values for intermediate values have been calculated using Equation 7.1. The selected process parameters of the experiment, with their limits, units and notations are given in Table 7.2.

Table 7.2 Process Variables with Limits, Unit & Notations

Process parameters	Units	Notation	Limits				
			-1.682	-1	0	+1	+1.682
Heat input	Watts	Q	98	136	192	248	286
Water temperature	^0C	Tw	50	56	65	74	80
Air velocity	m/s	Va	1.7	1.8	1.9	2	2.1

7.1.3 Development of design matrix

In factorial design, the experiments are conducted for all possible combinations of the parameter levels and these combinations written in the form of a table where the rows correspond to different trials and the columns to the levels of the parameters, form a design matrix. The design matrix selected for experiment is a three factor five level central composite rotatable design consisting of 20 sets of coded conditions. The design for the above said models comprises a full replication of 23 (=8) factorial design plus six centre points and six star points; these correspond to the first eight rows, the last six rows and rows nine to fourteen, respectively, in the design matrix.

All process parameter variables at the intermediate (0) level constitute the centre points and the combinations of each of the process parameter variables at either its lowest (−1.682) or highest (+1.682) with two other variables of the intermediate levels constitute the star points. In this matrix, twenty experimental runs provide ten estimates for the effect of three parameters. One estimate for the mean effect of all the three parameters, three linear estimates for main effects, three quadratic are included. Thus the design matrix has allowed the estimation of linear, quadratic and two-way interactive effects of the selected process parameter variables on the effectiveness.

7.1.4 Conducting the experiments as per the design matrix

The experiments were conducted as per the design matrix at random, to avoid the possibility of systematic errors infiltrating the system and also calculated the effectiveness by using Equation 6.1. Table 7.3 shows the design matrix and the experimental values of effectiveness.

Table 7.3 Design Matrix and Response

Design matrix value and responses (three factors, five levels)				
Design of matrix				Response
S.NO	Heat input (Q) Watts	Water temperature (Tw) ^{0}C	Air velocity (Va) m/s	Effectiveness (ε) %
1	-1	-1	-1	0.9548
2	+1	-1	-1	0.9147
3	-1	+1	-1	0.9375
4	+1	+1	-1	0.92
5	-1	-1	+1	0.8015
6	+1	-1	+1	0.8263
7	-1	+1	+1	0.9266
8	+1	+1	+1	0.9414
9	-1.682	0	0	0.8537
10	+1.682	0	0	0.84
11	0	-1.682	0	0.7831
12	0	+1.682	0	0.8705
13	0	0	-1.682	0.888
14	0	0	+1.682	0.8097
15	0	0	0	0.8398
16	0	0	0	0.8333
17	0	0	0	0.8578
18	0	0	0	0.8926
19	0	0	0	0.9023
20	0	0	0	0.8878

7.1.5 Evaluation of regression coefficients and development of mathematical model

The response function representing any function can be expressed as

$$Y = f(X1, X_2, X_3)$$

Where

Y = Effectiveness (ε) in %

X_1= Heat input (Q) in watts

X_2=Water temperature (Tw) in ^0C

X_3=Air velocity (Va) in m/s

The second order response surface model for the four selected factors is given by the equation

$$Y = \beta_0 + \sum_{i=1} \beta_i X_i + \sum_{i=1} \beta_{ii} X_i^2 + \sum_{i<j} \beta_{ij} X_i X_j$$

The second order response surface model could be expressed as follows

$$\varepsilon = B_0 + B_1Q + B_2Tw + B_3Va + B_{11}Q^2 + B_{22}Tw^2 + B_{33}Va^2 + B_{12}QTw + B_{13}QVa + B_{23}TwVa \qquad \text{........................} \qquad (7.2)$$

Where the coefficients B_1, B2, B_3 are linear terms and B_{11}, B_{22}, B_{33} are second order terms and B_{12}, B_{13}, B_{23} are the interaction terms. Quality America – DOE PC IV, software package was used to calculate these coefficients. The mathematical model were developed is given below

$$\varepsilon=0.867-0.003X_1+0.027X_2-0.027X_3+0.006X_1^2-0.001X_2^2+0.006X_3^2+0.002X_1X_2 +0.012X_1X_3+0.023X_2X_3 \qquad \text{.............................} \qquad (7.3)$$

Where X_1 is a coded value of heat input in watts, X_2 is a coded value of water temperature in ^0C and X_3 is a coded value of Air velocity in m/s.

OPTIMIZATION OF HEAT PIPE HEAT EXCHANGER

CHAPTER 8

OPTIMIZATION OF HEAT PIPE HEAT EXCHANGER

8.1 SYSTAT-INTRODUCTION

SYSTAT offers a large number of scientific and technical graphing options and a great deal of interactivity for a desktop statistics package. Compare subgroups, overlay charts, transform coordinates, and add geographic projections, change colors, symbols and more to create insightful presentations. Change graph locations, point-and-click to alter axis labels, scales, colors and symbols. Create unique graphs that bring out the true meaning in your data with advanced chart options including normal and kernel densities, multiplots, maps, Voronoi tessellations, function plots, contours, scatter plot matrices with 20 diagonal density choices and 126 non-parametric smoothing options, just to name a few. Analysis can be done at a faster rate by rotating your 3-D graphs to visually determine the perfect power or log transformation to normalize your data using the Dynamic Explorer. Create insightful presentations with advanced chart types such as maps, multiplots and kernel densities. Analysis with SYSTAT's interactive graphic tools is really interesting.

Thus by using SYSTAT a final graphical surface generation can be done for which a program has to be written and fed into the SYSTAT software, for which ANOVA regression is done and the equations are generated. These equations are used in a program written for SYSTAT. The program is similar to a normal program written for a CNC machine or a numerical controlled machine but it involves expressions and parameters like fplot, facet, zlab, xcuy, zmin, facet and many others. ANOVA regression plays a major role in the generation of an equation, program and thereby helps in surface generation.

8.2 SYSTAT SOFTWARE

SYSTAT 10.2 is one of the most powerful statistical and graphical analysis packages now on the market. SYSTAT is a comprehensive statistical software package for analyzing data and presenting results. It is set up in a graphical environment and most commands can be executed by using menus and selecting options in dialog boxes. While some may think Microsoft's Excel provides all the data graphing capabilities they will ever need, many computer users regularly need more powerful statistical analysis capability than is built into Excel. Businesses with a major commitment to quality control and continuous improvement require constant sampling of their product specifications to produce data that must be diligently managed by a team of engineers and other staff with the technical skills and knowledge to accurately perform these tests and correctly interpret the results. A spreadsheet alone cannot meet the needs of these professionals. Instead, they turn to highly specialized, powerful statistical analysis packages.

Professionals involved in medical research also need such powerful software to handle the research tools and techniques that are essential in being able to make carefully reasoned decisions based on data produced in their testing processes. In addition, higher level students will likely find themselves regularly involved in the design and implementation of research projects, and they too need SYSTAT to help them with the important statistical analysis of the results of the data gathering phase of their project. This analysis of research data is a good example of how important it is to integrate specialized statistical analysis software programs in these organizations and for these purposes. This is where the SYSTAT 10.2 program will provide the quality tool needed by these sophisticated computer users.

8.3 ENHANCEMENT OF SYSTAT

- Windows 2000 support.
- Command File Editor.

- Rank Regression.
- Post-hoc Tests for Repeated Measures.
- N-tiles and Percentiles.
- Basic Statistics for Cross Tabulations.
- Excel Import.

8.4 INCREASING THE ANALYTICAL POWER

With SYSTAT, there is no need to worry about finding the right statistic to use in your data analysis. Robust algorithms from leading statisticians give meaningful results to your analysis, even with extreme data. You can fit regression models in nested, 2-level data when assumptions of independent observations are violated and the estimates from standard least squares general linear model (GLM) are suspect. You can create missing value estimates using regression-based point estimation or an EM algorithm, and then save the data or the triangular matrix as input to GLM, ANOVA or other models.

Analysis geostatistical data with deep spatial statistics capabilities, including 2-D and 3-D images. Obtain complete distributions and standard errors using SYSTAT's bootstrapping capability implemented globally across 21 statistical procedures, even when normality assumptions are violated and no model is available.

8.5 MEANINGFUL RESULTS WITH LESS EFFORT

SYSTAT's intuitive Windows interface and flexible command language are designed to make research more efficient.

It is easy to locate advanced options through clear, comprehensive dialogs. Type commands directly into SYSTAT's interactive command window to fly through your analyses. Quickly navigate through detailed results using the browser-style Output Organizer. Dramatic changes are made in analysis with new keystrokes.

SYSTAT's command language is interactive, powerful, and easy to learn written commands using plain English with minimal, forgiving syntax that is consistent across all modules. Instantly visualize your results with SYSTAT's Quick graphs, produced automatically by most statistical procedures to provide immediate and intuitive feedback.

8.6 COMPLETE AUTOMATION

Speeding up data analyses with SYSTAT's flexible command language that provides complete coverage of menu-based functionality. Quickly run the same analysis on different data using token variables in command templates. Each time command file is run, a variable is selected. Create command files in no time.

Execute functions using the menus and dialog selections, while the command log helps in viewing the steps. Simply save the command log script to rerun the analysis. Track and report your statistical methodology to monitoring agencies using the command log. Create compelling reports by combining formatted statistical output with publication-quality graphs in SYSTAT's rich text output window then automation is done.

8.7 MORE GRAPHS

SYSTAT offers more graph types and options than any other desktop statistics package. Create insightful presentations with advanced chart types, such as maps, multiplots, and kernel densities. These are but a few of the many, many advance chart capabilities built into SYSTAT that really indicate the excellence that has been coded in this program. Speed up your analysis with SYSTAT's interactive graphic tools. Simply point-and-click to perfect your graph's appearance.

8.8 LESS EFFORT

With enough of difficult programming languages or elaborate interface designs, SYSTAT's intuitive Windows interface and flexible command language are designed to make research more efficient. Quickly locate advanced options through clear, comprehensive dialogs. Fly through analysis with interactive commands, and instantly visualize your results with SYSTAT's Quick Graphs.

best results. The program automatically seeks a course of action that will optimize your entire system's performance.

8.9 OPTIMIZATION USING SYSTAT

Optimization of heat pipe heat exchanger is done using SYSTAT software.

8.9.1 Interactive Effect of Air Velocity and Water Temperature on Effectiveness While Keeping Heat Input Constant

The program for generating the response surface of air velocity and water temperature is given below

PROGRAM:

```
EYE -6,-8, 6
BEGIN
FACET XY
FPLOT Z=0.867-0.003*-1.682+0.027*X-0.027*Y+0.006*-1.682*-1.682-
0.001*X*X+0.006*Y*Y+0.002*-1.682*X+0.012*-
1.682*Y+0.023*X*Y;,CONTOUR,
SURFACE=XYCUT CUT=8,ZTICK=8,XPIP=5,YPIP=5,XLAB='' , YLAB='' ,
ZLAB='',
XMIN=-1.682,XMAX=1.682,
YMIN=-1.682,YMAX=1.682

FACET
FPLOT Z=0.867-0.003*0+0.027*X-0.027*Y+0.006*0*0-
0.001*X*X+0.006*Y*Y+0.002*0*X+0.012*0*Y+0.023*X*Y;,
SURFACE=XYCUT CUT=8,ZTICK=5,ZPIP=5, XLAB='Water Temperature C'
, YLAB=' Air Velocity m/s.' , ZLAB='Effectiveness',
ZMIN=-2,ZMAX=2,
XMIN=-1.682,XMAX=1.682,
YMIN=-1.682,YMAX=1.682

FACET
FPLOT Z=0.867-0.003*1.682+0.027*X-0.027*Y+0.006*1.682*1.682-
0.001*X*X+0.006*Y*Y+0.002*1.682*X+0.012*1.682*Y+0.023*X*Y;,
SURFACE=XYCUT CUT=8,ZTICK=5,ZPIP=5, XLAB='' , YLAB='' ,
ZLAB='',
ZMIN=-2,ZMAX=2,
XMIN=-1.682,XMAX=1.682,
YMIN=-1.682,YMAX=1.682

END
```

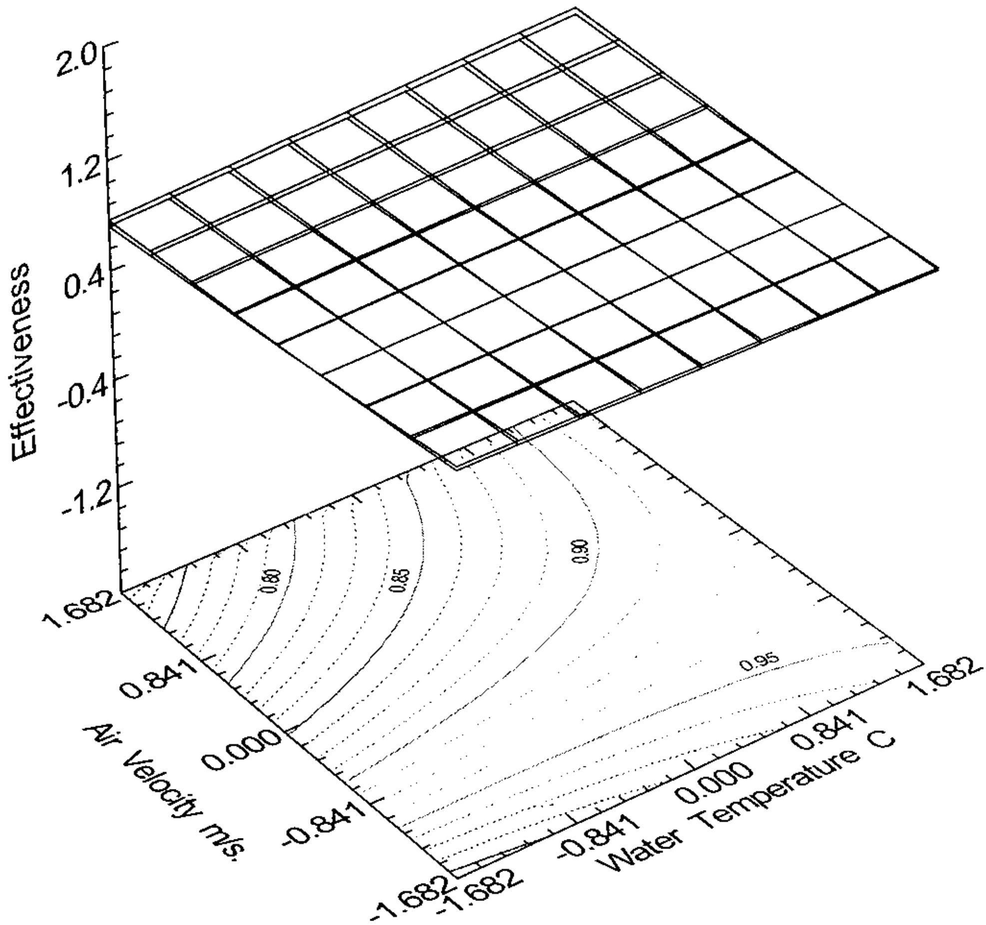


Figure 8.1 Interactive Graphs of Air Velocity and Water Temperature

The figure shows the interactive effect of air velocity and water temperature on the effectiveness of heat pipe heat exchanger. From the contour surface, it can be identified that within the range of 1.7m/s and 1.8m/s of air velocity, the effectiveness remains constant, which is maximum of 0.95. Within this range the water temperature alone has negligible impact on effectiveness. Beyond this range of air velocity, the effectiveness gets reduced gradually.

8.9.2 Interactive Effect of Air Velocity and Heat Input on Effectiveness While Keeping Water Temperature Constant

The program for generating the response surface of air velocity and water temperature is given below

PROGRAM:

```
EYE -6,-8, 6
BEGIN
FACET XY
FPLOT Z=0.867-0.003*X+0.027*-1.682-0.027*Y+0.006*X*X-0.001*-1.682*-
1.682+0.006*Y*Y+0.002*X*-1.682+0.012*X*Y+0.023*-1.682*Y;,CONTOUR,
SURFACE=XYCUT CUT=8,ZTICK=8,XPIP=5,YPIP=5,XLAB='' , YLAB='' ,
ZLAB='',
XMIN=-1.682,XMAX=1.682,
YMIN=-1.682,YMAX=1.682

FACET
FPLOT Z=0.867-0.003*X+0.027*0-0.027*Y+0.006*X*X-
0.001*0*0+0.006*Y*Y+0.002*X*0+0.012*X*Y+0.023*0*Y;,
SURFACE=XYCUT CUT=8,ZTICK=5,ZPIP=5,  XLAB='Heat Input Watts' ,
YLAB=' Air Velocity m/s.' , ZLAB='Effectiveness',
ZMIN=-2,ZMAX=2,
XMIN=-1.682,XMAX=1.682,
YMIN=-1.682,YMAX=1.682

FACET
FPLOT Z=0.867-0.003*X+0.027*1.682-0.027*Y+0.006*X*X-
0.001*1.682*1.682+0.006*Y*Y+0.002*X*1.682+0.012*X*Y+0.023*1.682*Y;,
SURFACE=XYCUT CUT=8,ZTICK=5,ZPIP=5,  XLAB='' , YLAB='' ,
ZLAB='',
ZMIN=-2,ZMAX=2,
XMIN=-1.682,XMAX=1.682,
YMIN=-1.682,YMAX=1.682

END
```

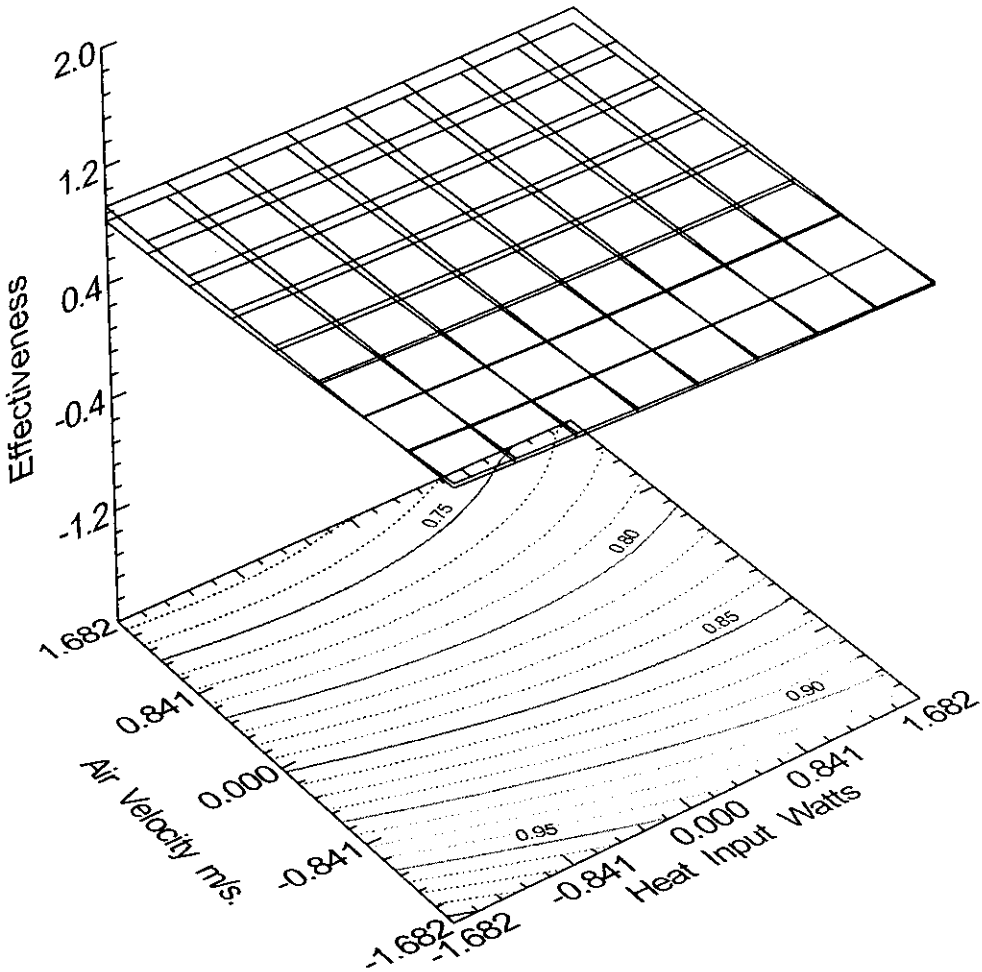


Figure 8.2 Interactive Graphs of Air Velocity and Heat Input

The figure shows the interactive effect of air velocity and heat input on the effectiveness of heat pipe heat exchanger. From the contour surface, it can be identified that within the range of 1.7m/s and 1.8m/s of air velocity and corresponding combination of heat input range of 98 W and 183W, the effectiveness remains constant, which is maximum of 0.95. Beyond this range of air velocity at any value of heat input, the effectiveness gets reduced gradually and vice versa.

8.9.3 Interactive Effect of Water Temperature and Heat Input on Effectiveness While Keeping Air Velocity Constant

The program for generating the response surface of water temperature and heat input is given below

PROGRAM:

```
EYE -6,-8, 6
BEGIN
FACET XY
FPLOT Z=0.867-0.003*X+0.027*Y-0.027*-1.682+0.006*X*X-
0.001*Y*Y+0.006*-1.682*-1.682+0.002*X*Y+0.012*X*-1.682+0.023*Y*-
1.682;,CONTOUR,
SURFACE=XYCUT CUT=8,ZTICK=8,XPIP=5,YPIP=5,XLAB='' , YLAB='' ,
ZLAB='',
XMIN=-1.682,XMAX=1.682,
YMIN=-1.682,YMAX=1.682

FACET
FPLOT Z=0.867-0.003*X+0.027*Y-0.027*0+0.006*X*X-
0.001*Y*Y+0.006*0*0+0.002*X*Y+0.012*X*0+0.023*Y*0;,
SURFACE=XYCUT CUT=8,ZTICK=5,ZPIP=5,  XLAB='Heat Input Watts' ,
YLAB=' Water TemperatureC.' , ZLAB='Effectiveness',
ZMIN=-2,ZMAX=2,
XMIN=-1.682,XMAX=1.682,
YMIN=-1.682,YMAX=1.682

FACET
FPLOT Z=0.867-0.003*X+0.027*Y-0.027*1.682+0.006*X*X-
0.001*Y*Y+0.006*1.682*1.682+0.002*X*Y+0.012*X*1.682+0.023*Y*1.682;,
SURFACE=XYCUT CUT=8,ZTICK=5,ZPIP=5,  XLAB='' , YLAB='' ,
ZLAB='',
ZMIN=-2,ZMAX=2,
XMIN=-1.682,XMAX=1.682,
YMIN=-1.682,YMAX=1.682

END
```

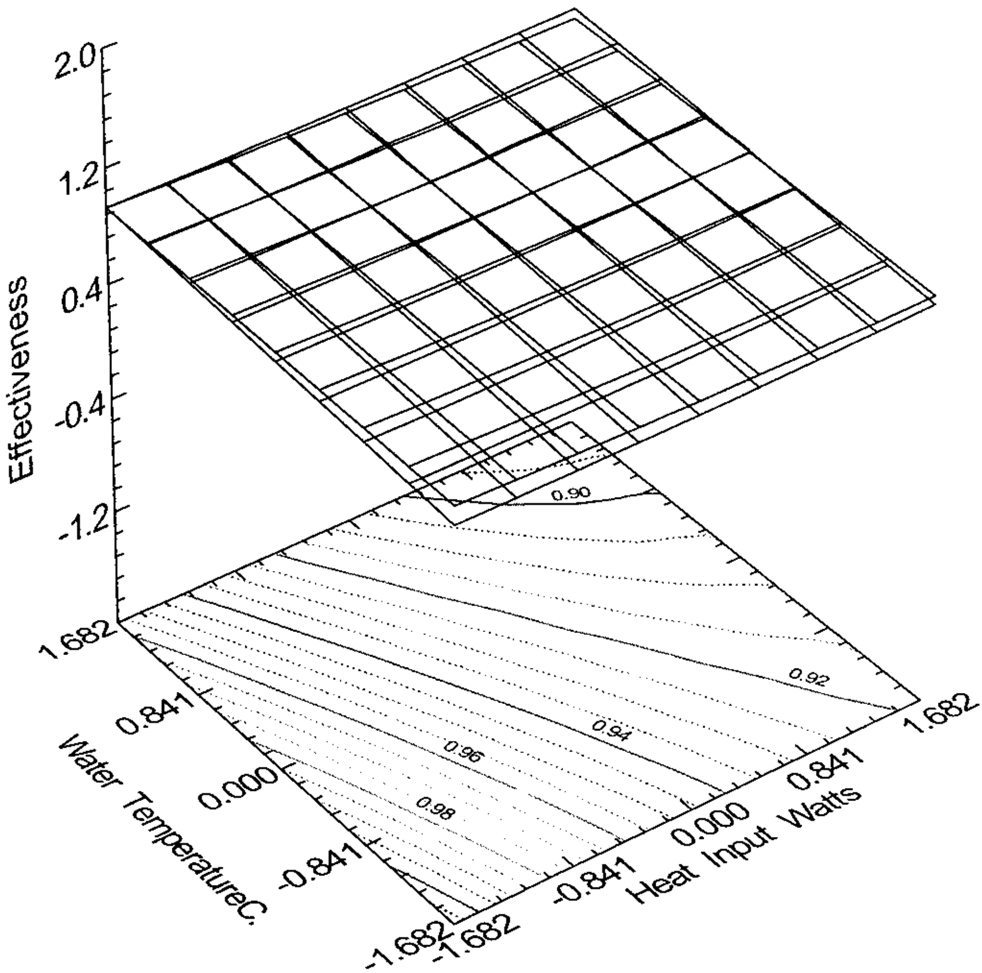


Figure 8.3 Interactive Graphs of Water Temperature and Heat Input

The figure shows the interactive effect of water temperature and heat input on the effectiveness of heat pipe heat exchanger. From the contour surface, it can be identified that within the range of 50 ^{0}C and 68 ^{0}C of water temperature and corresponding combination of heat input range of 98 W and 135 W, the effectiveness remains constant, which is maximum of 0.98. Beyond this range of water temperature at any value of heat input, the effectiveness gets reduced gradually and vice versa.

RESULTS AND DISCUSSIONS

CHAPTER 9

RESULTS AND DISCUSSIONS

9.1 COMPARISON OF EXPERIMENTAL AND CALCULATED EFFECTIVENESS

The mathematical model (Equation 7.3, chapter 7) developed by using Quality America – DOE PC IV was used to calculate the theoretical effectiveness.

Table 9.1 Comparison of Effectiveness

S.No	Effectiveness		Percentage error (%)
	Experimental	Calculated	
1	0.9548	0.927	2.911605
2	0.9147	0.893	2.372363
3	0.9375	0.913	2.613333
4	0.92	0.887	3.586957
5	0.8015	0.785	2.05864
6	0.8263	0.799	3.303885
7	0.9266	0.899	2.978632
8	0.9414	0.921	2.166985
9	0.8537	0.889021	-4.13737
10	0.84	0.878929	-4.63437
11	0.7831	0.818757	-4.5533
12	0.8705	0.909585	-4.48993
13	0.888	0.929389	-4.66089
14	0.8097	0.838561	-3.56437
15	0.8398	0.867	-3.23887
16	0.8333	0.867	-4.04416
17	0.8578	0.867	-1.07251
18	0.8926	0.867	2.868026
19	0.9023	0.867	3.912224
20	0.8878	0.867	2.34287

The above tabulations (table 9.1) describe the percentage deviations of effectiveness from actual to theoretical and the deviations falls with in the limit of 95% confidence level.

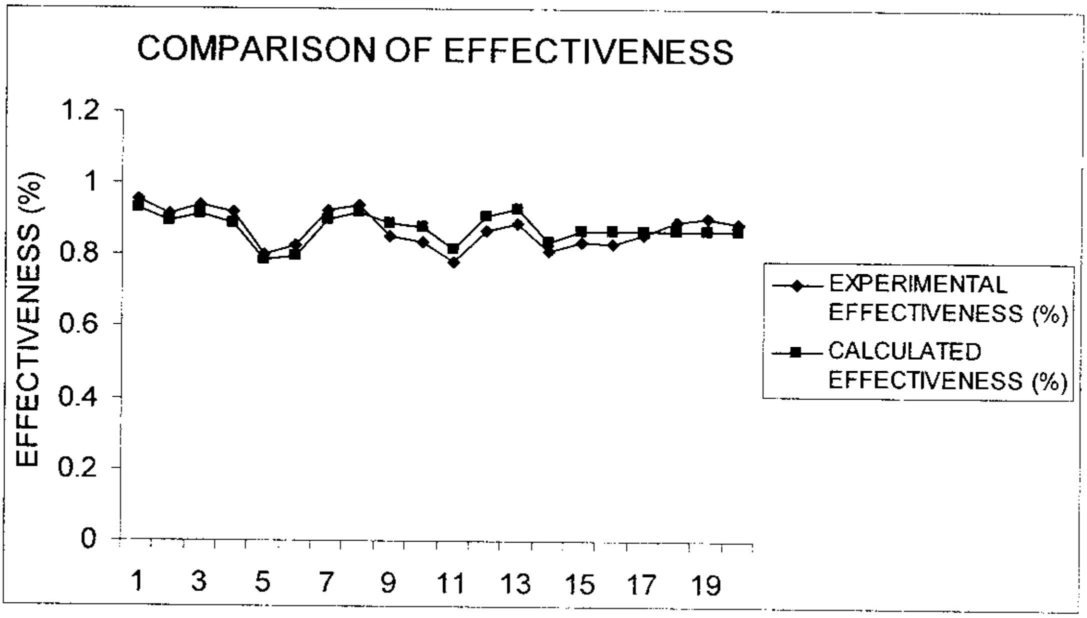


Figure 9.1 Comparison of Experimental and Calculated Effectiveness

The effectiveness which is obtained during the experiment was optimal and it is depicted from the above figure 9.1.

9.2 INTERACTIVE EFFECTS ON EFFECTIVENESS

As mentioned in chapter 8, the interactive effects of air velocity and water temperature (figure 9.2), air velocity and heat input & water temperature (figure 9.3), and heat input on heat pipe heat exchanger (figure 9.4) is analyzed. It may be noted that the third parameter in each interactive effect is kept constant.

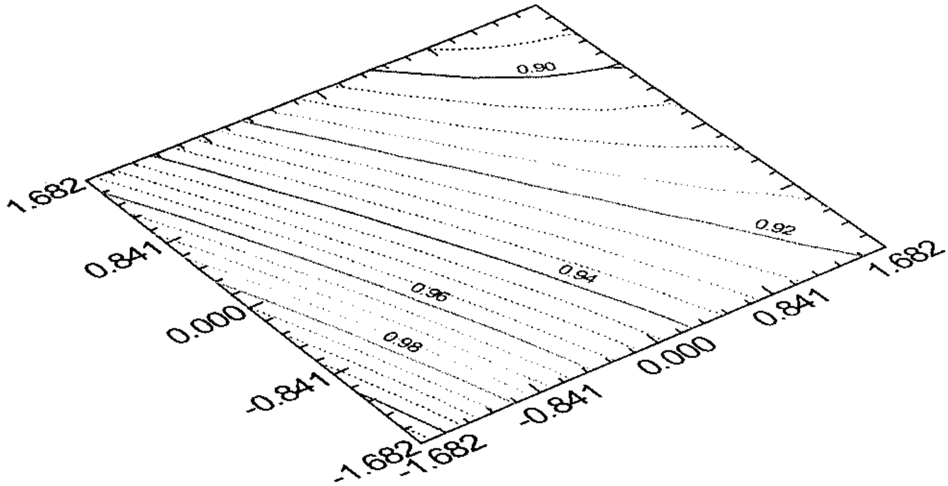


Figure 9.4 Interactive Effects of Water Temperature and Heat Input

From the three graphs, it can be concluded that the maximum effectiveness is obtained when the air velocity is constant with varying water temperature and heat input. Maximum effectiveness obtained is 0.98.

CONCLUSION

CHAPTER 10

CONCLUSION

To determine the thermal performance of thermosyphon heat pipe heat exchanger an experiment was conducted based on DOE and optimization by SYSTAT as described in earlier chapters.

The experiments were conducted as per the design matrix using Design of Experiments (DOE). Mathematical model was generated using the Quality America software for the effectiveness for the input parameters heat input, water temperature and velocity of air. The mathematical model developed is useful to analyze the thermal performance of the heat pipe heat exchanger. The calculated effectiveness is compared with the experimental effectiveness and the deviations falls with in the limit of 95% confidence level.

The optimization of the heat pipe heat exchanger is done using SYSTAT software. The interactive effects of air velocity and water temperature, air velocity and heat input & water temperature and heat input on heat pipe heat exchanger, the third parameter kept constant, is analyzed. It can be concluded that the maximum effectiveness is obtained when the air velocity is constant with varying water temperature and heat input and maximum effectiveness obtained is 0.98.

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REFERENCES

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