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Waste heat recovery using heat pipe heat exchanger (HPHE) for surgery rooms in hospitals

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Abstract

Research has been carried out 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 through computer simulation. Construction of heat pipes, including washing, inserting the wick, creating the vacuum, injecting the fluid and installation have also been carried out. After obtaining the appropriate heat flux, the air-to-air heat pipe heat exchanger was designed, constructed and tested under low temperature (15–55°C) operating conditions, using methanol as the working fluid. Experimental results for absorbed heat by the evaporator section are very close to the heat transfer rate obtained from computer simulation. Considering the fact that this is one of the first practical applications of heat pipe heat exchangers, it has given informative results and paved the way for further research. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Heat recovery; Heat pipe; Heat pipe heat exchanger

1. Introduction

Heat exchangers made of heat pipes are one of the most effective devices for waste

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Nomenclature

A	cross-sectional area of duct (m^2)
c_p	specific heat (kJ/kg K)
h_fg	enthalpy of vaporisation or latent heat (kJ/kg)
m	mass flow rate of air (kg/s)
M	figure of merit (kW/m^2)
q	axial heat transfer rate (kW)
q_act	actual heat transfer rate (kW)
q_c	rate of heat transfer from condenser (kW)
q_e	rate of heat transfer to evaporator (kW)
q_max	maximum heat transfer rate (kW)
Q_ent	entrainment limit on heat transfer rate (kW)
Q_s	sonic limit on heat transfer rate (kW)
R	universal gas constant (J/K kg mol)
r_v	radius of vapour space (m)
T_c	condenser duct temperature (°C)
T_e	evaporator duct temperature (°C)
T_v	temperature of vapour (°C)
T_w	surface temperature of pipe (°C)
T_sat	saturation temperature of fluid (°C)
ΔT_s	difference between T_w and T_sat (°C)
u	velocity of air through duct (m/s)
δ	thickness of thermal layer (m)
γ	ratio of specific heats
λ	characteristic dimension of the liquid/vapour interface (m)
μ_l	viscosity of the liquid (kg/m s)
θ	contact angle (degree)
ρ_l	density of the liquid (kg/m^3)
ρ_v	density of the vapour (kg/m^3)
σ_l	surface tension (N/m)

heat recovery. The advantage of using a heat pipe over conventional methods is that large quantities of heat can be transported through a small cross-sectional area over a considerable distance with no additional power input to the system. Furthermore, simplicity of design and manufacturing, small end-to-end temperature drops, extremely wide temperature application range (4–3000 K) and the ability to control and transport high heat rates at various temperature levels are unique features of heat pipes [1–3].

Heat pipes have been applied in many ways since their introduction in 1964. Some of the important applications of heat pipes are as follows: in the area of spacecraft cooling [4,5], electrical and electronic equipment cooling [6,7], medicine and human body temperature control [8,9] and as heat exchangers for heat recovery [10–13].

The use of the heat pipe heat exchanger will reduce primary energy consumption, thus reducing carbon dioxide production.

Commercial production of heat pipe heat exchangers began in the mid-1970s. Since that time, they have found numerous applications in many industries. Heat pipe heat exchanger applications can be divided into three main categories:

1. Heat recovery in air conditioning devices.
2. Heat recovery from the process exhaust stream to preheat air for space heating.
3. Heat recovery from the process exhaust stream to re-use in the process.

Although the operating condition of a heat pipe is simple, its appropriate design and construction is very complicated. Since numerous parameters should be controlled, experimental investigations are very important.

In this research, initially the material and dimensions of a single heat pipe, the types of wick and working fluids compatible with the pipe and wick were selected. The characteristic design and heat transport limitations of heat pipes for three types of wick (50 mesh nickel, 250 mesh nickel and 100 mesh stainless steel) and three working fluids (methanol, water and acetone) through a computer simulation of a single heat pipe were examined. The rate of heat input to the evaporator section was maintained within 20–400 W.

The results obtained from the computer simulation were used to construct the heat pipe. After fabrication of the heat pipe and obtaining the appropriate heat flux, a heat pipe heat exchanger with a heat exchange potential of 800 W for heat recovery from a surgery room in a hospital was designed, manufactured and tested.

2. Computer simulation of a single heat pipe

The operation of a heat pipe is easily understood by using a cylindrical geometry, as shown in Fig. 1. The components of a heat pipe are a sealed container (pipe wall and end caps), a wick structure and a small amount of working fluid in liquid state, which is in equilibrium with its own vapour. The length of the heat pipe is divided into three parts: the evaporator section, adiabatic section and condenser section. In the selection of a suitable combination of three basic components, inevitably a number of conflicting factors may arise and the principal bases for selection are discussed in Ref. [2].

In order to design the heat pipe, all related formulae and equations have been used in a computer program. Selection of wick and wall materials is based on the criteria discussed in Ref. [2]. With reference to the objective of the research, copper pipes with an outside diameter of 15 mm, inside diameter of 9 mm and length of 600 mm have been selected. Three types of wicks, 50 mesh nickel, 250 mesh nickel and 100 mesh stainless steel have been utilised. Three types of working fluid, namely, methanol, water and acetone, which according to reference [1], are compatible with the wick and pipe and applicable within the working temperature range (15–55°C), have been considered.

Through the computer simulation of a single heat pipe, the characteristic design of the heat pipe, number of wicks, volume and pressure, figure of merit, priming factor and heat transfer limits of working fluids have been investigated.

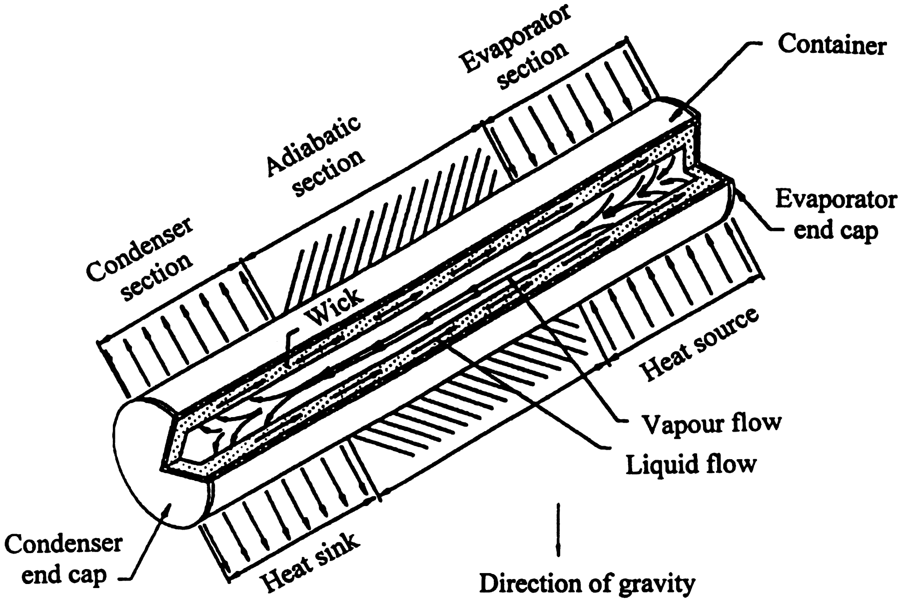

Fig. 1. Schematic of a conventional heat pipe showing the principle of operation and circulation of the working fluid.

Evaluating the figure of merit over the vapour temperature range allowed the performance of the three working fluids to be compared [2]. The figure of merit is given by:

$$M = \frac{\rho_l \sigma_l h_{fg}}{\mu_l}$$

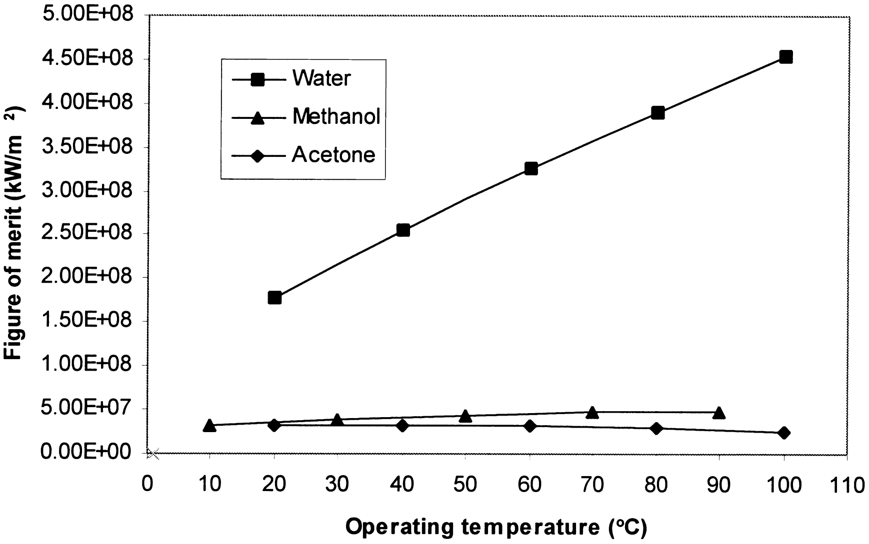

Fig. 2. Figure of merit for selected working fluids.

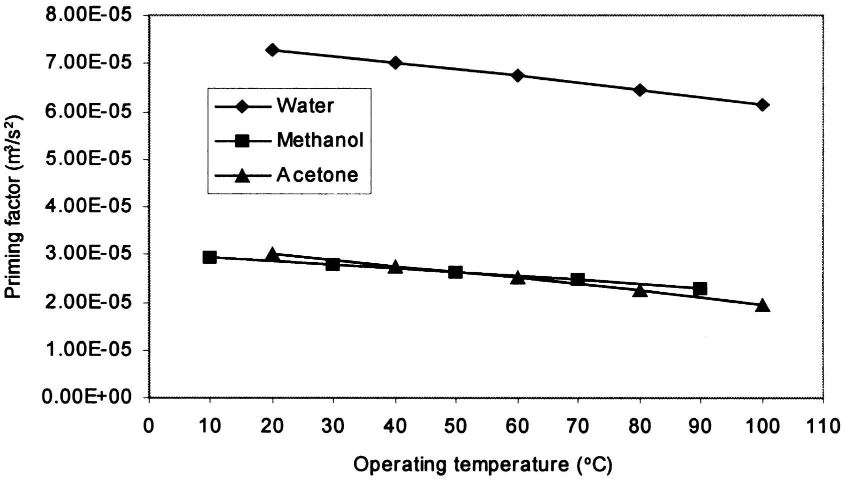

Fig. 3. Priming factor for selected working fluids.

The results are shown in Fig. 2 which reveal the advantage of water and to a lesser extent methanol, over acetone.

A further factor in fluid selection is priming ability. A comparison of the priming ability of fluids may be obtained from the ratio σ_l/ρ_l [2] and this is plotted against vapour temperature in Fig. 3. Water is shown to be superior to the methanol and acetone over the whole operating temperature range.

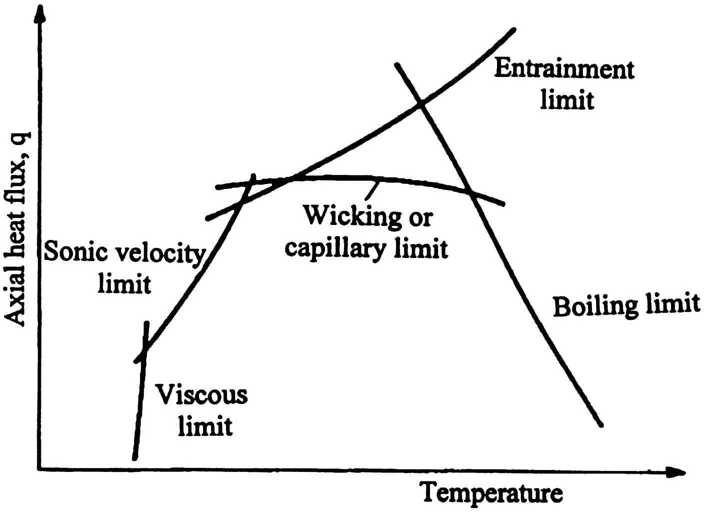

Fig. 4. Limitations to heat transport in the heat pipe.

3. Examination of limits

In the design of a heat pipe, the limitations on heat transport must be examined for each working fluid. Although heat pipes are very effective heat transfer devices, they are subject to a number of heat transfer limitations. These limitations determine the maximum heat transfer rate a particular heat pipe can achieve under certain working conditions. The type of limitation that restricts the operation of the heat pipe is determined by the one, which has the lowest value of heat transfer rate at a specific heat pipe working temperature. Fig. 4 shows schematically the axial heat flux as a function of heat pipe working temperature for different limitations [2]. It is necessary for the operating point to be chosen in the area lying below these curves. The actual shape of this area depends on the working fluid and wick material and will vary appreciably for different heat pipes.

The viscous limit is not applicable to the selected working fluids at the operating temperature range. Since the vertical heat pipe is used, the pressure differences between liquid and vapour are very small with respect to the total capillary and gravity head. The sonic, entrainment and radial limits on heat transport of a single heat pipe in the range of input heat to evaporator within 20–400 W were examined for each working fluid.

The axial heat flow rate due to the sonic limitation was calculated from the following equation [2]:

$$Q_s = \pi r_v^2 \rho_v h_{fg} \sqrt{\frac{\gamma R T_v}{2(\gamma + 1)}}$$

The values of Q_s versus temperature are plotted in Fig. 5.

The maximum heat transfer due to the entrainment limit was determined using the equation [2]:

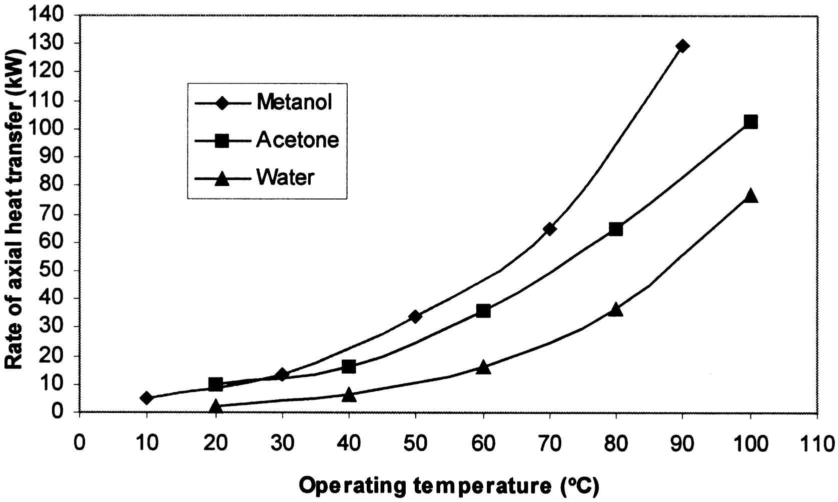

Fig. 5. Sonic rate of axial heat transfer limit.

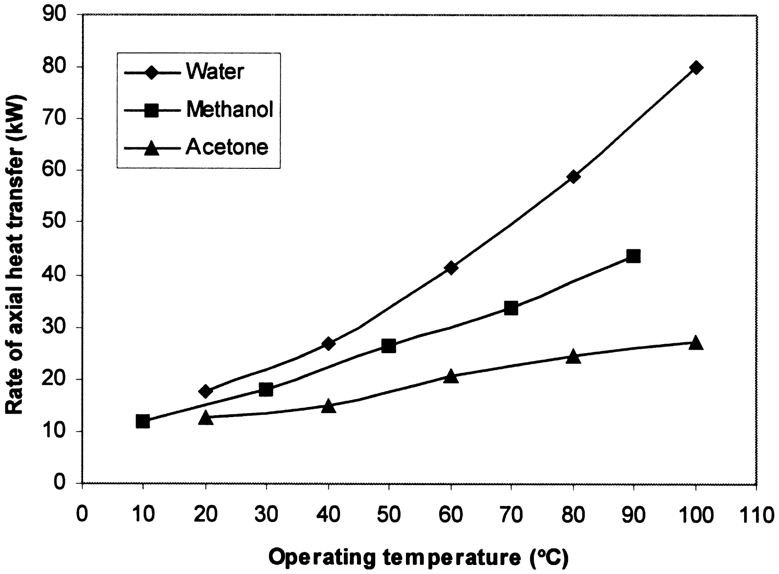

Fig. 6. Entrainment rate of axial heat transfer limit.

$$Q_{\mathrm{ent}} = \pi r_{\mathrm{v}}^2 h_{\mathrm{fg}} \sqrt{\frac{2\pi \rho_{\mathrm{v}} \sigma_{\mathrm{l}} \cos\theta}{\lambda}}$$

Where λ is the characteristic dimension of the liquid/vapour interface and for 100 mesh SS was taken as 0.036 mm and θ is contact angle and was taken zero. The values of Q_{ent} versus temperature are plotted in Fig. 6.

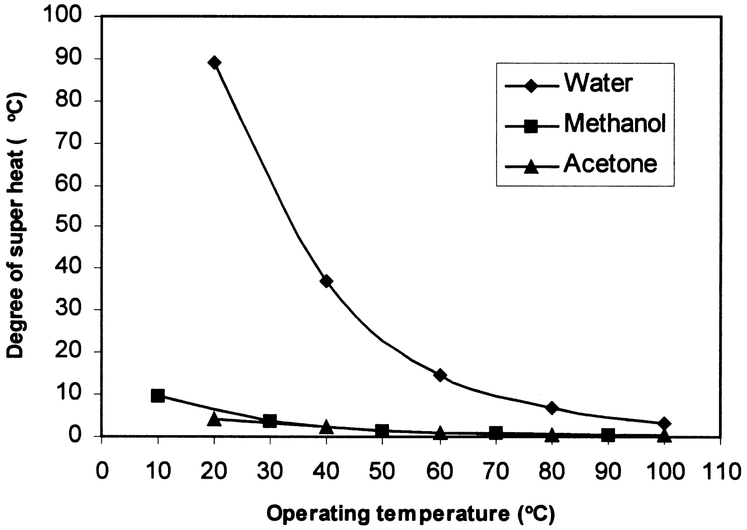

Fig. 7. Degree of superheat for the three working fluids.

It is seen from Figs. 5 and 6 that the sonic and entrainment limits of the three working fluids are well above the maximum required heat transport capacity (400 W).

Boiling in the wick may result in the vapour blocking the supply of liquid to all parts of the evaporator. It is therefore desirable to have a working fluid with a high degree of superheat ΔT_s to reduce the chance of nucleation. The degree of superheat to cause nucleation is given by [2]:

$$\Delta T_s = \frac{3.06\sigma_l T_v}{\rho_v h_{fg} \delta}$$

In this calculation the value of δ which is the thickness of the thermal layer was assumed to be 0.15 mm. This is the thickness of one layer mesh.

The degree of superheat temperature versus operating temperature is plotted in Fig. 7 for the three working fluids.

4. Selection of working fluid

Since water has a high degree of superheat temperature especially at the low pressure involved in this application, water is not applicable. For example, for the operating temperature of 45°C the degree of superheat is about 20°C. Methanol has the larger Merit No. and capillary limit and also an acceptable degree of superheat with respect to acetone in the temperature range 15–55°C, therefore it has been selected. At the maximum working temperature (80°C), the vapour pressure of methanol is 2.3 bar. Considering a reasonable safety factor, the wall thickness of the pipe is taken to be 3 mm.

5. Design and construction of heat pipes

The selected range of heat input was within 20–400 W for the single heat pipe. It is necessary to have a heat pipe capable of transferring a minimum of 100 W at the temperature range between 15–55°C. Through computer simulation the heat pipe was examined in the range of 20–400 W. According to the desired heat transfer rate (100 W) and required cross-sectional area of wick and wick thickness, the number of wicks were obtained. It was found out that one layer of mesh was sufficient.

Finally, according to the desired characteristics of the heat pipe and with reference to Figs. 2 and 4–7 obtained through the computer simulation, the heat pipe with the following features was designed.

Material of pipe, copper
Diameter of pipe, 15 mm
Length of pipe, 600 mm
Length of evaporator section, 300 mm
Length of condenser section, 300 mm
Thickness of pipe, 3 mm

Type of wick, 100 mesh SS
Number of layers, 1
Working fluid, methanol
Heat duty per pipe, 100 W.

After obtaining the above characteristics for the single heat pipe, eight heat pipes were manufactured. This process consisted of washing, inserting the wick, creating the vacuum, injecting the working fluid and testing of each individual heat pipe. The satisfactory experimental results from the constructed heat pipe can be taken as a good indication of the veracity of research and design carried out by a computer simulation.

6. Experimental set up

The test rig has been designed and constructed to test the effectiveness and validate the developed computer program of the air-to-air heat pipe heat exchanger shown in Fig. 8. Fig. 9 is the test rig used for this investigation. A heat exchanger consisting of eight individual heat pipes was used in the tests. The specifications for the unit are:

Three rows of heat pipes
Methanol as working fluid
Heat pipes in staggered equilateral triangle arrangement of 45 mm centres
Hard drawn copper pipes, 15 mm OD, 9 mm ID

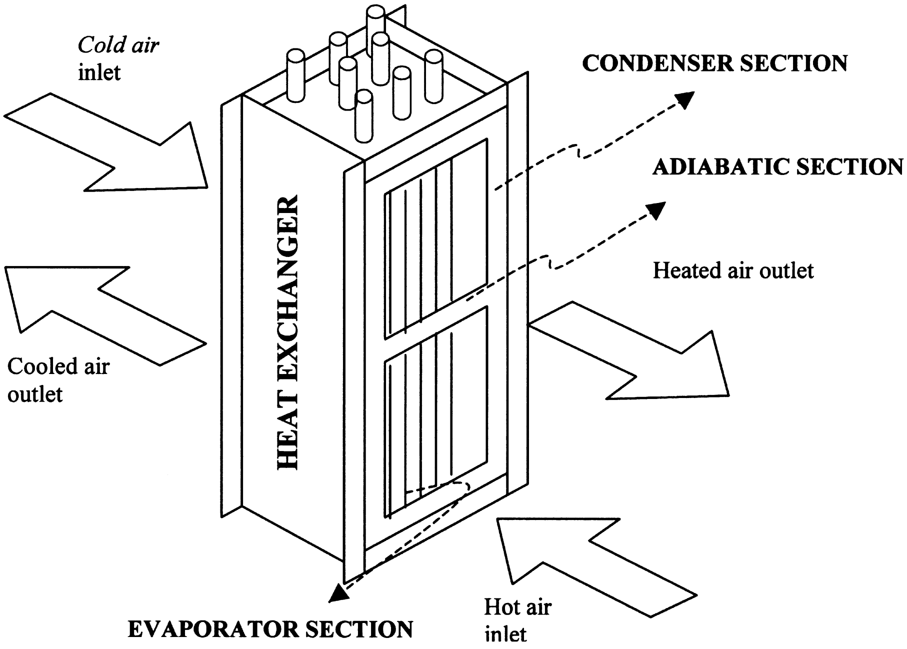

Fig. 8. Schematic of the heat pipe heat exchanger.

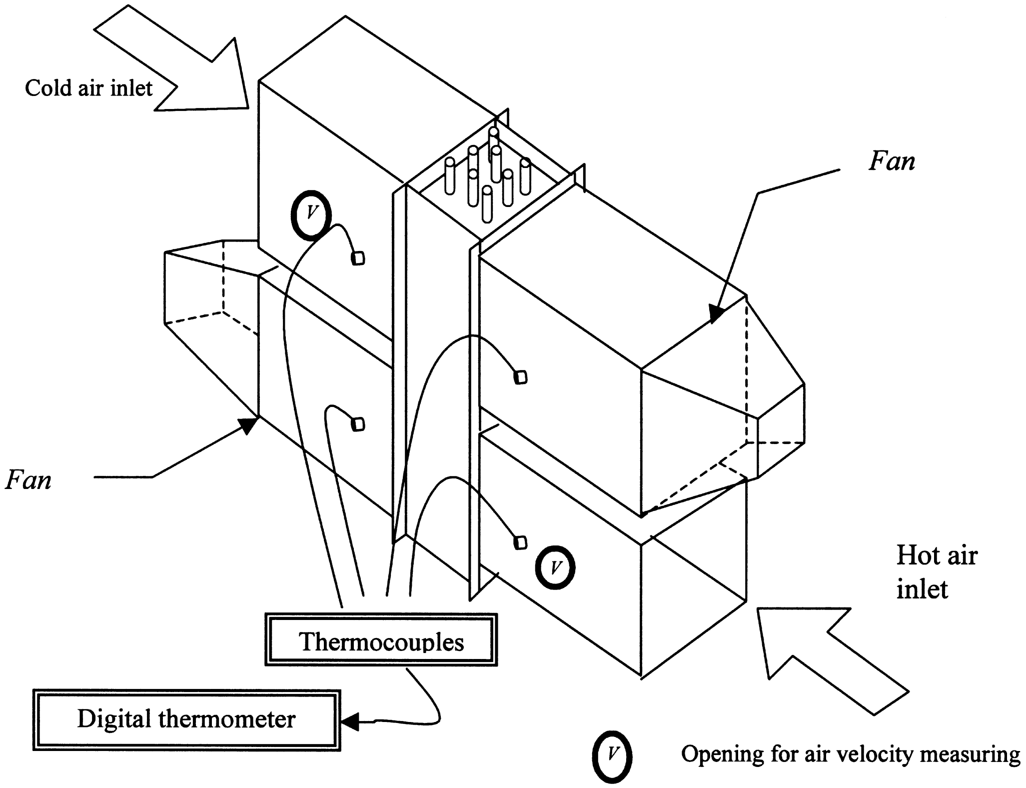

Fig. 9. The schematic of test rig.

Equal evaporator and condenser lengths, 300 mm each
Total dimensions of unit (width × height × depth) = 150 × 600 × 150 mm
Galvanised sheet steel flanges.

The experimental rig consists of two fans that provide a flow rate of 0.103 m^3/s through evaporator and condenser. The air velocities of both streams were measured by air velocity meters and were 2.3 m/s. To monitor temperatures, K type thermocouples were used and this measurement was processed by digital thermometer. The atmospheric air is heated by the three electric heating elements (total power 1500 W). After giving part of this heat to the evaporator section, the air is discharged to the atmosphere.

7. Experimental results and discussions

A series of tests was performed in order to investigate the characteristics of the heat pipe heat exchanger, by blowing warm and cool air with constant mass flow rate over the heat pipe heat exchanger. Since the model is designed for use in a hospital surgery, the tests were carried out in the temperature range 15–55°C. The average temperatures obtained are as follows:

Average temperature of inlet air to evaporator section, $T_{\mathrm{e,in}} = 55°\mathrm{C}$
Average temperature of outlet air from evaporator section, $T_{\mathrm{e,out}} = 49°\mathrm{C}$
Average temperature of inlet air to condenser section, $T_{\mathrm{c,in}} = 17°\mathrm{C}$
Average temperature of outlet air from condenser section, $T_{\mathrm{c,out}} = 21°\mathrm{C}$.

The rate of axial heat transfer by conduction of individual heat pipe was calculated and found to be negligible in comparison with heat transport to air.

With reference to mass flow rate of warm and cool air, the heat transfer rates to the evaporator and condenser sections are calculated as follow:

$$q_{\mathrm{e}} = mc_{\mathrm{p}}(T_{\mathrm{e,in}} - T_{\mathrm{e,out}}) = \rho uAc_{\mathrm{p}}(T_{\mathrm{e,in}} - T_{\mathrm{e,out}})$$

$$= 1.08 \times 2.3 \times (0.15 \times 0.3) \times 1008.1 \times (55 - 49) = 676.1\ \mathrm{W}$$

$$q_{\mathrm{c}} = mc_{\mathrm{p}}(T_{\mathrm{c,out}} - T_{\mathrm{c,in}}) = \rho uAc_{\mathrm{p}}(T_{\mathrm{c,out}} - T_{\mathrm{c,in}})$$

$$= 1.24 \times 2.3 \times (0.15 \times 0.3) \times 1006.7 \times (21 - 17) = 516.8\ \mathrm{W}$$

It is seen that the average rate of heat input to the evaporator section of heat pipe ($676.1/8 = 84.5$ W) found by experiment is close to the heat transfer rate (100 W) predicted by computer simulation.

The effectiveness of the heat exchanger is defined as the ratio of the actual rate of heat transfer by the heat exchanger to the maximum possible heat transfer rate between the air streams [14–16]. Assuming, there is no water condensation in air streams and also assuming the specific heat of air passing through the heat exchanger to be constant then the effectiveness of heat pipe heat exchanger is represented as:

$$\varepsilon = \frac{q_{\mathrm{act}}}{q_{\mathrm{max}}} = \frac{T_{\mathrm{e,in}} - T_{\mathrm{e,out}}}{T_{\mathrm{e,in}} - T_{\mathrm{c,in}}} = \frac{55 - 49}{55 - 17} = 0.16$$

The low value of effectiveness was attributed to lack of fins, high pitch to diameter ratio and high air face velocity.

8. Conclusions

1. 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.
2. 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.
3. The low effectiveness of the heat exchanger (0.16) was attributed to the high pitch to diameter ratio of the pipe and also lack of fins.
4. It is important to use the most appropriate method for producing the vacuum and filling the heat pipe. Similarly the most appropriate way of sealing of the pipe ends is necessary.

5. With reference to the experimental results obtained, the following points play vital roles in increasing the efficiency and effectiveness of HPHE:
    5.1. Using finned pipes
    5.2. Increasing the number of rows
    5.3. Complete insulation of the test rig
    5.4. Perfect sealing of pipes.

References

[1] A. Faghri, Heat Pipe Science and Technology, Taylor & Francis, USA, 1995.

[2] P.D. Dunn, D.A. Reay, Heat Pipes, third ed., Pergamon Press, 1994.

[3] J.G. Marten Terpstra, Van Vean, Heat Pipes Construction and Application, Elsevier Applied Science, London, New York, 1987.

[4] R. Brown et al., Performance evaluation of the grumman prototype space erectable radiator system, AIAA Paper No. 90-1766 (1990).

[5] R. Brown et al., Design of the SHARE II Monogroove Heat Pipe, Proc. AIAA 26th Thermophysics Conference, Paper No. AIAA 91-1359 (1991).

[6] L.L. Vasilier, et al., Heat pipes for electronic equipment cooling systems, in: Proc. 7th Int. Heat Pipe Conference, Minsk, USSR, 1990.

[7] A. Basiulis, et al., Heat pipes for cooling of high density printed wiring board, in: Proc. 6th Int. Heat Pipe Conf., Grenoble, France, 1987, pp. 685–691.

[8] A. Faghri, et al., Heat pipes for hands, Mech. Eng. 111 (6) (1989) 72–75.

[9] A. Faghri, Temperature Regulation System for the Human Body Using Heat Pipes, US Patent 5,269,369 Issued Des. 14 (1993).

[10] G. Liu, et al., The application of heat pipe heat exchanger in exhaust gas heat recovery system and its thermodynamic analysis, in: 8th Int. Heat Pipe Conference, Beijing, China, 1992, pp. 582–585.

[11] J.Y. Sun, R.J. Shyu, Waste Heat Recovery Using Heat Pipe Heat Exchanger for Industrial Practices, in: Proc. 5th Int. Heat Pipe Symposium, Melbourne, Australia, 1996.

[12] V. Dube, I. Sauciuc, A. Akbarzadeh, Design Construction and Testing of a Thermosyphon Heat Exchanger for Medium Temperature Heat Recovery, in: Proc. 5th Int. Heat Pipe Symposium, Melbourne, Australia, 1996.

[13] W.U. Xiau Ping, P. Johnson, A. Akbarzadeh, A study of heat pipe heat exchanger effectiveness in an air conditioning application, in: Proc. 5th Int. Heat Pipe Symposium, Melbourne, Australia, 1996.

[14] J.O. Tan, C.Y. Liu, Predicting the performance of a heat pipe heat exchanger using the NTU method, Intl. J. Heat Fluid Flow 11 (4) (1990) 376–379.

[15] W.M. Kays, A.L. London, Compact Heat Exchanger Design, third ed., McGraw-Hill, New York, 1984.

[16] F.P. Incorpera, D.P. DeWitt, Fundamentals of Heat and Mass Transfer, third ed., John Wiley and Sons, Toronto, 1996.