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Comparative study of heat pipes performance with different working fluids and orientations

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Abstract In recent years heat pipes technology have been widely used in high performance air-cooled heat sinks for cooling electronic equipments. The objective of this paper is to conduct a comparative study on heat pipe performance with different working fluids subjected to different orientations. The working fluids chosen for the study were water and ethanol and the material of heat pipes is copper with the screen mesh as a wick structure. The experimental results show that the heat transported by the heat pipes of water working fluid are considerably more than that of the heat pipes of ethanol working fluid.
Keywords Heat pipe, wick structure, working fluids, screen mesh.

دراسة مقارنة أداء الأنابيب الحرارية مع اختلاف سوائل التشغيل والاتجاهات

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الملخص تكنولوجيا الأنابيب الحرارة أصبحت تستخدم على نطاق واسع في تبريد المعالجات والمعدات الإلكترونية عالية الأداء. هذه الانابيب تعمل بمفعول الضغط الداخلي المنخفض الذي يخفّض من درجة غليان السائل المستخدم ، و الذي يتبخّر بفعل الحرارة في الطرف الساخن، و بفعل الضغط والاختلاف الحراري فإن البخار ينتقل عبر قناة في وسط الأنبوب إلى الطرف البارد حيث يتكثّف البخار و يرجع مرة أخرى إلى الطرف الساخن بفعل الظاهرة الشعرية. تهدف هذه الدراسة إلى مقارنة أداء الأنبوب الحراري مع سوائل عمل مختلفة وذلك باختلاف اتجاهات التشغيل. سوائل التشغيل التي تم اختيارها في هذه الدراسة هي الماء والإيثانول المطلق، أيضا فإن الأنابيب الحرارية كانت مصنعة من النحاس مع شبكة من الرقائق السلكية. أظهرت النتائج التجريبية أن القيمة القصوى لنقل الحرارة في الأنابيب الحرارية المائية زاد بصورة ملحوظة عن أنابيب الحرارة المليئة بالإيثانول المطلق.
الكلمات المفتاحية: أنبوب الحرارة ، الرقائق السلكية ، سوائل التشغيل ، شبكة.

1. Introduction

A heat pipe is a device that transfers heat by using both the phase change and thermal conductivity [1]. It is an efficient device for heat transfer management between two solid surfaces. A heat pipe has both a cold and hot ends. The hot end is at a lower pressure and causes the working liquid to transform into a vapour through the absorpting of heat from the hotter surface of the interface. The cold end causes the vapour to change back into a liquid which releases heat [1]. This liquid can then be sent back to the hot end by gravity or capillary force where the process begins again with the liquid turning into a vapour. The pressure within the heat pipe can be adjusted in order to maximize the phase change. The schematic of a conventional heat pipe is shown in Figure 1.

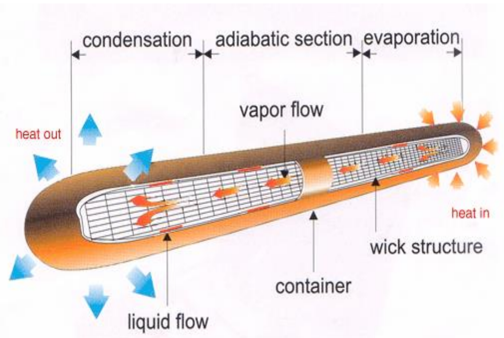

Fig.1 Schematic and operation of heat pipe [2].

2. Heat Pipe Components.

2-1. Container.

An envelope that forms the heat pipe after it has been evacuated and sealed is called the container. Different materials such as metals, glass, plastic, even ceramics and many others are used as container material [3]. Metals are mostly used as container material due to their high thermal conductivity. Copper is the most common material used for container. Groll et al [3], gave a comprehensive overview about heat pipes used for cooling of electronic components especially with regards to material selection and possible of material combination.

2-2. Screen Mesh Wicks

Canti *et al* [4] stated a good definition of a wick inside a heat pipe and also provided an overview of stainless steel as a wick material for a heat pipe. According to them the understanding of the thermal hydraulics of the wick is needed for the heat pipe design and manufacturing. They presented work on stainless steel, which is not the most common material for either sintered wicks or mesh wicks. This review is merely focused on the screen mesh part of their work. Through using very simple apparatus they provided a detailed analysis of the properties, like the capillary height/ head, permeability and the heat fluxes possible. An interesting part of their work was that they achieved heat fluxes between 55 and 70 W/cm^2 for a composite wick, made out of a combination of sintered and mesh wicks, which is by some degree higher what is assumed to be the critical heat flux for screen meshes.

Authors in [5] have also presented very interesting fundamental research around screen meshes. Their work shows how to obtain the porosity of a certain screen mesh directly from using its geometrical data like wire diameter, aperture and crimping factor. They provided a correlation between their experimental and analytical study. They found the difference as almost 3%. Also they provided information on how to treat multilayer screen wicks which are commonly used in heat pipes. It is a very high task of conducting work on fill/ fluid charge calculations of heat pipes.

The problems of fluid loading as well as investigating the effects of different numbers of wick layers within the screen mesh of a heat pipe were worked by Kempers, Ewing and Ching [6]. They found that the overall thermal resistance does not increase in a linear way with an increasing number of mesh layers, but almost reaches a stable state once three layers are implemented. The next phenomenon investigated was the amount of working fluid required. Their results coincide with what has been stated by Peterson [7]. They found that the heat pipes with less liquid load had an inferior overall thermal resistance but a reduced highest heat transfer rate as well. The ideal heat pipe has a saturated wick and no excess working fluid whilst the heat pipes with excess working fluid have in nearly all orientations, apart from the vertical one, a higher maximum heat transfer rate but also a higher overall thermal resistance.

The work of Brautsch and Kew [8] investigated the heat transfer capabilities of the wick and it was very interesting as the work compares the heat transfer capabilities of each wick. The wick types investigated coincides very nicely with wick geometries available for uses in heat pipes as well, and are 50 meshes, 100 meshes, 150 meshes and 200 meshes. Within the work conducted and presented as part of this thesis, 250 meshes have been used and therefore there is a great relevance of their work to this work.

Regarding the screen mesh heat pipes, the last study to be mentioned here is the study conducted by Authors in [9]. They defined heat pipe as in its conventional form, "it consists of a preserved tube that is partly packed with a working liquid, and wick saturated with a working liquid, lines the inner sides of the tube". Within their study, they have investigated three different wick types, first a coarse screen mesh type of 100 copper mesh, secondly a fine sintered copper wick and third a combination of the two where the sintered wick is applied in the evaporator, whilst the screen is applied in the adiabatic section as well as the condensation section. They concluded that the performance of combined wick is very high quality and as a consequence it adds to the performance of the heat pipe. If the heat load and cooling conditions are kept the same, it can perform double task. A high surface area for evaporation in the evaporation section is combined with a low thermal resistance in the condenser section in their combined wick.

2-3. Working Fluids.

There are three basic component of a heat pipe, including the capillary structure or wick, container, and working fluid. The best working fluid is determined by a number of factors. There can be several fluids, which are appropriate for a certain temperature range, each of which may have its own characteristics. These unique characteristics help determine which fluid is most acceptable for the particular application. Some of the considerations, which must be taken into account, are as follows [10]- [11]:

- Liquid absorption capability of the pipe wall and wick.
- Thermal stability of the fluid.
- Compatibility of the fluid with the wall material and wick.
- The thermal conductivity of the liquid.
- Vapour pressure, which is acceptable for the particular operating range of the heat pipe.
- The latent heat of the liquid.
- The viscosity of the liquid in both its fluid and gaseous phases.
- Pour and freezing points of the liquid.

3. Heat transport limitations

The capillary pressure difference occurring in the heat pipe should always be greater than the summation of all the pressure losses occurring through the vapour and fluid flow trails in order to proper functioning of a heat pipe. The pressure losses increase as the heat-transfer rate increases. This can be overcome by enhancing the capillary pressure difference. The pressure losses increase to a great extent if there is a continuous increase of heat transfer. The total capillary pressure difference at one heat-transfer rate is no longer equal or greater than the total pressure losses. This relation is called a capillary limit and it can be expressed as given below.

$$\Delta p_{c,max} \geq \Delta p_l + \Delta p_v + \Delta p_g \quad (1)$$

In this case $\Delta p_{c,max}$ is the maximum capillary pressure disparity produced inside capillary wicking structure, Δp_l is the amount of inertial and viscous pressure drops occurring in liquid phase, Δp_v is the amount of viscous pressure drops and inertial which is occurring in vapour phase and Δp_g is the hydrostatic pressure drop.

When the maximum capillary pressure difference is equal to or greater than the summation of these pressure drops, the capillary structure is capable of returning an adequate amount of working fluid in order to prevent dry out of the evaporator wicking structure. On the basis of, working fluid, the wicking structure, vapour flow channel, evaporator heat flux and operating temperature this situation varies [12].

4. Quantity of heat

The equation given below can be used to find the maximum heat transport in a heat pipe at a given vapour temperature.

$$Q_{max} = \dot{m}_{max} L \quad (2)$$

$\dot{m}_{max}$ is the maximum liquid flow rate in the wick which can be determined by the following equation.

$$\dot{m}_{max} = \frac{\rho_l k A_w}{\mu_l l_{eff}} \left\{ \frac{2\sigma_l}{r_c} cos\theta - \rho_l g l_{eff} sin\emptyset \right\} \quad (3)$$

5. Experimental Methodology.

The experiments were limited to copper–water and copper–ethanol heat pipes, with copper screen mesh as the wick. The specifications data for heat pipe are listed in Table 1.

Table 1.Specifications of heat pipe

Specifications	Dimensions
Radius in the condensing section (m)	$0.847x10^{-4}$
Outlet diameter (mm)	6
Thickness of the heat pipe (mm)	0.5
Inlet diameter or vapour diameter (mm)	4.64
Characteristic dimension of the liquid-vapour (mm)	0.036
Wick porosity, (dimensionless)	0.66
Wire diameter (cm)	0.0045
Length of heat pipe section (cm)	20
No. of layers of wick	2
Effective length (cm)	14
Wick cross-sectional area (m^2)	6.5249×10^{-6}
Wick permeability (m^2)	0.302×10^{-10}

The pipe performance is tested with one type of wicks. The wire diameter and the porosity of material calculations will provide the quantitative analysis of the design. The weight of the fluid in the pipe should be enough to saturate the free space and the mesh volume. There should be no excess water left. In order to conduct a performance evaluation experiment fill calculations need to be made with the assessment of venting and charge technique. The venting and the performance are linked to the power provided for the performance evaluation operations. Venting of pipes is the first step in the performance evaluation of heat pipes.

5-1. Venting and filling Techniques

Venting and filling is the process of entering the working fluid into the copper tube under negative pressure and for preparing the copper tube to perform as a heat pipe. This process is very important for the test of a heat pipe. An inaccurate venting may result into the wrong design of operation or the failure of the experimental setup at once. There are four techniques of venting deployed in laboratories and recognized by the industries. Engelhard [13]has quoted Peterson [7] describing the four techniques of venting;

- Venting through evacuation and back filling.
- Use of a liquid fill and vapour generation technique.
- Use of a solid fill and sublimation technique, and
- Charging using a supercritical vapour technique.

The first two techniques are more compatible with the standard working fluid like water and ethanol which are to be used in our experiment. In the evacuation and back filling technique, a negative pressure of 1.333×10^{-7} bar is created in the copper tube (Figure 2).

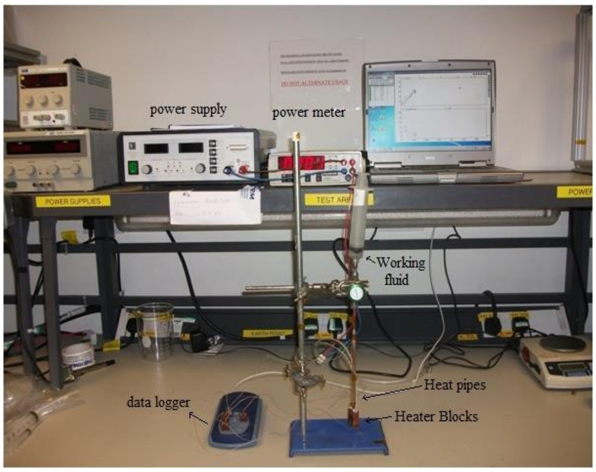

Fig. 2 Process of filled of heat pipe

Filling of accurate amount of fluid into the heat pipe is also required for the efficiency of the operation. A calculated amount of filling weight is required to exist in the heat pipe for production of sufficient volume of vapours. The weight of water further calculates the amount of heat transferred by the heat pipes. The venting temperature should be higher than that of the operational temperature of the working fluid in order to provide an adjustable limit to the working fluid for conversion into gaseous form. For the reason, that higher operational temperature might increase the saturation pressure inside the tube which will further tend to elongate the tube, that would endanger the mechanical strength of the heat pipe and the entire apparatus. Table 2 lists the statistics of weight gain by the heat pipes filled with fluid.

Table 2: Weight of experimental fluids in the heat pipe

Type	Heat pipe 1	Heat pipe 2
Wick material	Mesh	Mesh
Working fluid	Water	Ethanol
Wight of empty heat pipe	20.29g	19.79g
Wight of heat pipe after filling	20.93g	20.74g
Δw(g)	0.64	0.95

5-2. Experimental Setup

The experimental apparatus is consisting of two copper heat pipes, working fluids, and the rig can be tilted for angles of (0°, and 90°). The Photo and Schematic diagram of the rig are shown in the Figures 3 and 4 respectively. A computer is connected with a data logger. A power of 10 W is supplied to the heat pipes. When the fluid inside the tube is vaporized completely, the power is switched off and the apparatus is allowed to cool down. Once the apparatus is cooled, it is switched on once again for one hour. The temperature is monitored carefully during the test. The apparatus is connected to a number of DC supplies to heat the pipes evenly. The cold plates are provided to dissipate the heat of the central processing unit. The coolant system is a system of recirculation fluid flow chilling system that is combined by a flow meter as well as a bypass system to route the excess fluid. This assembly is required to control the drop in the pressure of the system and to monitor the chilling. Two thermocouples, one fixed at the inlet stream and the other at the outlet stream to ensure the accurate reading of energy transfer and to determine any of the heat failure in the system during the experiment. The bypass switch prevents the excess steam from entering into the system, thus preventing the reciprocating chillier from working under heterogeneous pressures of the system and enables it to work efficiently. Engelhard [13] mentioned that ultimately the achievable flow rate of the given system is determined by the pressure drop through the cold plates. The flow through the cold plates can be controlled in a very accurate manner through a needle valve directly.

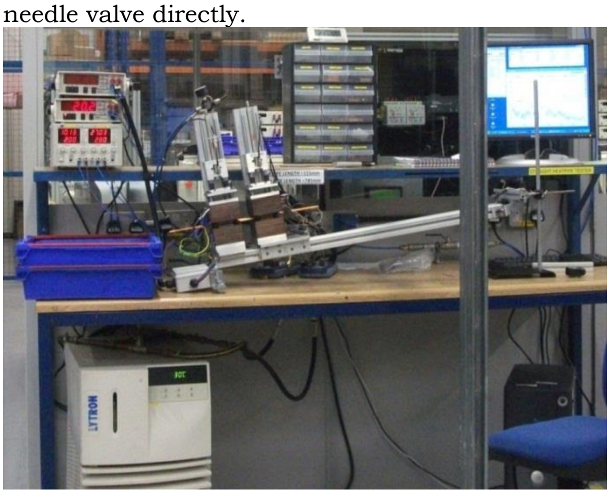

Fig. 3 Test rig and instrumentation used for the thermal testing

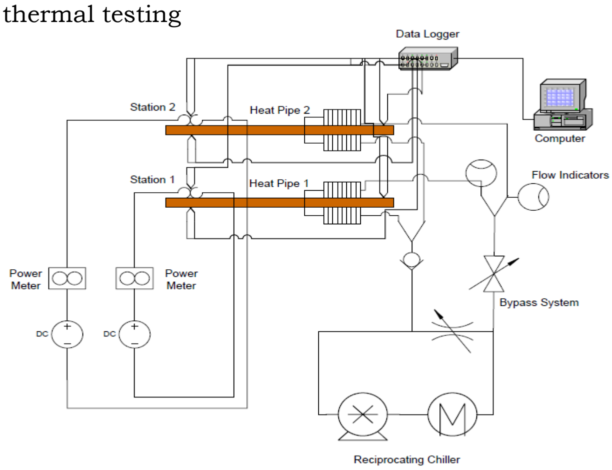

Fig. 4 Schematic diagram of the test rig

6. Results and discussion

Two different working fluids water and ethanol which have varying useful working range of temperature are tested in this study. The heat pipe at vertical position which is plotted by the logger as illustrated in Figures 5, 6, 7 and 8.

Figure 5. shows the vertical heat pipe with mesh wick and water as working fluid. The axial temperature drop (Dt) from the condenser to end of the heat pipe evaporator is less than 2° C for all data measured; in most cases it is ~ 1° C. This clearly indicates that the heat pipe is quite satisfactory, and maintains temperature almost constant, which is also, reflected operating thermal resistance, in the vertical arrangement. The heat pipe continues to perform well beyond an operational temperature of 140° C in this direction. The horizontal position appears to show a slightly lower power (85W*)* at the same temperature (140° C) than the vertical angle of similar condition (Figure 6). The difference is, however, small and may be due to the gravity force that drags the working fluid and it settles down in the bottom of the container. It can be observed that, the position of heat pipe may impact the performance. These results confirm those obtained by Patrik, N. *et al* [2].

In case of ethanol (95 g) as working fluid the measurements of thermal performance of heat pipe with vertical angle as shown in Figure 7 and Table 2. Power input is increased in steps and the temperature of heat source was 120° C. It can be noted that, the axial temperature drop is almost constant for 20W and start increasing for 30 W heat input. This clearly indicates that the heat pipe is functioning quite satisfactorily in that limits. Heat pipe operates on maximum performance and maximum mass flow transfer in this position. Patrik, N.*et al,* [14] in their study also reported that, the ideal working position of heat pipe is vertical position.

Although, the heat pipe is satisfactory to 40 W in the vertical position with temperature gain of fluid up to 120° C, the heat pipe which tested in the horizontal arrangement, the fluid started drying out at 10W and when the power supply reaches a 20 W, the test is stopped (Figure 8). In addition, the temperature of adiabatic cooling section was much higher than that of condensation section. These facts mention a huge and rapid increase of pressure of working fluid, which increases the temperature difference (Dt). The present results, could be attributed to the capillary pressure and surface tension of ethanol.

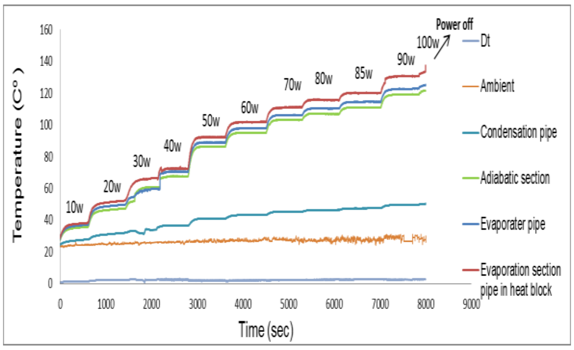

Fig. 5. Measured data of heat pipe with water as working fluid operating at angle 90°.

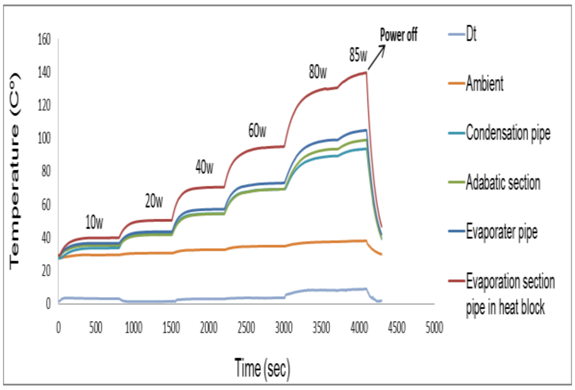

Fig. 6 Measured data of heat pipe with water as working fluid operating at angle 0°

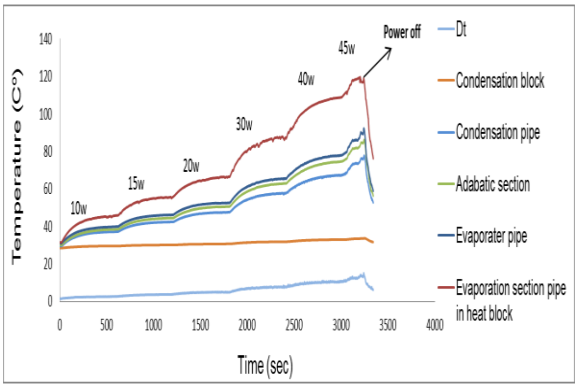

Fig. 7 Measured data of heat pipe with ethanol as working fluid operating at angle 90°.

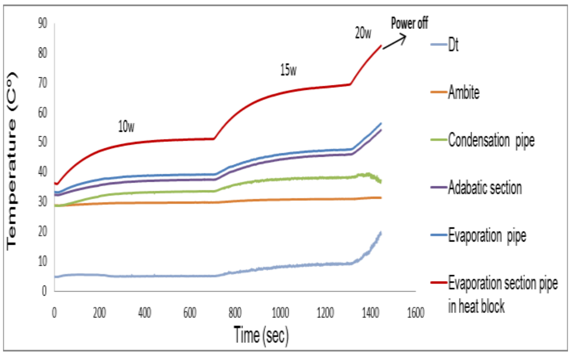

Fig. 8 Measured data of heat pipe with ethanol as working fluid operating at angle 0°.

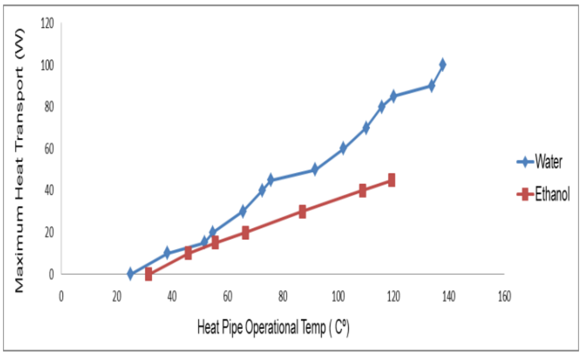

Fig. 9 Performance of copper water/ethanol heat pipe at angle 90°.

A comparison between the performances of water/ethanol in heat pipe at vertical position is shown in Figure 9. At lower heat input (45W), the gain of temperature in ethanol up to 120° C is higher compared to water temperature at the same heat input. This was attributed to the difference in boiling point and the dew point of the ethanol. Moreover, the contact angle of water to metallic surface is larger than ethanol. In this way heat pipe with screen mesh and water as working fluid at a vertical position may be regarded as an efficient. However, ethanol can reach a high temperature at low power levels.

7. Conclusion

A careful experimental of working fluids was made with different angles of the heat pipe such as, 0°, and 90°, and from which the following can be concluded.

- The experimental test have shown water as a standard working fluid in both positions (vertical and horizontal), where all the parameters appear very smoothly.
- Ideal working position of ethanol heat pipe is vertical position.
- Heat pipes with ethanol as working fluid cannot be operated in a horizontal situation.
- Ethanol can reach a high temperature at low power levels.

NOMENCLATURE

A_w Wick area [m^2]
g Acceleration due to gravity [m/s^2]
k Wick permeability [m^2]
L Latent heat of vaporisation or Enthalpy of vaporisation [J/kg]
l_{eff} Effective length of heat pipe [m]
$\dot{m}$ Mass flow [kg/s]
Q Quantity of heat [W]
r_c Capillary radius [m]
μ_l Dynamic viscosity of liquid [N/m^2]
ρ_l Density of liquid [kg/m^3]

σ_l Surface tension [N/m^2]
θ Contact angle
Ø Tilt angle

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