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Effective thermal conductivity of heat pipes

A. Abo El-Nasr, S. M. El-Haggar

Abstract Several heat pipes were designed and manufactured to study the effect of the working fluids, container materials, and the wick structures on the heat transfer mechanism of the heat pipes. Also, the effect of the number of wick layers on the effective thermal conductivity and the heat transfer characteristics of the heat pipes have been investigated.

It was found that the flow behavior of the working fluid depends on the wicking structures and the number of wick layers. The heat transfer characteristics and the effective thermal conductivity are related directly to the flow behavior. Increasing the number of wick layers (up to 16 layers) increases the heat flux with smaller temperature differences. The flattening phenomena of the thermal resistance was observed after 16 wicks layers due to the entrainment limit.

Effektive Wärmeleitfähigkeit von Wärmerohren

Zusammenfassung Mehrere Wärmerohre wurden ausgelegt und hergestellt, um die Einflüsse von Arbeitsmedien, Behältermaterialien und Dochtstrukturen auf den Wärmeübertragungsmechanismus solcher Apparate zu studieren. Es wurde auch untersucht, welche Auswirkungen die Anzahl der Dochtschichten auf die effektive thermische Leitfähigkeit und das Wärmeübergangsverhalten der Wärmerohre hat. Es zeigte sich, daß das Strömungsverhalten des Arbeitsmediums von Struktur und Zahl der Dochtschichten abhängt. Wärmeübergangscharakteristik und effektive Wärmeleitfähigkeit beeinflussen unmittelbar das Strömungsverhalten. Mit steigender Anzahl der Dochtschichten (bis 16 Schichten) wächst die Wärmestromdichte bei geringeren Temperaturdifferenzen. Infolge Wirksamwerdens der Entrainment-Grenze ergab sich bei mehr als 16 Dochtschichten keine weitere Widerstandsverminderung.

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Nomenclature

A	surface area
d	wick wire diameter
D	effective diameter of the vapor flow
h	heat transfer coeff. due to convection
k	thermal conductivity
l, L	heat pipe length
N	number of aperature per unit length
Q	heat transfer
r	radius
R	resistance
t	thickness
T	temperature
ΔT	overall temperature difference

Subscripts

a	adiabatic
c	condensor
e	evaporator
eff	effective
i	inner
o	outer
ov	overall
s	solid material of wick
v	vapor
w	wick

1 Introduction

A heat pipe [1] is basically a sealed container, normally in the form of a tube, containing wick lining the inside wall. The purpose of the wick is to transport a working fluid, contained within the heat pipe, from one end to the other by means of capillary action. In the case of gravity assisted heat pipes working fluid transported by gravity and capillary action. Heat pipes elements give a very high effective thermal conductivity compared with the use of a homogeneous piece of any known metal having the same configuration because of the usual thickness of the wick structure and the small temperature drop at the vapor flow passage. The effective thermal conductivity of the heat pipe can be as much as 500 times that of solid copper rod of similar geometry [2]. Heat fluxes as high as 15 kW/cm^2 have been measured [3] with lithium as the working fluid at temperatures of 1500°C.

The maximum heat performance in a normal heat pipe is restricted [4–6] by some limits such as viscous, sonic, entrainment, flooding, wicking, and boiling limits [7–9]. The normal operation of heat pipes, under moderate temperature conditions, is distributed by a wicking limit because dry-out phenomenon can occur in the wick at the heating section [10]. So, accurate prediction of maximum heat transfer rates is required to design a heat pipe operating at moderate temperature. The prediction method for maximum heat transfer rates at the wicking limit has been developed [11] by applying the well known Darcy's equation and assuming constant permeability within a wick.

When operating the heat pipe below the maximum overall heat transfer rate (limits),the performance of a heat pipe can be characterized by the overall thermal resistance R_{OV}. So, the actual overall heat transfer rate can be defined as:

$$Q=\frac{\Delta T}{R_{OV}}$$

where ΔT is the overall temperature difference between the heat source and the heat sink and R_{OV} can be represented by the idealized thermal resistance network shown in Fig. 1 where R_1–R_{10} can be defined as follows [12];

$$R_1=\frac{1}{h_e A_e}=\text{source-evaporator resist.}$$

$$R_2=\frac{\ln(r_o/r_i)}{2\pi l_e k_x}=\text{Evapor. wall resist.}$$

$$R_3=\frac{\ln(r_i/r_v)}{2\pi l_e k_w}=\text{Evaporator wick resist.}$$

$$R_4=\frac{\sqrt{RT_{\text{eff}}^3/2\pi}}{L^2 l_e r_i \rho_v}=\text{Evapor liquid resist.}$$

$$R_5=\frac{T_{\text{eff}}\Delta\rho_v}{LQ\rho_v}=\text{Vapor duct resist.}$$

$$R_6=\frac{\sqrt{RT_{\text{eff}}^3/2\pi}}{L^2 l_c r_i \rho_v}=\text{Cond. G-L interface resist.}$$

$$R_7=\frac{\ln(r_i/r_v)}{2\pi l_c k_w}=\text{condenser wick resist.}$$

$$R_8=\frac{\ln(r_o/r_i)}{2\pi l_c k_w}=\text{Cond. wall resist.}$$

$$R_9=\frac{1}{h_c A_c}=\text{Condenser-sink resist.}$$

$$R_{10}=\frac{l_e+l_a+l_c}{A_x k_x+A_w k_w}=\text{Wall/wick axial resist.}$$

where R_1 and R_9 depend on the type of the heat source and heat sink, R_{10} can be neglected compared with the overall resistance, R_4, R_5, and $R_6=0$ since the heat pipe is working just below the limits [12], k_x is the thermal conductivity of the container wall and k_w is the thermal conductivity of the wick material. So, the effective thermal conductivity of the heat pipe, k_{eff}, was derived based on simple wick structure (one layer) and given by

$$k_{\text{eff}}=\frac{k_1[k_1+k_s-(1-\varepsilon)(k_1-k_s)]}{k_1+k_s+(1-\varepsilon)(k_1-k_s)} \quad \text{where } \varepsilon=1-\frac{\pi N d}{4},$$

N is the number of aperature per unit length and d is the wick wire diameter.

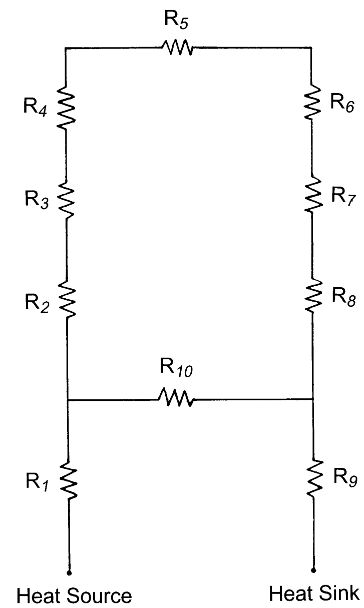

Fig. 1. Thermal resistance network of a heat pipe

The effective thermal conductivity of the heat pipe is neither related to the thermal conductivity of the saturated wick with the working fluid nor the thermal conductivity of the pipe material. The effective conductivity of the wick saturated with the working fluid is required for calculating the thermal resistance of the wick at the condenser and the evaporator. The allowable wick thickness (depending on type and number of wick layers) is an important factor in determining the effective conductivity [13, 14].

These feature give the heat pipe exceptional design flexibility thus optimizing the design of a heat exchanger for recovery of industrial waste heat. This is particularly true in the gas-to-gas heat exchanger [15], and solar energy utilization [16].

In the present work, several heat pipes were designed and manufactured to study the maximum heat transport capabilities and thermal resistance. The effect of wick structures, number of wick layers, container materials, vapor area, and working fluids on the effective thermal conductivity were studied.

2
Experimental set-up and procedure

To study the thermal characteristics of a heat pipe, 18 heat pipes with copper container material having different number of copper wick layers (1–18), heat pipe with stainless steel container material having one stainless steel wick layer and copper thermosyphone tube (wickless heat pipe) were manufactured. The dimensions of the heat pipes are the same with inner diameter (I.D.) of 0.015 m and a total length (L) of 0.08 m and include different number of wire mesh of 200 mesh size for copper and stainless, up to 18 wick layers. The apparatus consists of a heat pipe connected with a heating element at the bottom and cooling jacket at the top as shown in Fig. 2. A variac power supply 4 KW was used to control the heat input to the heater at the evaporator section with different

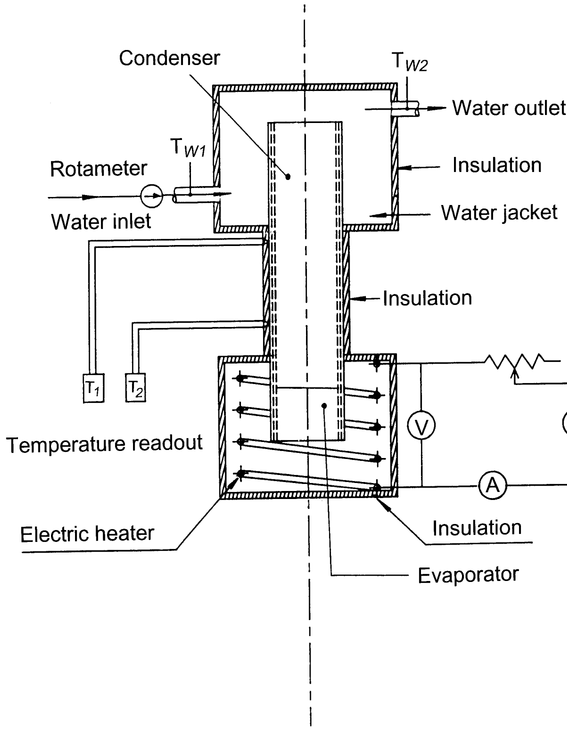

Fig. 2. Experimental apparatus

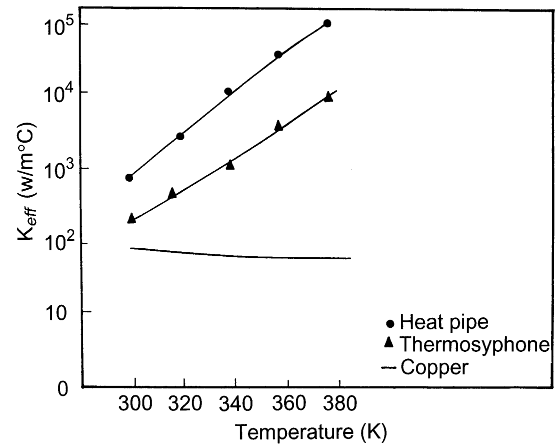

Fig. 3. Comparison of the effective thermal conductivity of single layer heat pipe with thermosyphon and copper rod

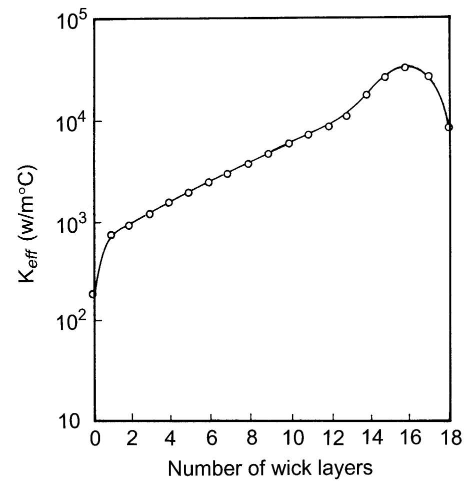

Fig. 4. Effect of number of wick layers on the heat pipe effective thermal conductivity

powers. An ammeter and a voltmeter were connected to the electrical circuit of the variac to measure the current and the volt to calculate the power supply. The adiabatic section between the condenser and the evaporator was well insulated to minimize heat loss. The apparatus was checked for leakage under pressure and vacuum. Four Ni–Cr/Ni–Al thermocouple to measure the temperature along the heat pipe and the inlet/output water temperatures of the cooling water at the condenser section were fitted with the clamping assembly and connected to a potentiometer. A multi point thermocouple switch was mounted to get the reading of each thermocouple alone. The water flow rate through the water jacket was measured using a calibrated rotameter.

The heat pipe were cleaned using acetone, alcohol, and distilled water, respectively. After the cleaning procedure, the heat pipes were dried then charged with the required volume, for each pipe, of the working fluid. The amount of the working fluid is dependent on the number of wick layers, mesh sizes, pipe diameters, evaporator length and types of working fluid [17].

3 Results and discussion

The variation of the effective thermal conductivity of the copper rod, the thermosyphon tube and the heat pipe using one wick layer with the working temperature are shown in Fig. 3. The characteristic geometry of the copper rod and heat pipe are the same. Note that the effective thermal conductivity of the heat pipe is greater than the thermosyphon tube. But, the difference in the effective thermal conductivity between the heat pipe and thermosyphon tube increases with increasing the working temperature. The copper rod has the lowest effective thermal conductivity compared with the heat pipe or the thermosyphon.

The effective thermal conductivity of the heat pipe can be improved by increasing the number of wick layers inside the heat pipe. Increasing the number of wick layers increases the heat flux transferred from the evaporator to the condenser. Figure 4 shows the effective thermal conductivity of the heat pipe with 18 different heat pipes, each having a different number of wick layers, as well as thermosyphone tube (wickless heat pipe). The effect of number of wick layers on the effective thermal conductivity of the heat pipe is very important where the effective thermal conductivity increases up to 16 layers and then decreases back.

The increase in the effective thermal conductivity can be attributed to the amount of heat carried out by each layer through the evaporation of the liquid transfer within each layer. The force required to transfer the liquid through the wick is proportional to the liquid pressure drop which is the source for all the parallel wick layers. In other words, the heat flux is a cummulative parameter depends on the number of wick layers. The decrease in the effective thermal conductivity after

16 layers is due to decrease of the vapor area compared with the cross-sectional area of the heat pipe. In other words, the area of the vapor is not enough to allow the vapor to transfer the required heat to the condenser [18]. At this stage, the entrainment limit will be dominant and lower than the wicking limit. This will limit the transfer of heat from the evaporator to the condenser.

The vapor cross-sectional area is affected by the number of wick layers. Figure 5 shows the thermal resistance of 18 heat pipes with different number of wick layers and one thermosyphone tube. The thermal resistance of the heat pipe can be defined as the $1/(K_{eff}\, t_w)$ where t_w is the wick structure thickness. The thermal resistance dropped dramatically from the thermosyphon case where there is no wick layer to the case of one wick layer heat pipe. Increasing the number of wick layers decreases the thermal resistance until the number of wick layer reached 16 layers. After that, the entrainment limits is more dominant than the heat transfer characteristics of the heat pipe. This can explain the flattening phenomena of the resistance after 16 layers.

The effect of working fluid and its compatability with he container material on the effective thermal conductivity of the heat pipes and thermosyphon were studied as shown in Fig. 6. In this figure, the effective thermal conductivity of the heat pipe with one wick layer versus the working fluid temperature is plotted for two container material and three working fluids. It is observed that the effective thermal conductivity, at steady state, of the heat pipe is strongly affected by the working fluid within the range of temperature (313–373 K) used in this study. On the other hand, the effective thermal conductivity of the heat pipe is slightly affected by the container material until a certain fluid temperature where there is no any influence of the container material on the effective thermal conductivity of the heat pipe. Therefore, selecting the suitable working fluid for a certain temperature range is very important for the performance of the heat pipes as shown Fig. 6. This is due to the properties of the working fluid, where the heat load will be transferred from the evaporator to the condenser by the latent heat of vaporization at that temperature range.

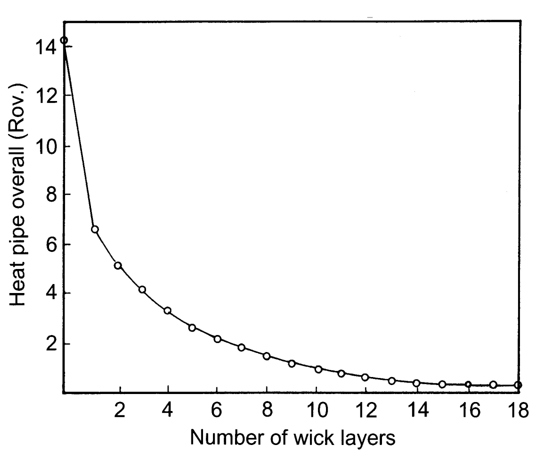

Fig. 5. Effect of number of wick layers on the heat pipe thermal resistance

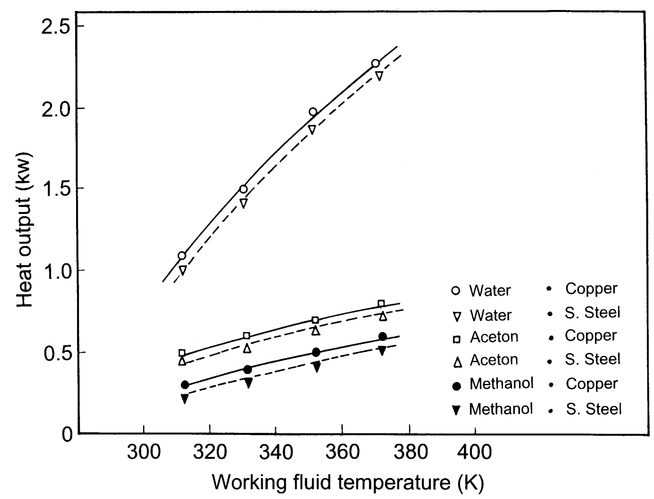

Fig. 6. Effect of working fluid and container material on the condenser heat output

4 Conclusion

Experimental study of the heat transfer behavior of the heat pipes indicated that due to their high effective thermal conductivity and compact size the heat pipes are very effective devices compared with the conventional devices of heat transfer. Because the thermal resistance is a function of the vapor cross-sectional area and effective thermal conductivity which is affected by the number of wick layers, the thermal resistance of the heat pipe decreases with increased number of wick layers (up to 16 layers). Therefore, increasing the number of wick layers enhance the ability of the heat pipe to transfer heat. The flattening phenomena of the thermal resistance was observed after layers due to the entrainment limit. Selecting the proper working fluid compatible with the container material is very important for the success of the heat pipe as an effective heat transfer device.

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