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Experimental study to determine the value of the equivalent thermal conduction coefficient in capillary heat pipe

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Abstract Boiling and condensation heat transfer in two-phase flow (Liquid-vapor phase) in capillary heat pipe is quite complicated. When the temperature difference between the boiling temperature of solvent and inside surface temperature of heat pipe is small, we may assume that heat transfer in capillary wick is the same as equivalent thermal conductivity process of solid and liquid. In this article, the value of the equivalent thermal conduction coefficient of capillary wick (metal mesh) is defined by experimental methods.

1 Introduction

A heat pipe is a hermetically sealed evacuated tube normally containing a mesh or sintered powder wick and a working fluid in both the liquid and vapor phase. When one end of the tube is heated the liquid turns to vapor absorbing the latent heat of vaporization. The hot vapor flows to the colder end of the tube where it condenses and gives out the latent heat. The recondensed liquid then flows back through the wick to the hot end of the tube. Since the latent heat of evaporation is usually very large, considerable quantities of heat can be transported with a very small temperature difference from one end to the other. The vapor pressure drop between the evaporator and the condenser is very small; and, therefore, the boiling – condensing cycle is essentially an isothermal process. Furthermore, the temperature losses between the heat source and the vapor and between the vapor and the heat sink can be made small by proper design.

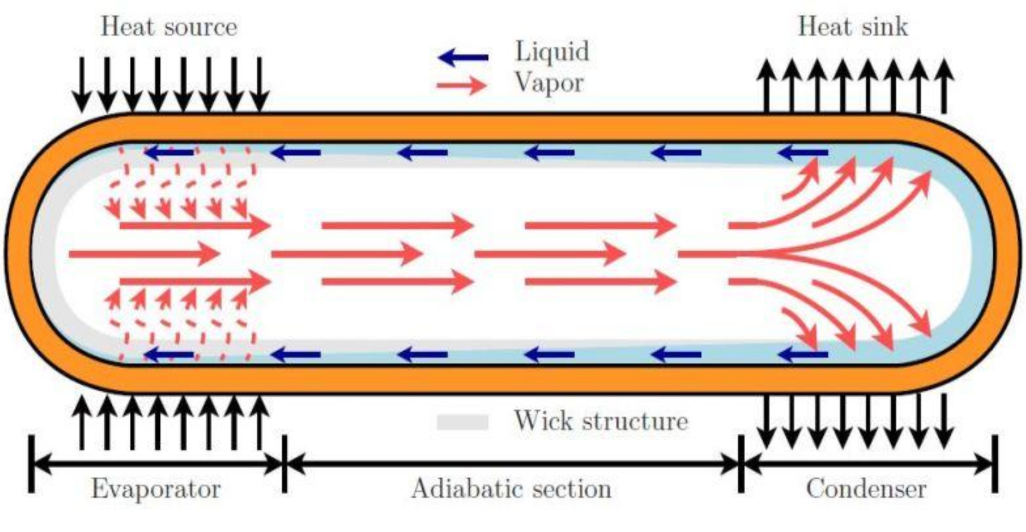

Figure. 1 Illustration of a capillary heat pipe.

Therefore, one feature of the heat pipe is that it can be designed to transport heat between the heat source and the heat sink with very small temperature losses. The amount of heat that can be transported as latent heat of vaporization is usually several orders of magnitude larger than can be transported as sensible heat in a conventional convective system with an equivalent temperature difference. Therefore, a second feature of the heat pipe is that relatively large amounts of heat can be transported with small lightweight structures. The performance of a heat pipe is often expressed in terms of equivalent thermal conductivity. The huge effective thermal conductivity of the heat pipes can be illustrated by the following examples. A tubular heat pipe using water as the working fluid and operated at 150ºC would have a thermal conductivity several hundred times that of a copper bar of the same dimensions.

2 Methods of experimental determination

2.1 Calculation method

The total heat capacity of the capillary heat pipe Q is determined by the temperature difference Δt and the total thermal resistance R (including the external thermal resistance Re and the internal thermal resistance Ri). In the heat-stabilized mode:

$$Q = Q_i \tag{1}$$

$$Q_i = \frac{\Delta t_i}{R_i} \tag{2}$$

$$\Delta t_i = t_{is} - t_{in} \tag{3}$$

Where:

- t_{is}: The temperature on the inner surface of the evaporator region, ^{o}C
- t_{in}: The temperature on the inner surface of the condenser region, ^{o}C
- Q_i: The internal heat flux of the heat pipe, W
- Q : The total heat flux of the heat pipe, W

When the temperature difference between the boiling temperature of solvent and inside surface temperature of heat pipe is small, we may assume that heat transfer in capillary wick is the same as equivalent thermal conductivity process of solid and liquid with the equivalent thermal conduction coefficient λ_{eff} (same value in the evaporator region and the condenser region). While ignoring the resistance of steam move from the evaporator region to condenser region because of the small value:

$$R_i = R_s + R_n = \frac{\delta}{\lambda_{eff}.F_{is}} + \frac{\delta}{\lambda_{eff}.F_{in}} \tag{4}$$

Where:

- R_i : Total internal thermal resistance, K/W
- R_n : Thermal resistance of the condensation process, K/W
- R_s : Thermal resistance of the evaporation process, K/W
- δ : The total thickness of the mesh, $\delta = 2.n.d$
- n: The number of the mesh
- d: Diameter of the mesh
- F_{is}: The inner surface area of tube (evaporator region), $F_{is} = \pi.d_i.L_s$, m^2
- F_{in}: The inner surface area of tube (condenser region), $F_{in} = \pi.d_n.L_n$, m^2
- d_i: The inner diameter of tube (evaporator region), m
- d_n: The inner diameter of tube (condenser region), m

L_s: The length of the evaporator region, m
L_n: The length of the condenser region, m
λ_{eff}: The equivalent thermal conduction coefficient of capillary wick,W/m.K

$$\lambda_{eff} = \frac{n.2.d}{R_i.\pi.d_i}.\left[\frac{1}{L_s} + \frac{1}{L_n}\right] \tag{5}$$

The value of total internal thermal resistance R_i is determined by experiment when measure the value of Q_i and Δt_i:

$$R_i = \frac{Q_i}{\Delta t_i} \tag{6}$$

2.2 Building a model experiment of capillary heat pipe

Fabrication capillary heat pipe and capillary wick: We chose the heat pipe with parameters as follows: The heat pipe is made of copper with parameters: d_i = 30mm, L_a = 0,1m (the length of adiabatic region), L_s = 0,25m, L_n = 0,15 m, L = L_s + L_a + L_n = 0,5m. Capillary wick consists of 3 layers of metal mesh with: d = 0,15mm, w = 0,25mm (width of meshes), meshes number N = 68 (number of meshes on 1inch is 25.4mm). The mesh is made of metal with λ = 16W/m.K. Heat pipe is wrapped insulation to heat loss accounts for 2%. The fluid inside heat pipe is distilled water and makes up about 45% the volume of the evaporator region. The heat pipe is placed horizontally with angle $\phi \approx 10^0$. Choose heat supply, cooling, temperature measuring device: The heat supply is selected by electrical input with capacity Q = 450W. Use water to cooling and thermalcouples to measure temperature.

2.3 Method of processing experimental data

The internal capacity of the heat pipe Q_i is defined:

$$Q_i = Q_c - Q_{tt} \tag{7}$$

$$Q_c = U.I \tag{8}$$

$$Q_{tt} = \alpha.F_s.(t_w - t_{kk}) \tag{9}$$

Where:

U: Voltage, V
I: Amperage, A
α: Convection heat transfer coefficient, W/m^2.K
F_s: External surface area of insulating layer (evaporator region), m^2
t_w: External surface temperature of insulating layer (evaporator region)
t_{kk}: Ambient temperature, ^{o}C

Temperature difference of inner surface between the evaporator and condenser region Δt_i:

$$\Delta t_i = t_{is} - t_{in} \tag{10}$$

t_{is}: The average inner surface temperature of evaporator region, ^{o}C
t_{in}: The average inner surface temperature of condenser region, ^{o}C

The value of t_{is} and t_{in} obtained from measurements of the thermocouples when the inner surface temperature of tube considered the same as the outside (obtained from measurements of the thermocouple).

2.4 Experiment results

From the above parameters with steam temperature t = 50^{0}C, ambient temperature t_{kk} = 29^{0}C, external surface temperature of insulating layer t_w = 33^{0}C, convection heat transfer coefficient $\alpha \approx$ 3 W/m^2.K, we have calculated and obtained value of the equivalent thermal conduction coefficient of capillary wick:

$$\lambda_{eff} = \frac{n.2.d}{R_i.\pi.d_i}.\left[\frac{1}{L_s}+\frac{1}{L_n}\right] \approx 1{,}94 \text{ W/m.K}$$

According to the theory of the diagram serial:

$$\lambda_{eff} = \frac{\lambda_r.\lambda_l}{\varepsilon.\lambda_r + (1-\varepsilon).\lambda_l} \approx 0{,}87 \text{ W/m.K}$$

According to the theory of Reyleigh:

$$\lambda_{eff} = \lambda_l.\frac{[(\lambda_l+\lambda_r) - (1-\varepsilon).(\lambda_l - \lambda_r)]}{[(\lambda_l+\lambda_r) + (1-\varepsilon).(\lambda_l - \lambda_r)]} \approx 1{,}06 \text{ W/m.K}$$

According to the theory of Alexander:

$$\lambda_{eff} = \lambda_l.\left(\frac{\lambda_r}{\lambda_l}\right)^{(1-\varepsilon)^{0,59}} \approx 2{,}7 \text{ W/m.K}$$

Where:

λ_r: Thermal conduction coefficient of solids, $\lambda_r \approx$ 16 W/m.K

λ_l: Thermal conduction coefficient of liquid, $\lambda_l \approx$ 0,648 W/m.K

ε: Porosity of the wick, $\varepsilon = 1 - \pi.N.d/4 \approx 0{,}738$

3 Conclusion

From comparison with the results we see that the equivalent thermal conduction coefficient of capillary wick can be determined by experimental method presented above. However the result depends on wick or capillary structure as number of layer, number of meshes, porosity of the wick etc… We'll test on a variety of different wick or capillary structure to achieve more accurate results in the future.

Refenrences

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