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SHORTER COMMUNICATIONS

MINIMUM MENISCUS RADIUS OF HEAT PIPE WICKING MATERIALS*

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INTRODUCTION

ONE OF the major features in the transport processes inside a heat pipe is the wick capillary pumping action for the return of condensate from the condenser to the evaporator. The limit of this capillary pumping plays a most significant role in the heat pipe design. This limit is reached when the maximum capillary pumping pressure can no longer sustain the pressure drops in the liquid and vapor phases, and the gravitational head. The maximum capillary pumping pressure is given by [1, 2]

$$\Delta p_c = 2\sigma/R_c \qquad (1)$$

where σ is the liquid–vapor surface tension and R_c is the minimum meniscus radius. It is obvious that a better understanding of R_c is crucial to the prediction of capillary pumping limit.

Numerous experimental investigations have been reported on the minimum meniscus radius through the measurements of maximum capillary pumping head h and the use of the relation:

$$H \equiv \frac{h}{\sigma g_e/(\rho_f - \rho_g)g} = \frac{2}{R_c} \qquad (2)$$

where ρ_f and ρ_g are the densities of liquid and vapor respectively, g is the gravitational acceleration, and the subscript e refers to the earth normal condition. The experiments include the wick–rise tests for sintered screens, fibers and powders [1] and for screens [3], and the wick–fall tests for screens [2] and for packed particles [4]. In addition, wick-pressure tests have been conducted [5] to determine R_c for screens. Data of R_c for channel wicks have also been reported through measurements of the heat transfer limit [6]. In this case, due to the cylindrical shape (instead of spherical for other wicks) of the meniscus, the factors of two should be omitted in equations (1) and (2).

The present note is to discuss and present ways of calculating the minimum meniscus radius for various types of heat pipe wicking materials. Additional wick–fall tests have also been performed for screens to substantiate the predictions as well as other reported experimental findings.

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CALCULATION OF THE MINIMUM MENISCUS RADIUS

The minimum meniscus radius of a wick is in general strongly dependent on the geometric properties of the wick element and the pores. The characteristic geometric parameter of the wick element is the wire diameter for screens, the fiber diameter for fibers, and the particle diameter for packed particles. The geometric properties of the pores are many and consist of pore size (or diameter), porosity, permeability, interconnectiveness, specific surface, tortuosity, etc. [7], some of which are mutually related. In terms of effect on the minimum meniscus radius, the pore size is probably most important while the others are of second-order influence. This simple consideration suggests that $R_c = R_c(\delta, d)$ where δ is the pore diameter and d is the diameter of the wick element. In the case of packed-particle wicks, of course, δ and d are related, while for channel wicks the only characteristic geometric parameter is the channel width.

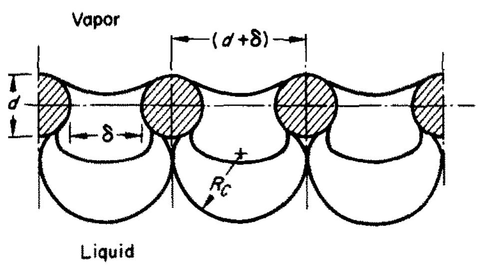

FIG. 1. Variation of the meniscus radius.

For screen wicks, consider the simple case of one layer of screen which sustains a liquid pumping head. As shown in Fig. 1, the meniscus radius decreases with the increase of pumping head until it reaches R_c and the meniscus is ruptured. On the basis of this simple model, R_c is approximately given by

$$R_c = (d + \delta)/2. \qquad (3)$$

The above equation can also be obtained through a force balance at the equilibrium position just before the rupture. Thus

$$4(d + \delta)\,\sigma = (d + \delta)^2 h(\rho_f - \rho_g)\,(g/g_e). \tag{4}$$

Combination of equations (2) and (4) results in equation (3). Ernst [8] first suggested equation (3) on the basis of its success in correlating Katzoff's data [3], but no physical or analytical basis was given. It should be noted that equation (3) would not hold when the meniscus is interfered by another layer of screen such as in the case of the highly compressed multilayer screen wick called also the superwick [9, 10]. The pumping characteristics of superwick are probably closer to that of the fiber wick than that of the ordinary screen wick.

Fiber wicks are made of metallic or synthetic fibers felted together in a randomly interlocked structure, which necessitates the definition of an effective pore size. It is well established in the study of isotropic porous media [7] that the effective pore diameter is

$$\bar{\delta} = (32K/\varepsilon)^{\frac{1}{2}} \tag{5}$$

where K and ε are the permeability and the porosity respectively, and both can be measured independently. In accordance with equation (3) for screen wicks, it is logical to establish, for fiber wicks,

$$R_c = (d + \bar{\delta})/2 = [d + (32\,K/\varepsilon)^{\frac{1}{2}}]/2 \tag{6}$$

where d is the fiber diameter.

Packed-particle wicks are made of spherical particles closely packed. The effective pore size and the sphere diameter are interrelated and the specific relation depends on the type of particle packing. The minimum meniscus radius should be simply one half of the effective pore diameter and Luikov [11] has calculated for cubically packed particles

$$R_c = \delta/2 = (0{\cdot}41\,d)/2 = 0{\cdot}205\,d \tag{7}$$

and for hexagonally packed particles

$$R_c = \delta/2 = (0{\cdot}155\,d)/2 = 0{\cdot}0775\,d. \tag{8}$$

The R_c data of Ferrell and Alleavitch [4] agree well with equation (7).

For channel wicks, as pointed out by Bohdansky *et al.* [6], $R_c = w/2$ where w is the channel width.

RESULTS AND DISCUSSION

In order to provide additional independent data, wick-fall tests have been conducted in the present investigation for various sizes of screen wicks ranging from mesh 100 to 325 in Freon 11 and distilled water. The experimental apparatus is similar to the one used by Katzoff [2]. A single layer of screen, glued on top of the glass tube, was initially submerged in the liquid and then lifted out of liquid at a constant speed of 0·22 cm/s by a motor. The maximum pumping head h was recorded at the instant when the liquid column broke away from the screen. For each case, a number of runs were made and the deviation among the observed h values was within ten per cent.

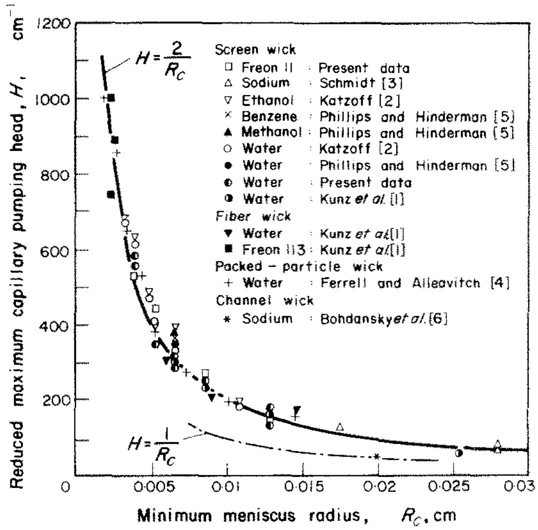

FIG. 2. Correlation between maximum capillary pumping head and minimum meniscus radius.

Measured h values from various investigations are shown in Fig. 2 vs. the calculated R_c values based on equations (3), (6) and (7). The successful correlation of all these data clearly demonstrates the validity of the equations given for the determination of R_c. The correlation is indeed remarkable in view of the fact that these data were obtained from various independent investigations based on different test methods for a wide variety of test liquids and wicking materials. Four measured h values are not included in the figure: one for the superwick [9] and three for sintered powders [1]. The superwick result cannot be correlated due to lack of information about K and ε to calculate R_c. In the case of sintered powders, the experimental results do not seem to be reliable since the three points are not self-consistent with respect to equation (2).

The group, $[\sigma g_e/(\rho_f - \rho_g)g]$, as given in equation (2) is an important parameter that characterizes the maximum capillary pumping potential of the fluid. In terms of this potential, liquid metals rank the highest, water and organic liquids the second, the refrigerants and cryogens the lowest.

The results here seem to indicate that R_c depends solely on the geometric properties of the wick. Two possible effects of non-geometric nature, however, deserve some consideration. In the actual operation of heat pipes, evaporation causes mass flow in the wetted wick, that, in turn distorts the shape of the meniscus. This effect should be of second-order nature but is difficult to estimate quantitatively. Evaporation also introduces a dynamic pressure difference across the liquid–vapor interface, but this difference can be shown to be always negligible as compared to the static pressure difference. This is further confirmed by the successful correlation of the data of Freon 11, which were obtained under intense evaporation conditions at room temperature. Another possible effect is that of the contact angle. That this effect is negligible as implied in the present correlation can be explained through the physical model for screen wicks shown in Fig. 1. Each meniscus is tangent to its adjacent ones at the instant of rupture. The surface tension force at the tangent point acts vertically upward and is balanced by the downward pull of the liquid column. This model is analogous to that of the ring method for surface tension measurements [12], in which the dependence on contact angle was found to be indeed small [12, 13].

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COMPRESSIBLE GAS FLOW THROUGH A POROUS MATERIAL

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NOMENCLATURE

a, sound speed;
A, total cross-sectional area normal to the streamwise direction;
A_p, cross-sectional area of pore space normal to the streamwise direction;
c, constant related to losses due to separation and turbulence;
k, permeability;
L, length of porous material;
L_{max} length of porous material required for choking;
M, Mach number, u/a;