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Capillary and wetting properties of copper metal foams in the presence of evaporation and sintered walls

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ABSTRACT

An experimental study has been done to define the capillary and wetting characteristics of a novel type of copper metal foam which is to be used as a wick in flat heat pipes for electronic cooling. Unlike other metal foams, a microstructure including micro scale particles and larger capillary paths can be observed in this type of copper metal foam. Due to the significant importance of the capillary properties such as permeability (K) and effective pore radius (r_{eff}) in defining the capillary limit of heat pipes, the rate of rise method based on the measured mass was used to extract these parameters. Foams of different porosities (68–85%) were fully characterized with multiple fluids (water, acetone, and ethanol). The ratio K/r_{eff} was found to be almost 5 times larger than that reported for sintered copper powder, a common wicking material in heat pipes. The impact of evaporation and walls sintered on one side or on both sides of foam strips has been studied in open and partially saturated ambient. The evaporation rate during wicking was measured by subtracting the stored mass of liquid in the foam from the total wicked mass. It was found that the rate of evaporation while the liquid is rising is significantly lower than the evaporation rate of a saturated sample with stationary liquid. It was also observed that sintering copper walls has almost no effect on the capillary rise and on the evaporation rate. By combining measurements done with acetone and water, the internal contact angle of water in hydrogen treated copper foams was found to be lower than on a flat plate and varies from 10° to 37° depending on the foams porosity. This work therefore provides the first characterization of K, r_{eff}, and internal contact angle for these novel metal foams, but also clarifies the conditions under which the rate of rise measurements should be done for proper parameter extraction.

1. Introduction

Wicking materials are the main part of two phase cooling devices increasingly used for thermal management of electronics, such as flat heat pipes and heat spreaders. Due to their capillarity and open pore structure, they carry liquid from the condenser side to the evaporator side in heat pipes or heat spreaders. When one end of a heat pipe is connected to a heat source, such as a hot microprocessor, heat is removed by the evaporation of the liquid enclosed in the pipe. The vapor travels to the other end of the heat pipe where it condenses [1]. The liquid is pumped back to the hot end by the capillary action of the wicking material inserted in the pipe or chamber. The operating range of heat pipes is subjected to several physical limits. For the case of a flat heat pipe utilizing copper metal foam as wicking material, the dominant limit will be capillary limit [2]. This limit is reached when the capillary pumping of the wicking material is not sufficient to supply the required rate of liquid to evaporator and hence, the evaporator will dry out. Therefore, the pumping capacity of the wicking material is a key parameter in the performance of heat pipes. Typical wicking materials include sintered copper powders, copper meshes and more recently copper metal foams. These wicking materials are characterized by their permeability, pore size, porosity, and thermal conductivity. Copper metal foams used in this research (made by Metafoam technologies Inc.) have shown promising results in heat pipes [3] but their wicking performance has not yet been fully characterized.

Capillary properties of a wicking material such as permeability (K) and effective pore radius (r_{eff}) are critical in defining the capillary limit of heat pipes, because their ratio (K/r_{eff}) is a measure of pumping capacity of the wicking material [4]. Permeability can be defined as the porous material resistance against the liquid passing through it. A high permeability will result in a lower liquid pressure drop. Permeability is a pure function of the porous material microstructure and does not depend on the liquid used. Effective pore radius on the other hand, depends on the wetting properties of the liquid in the porous structure. The meniscus profile formed at the liquid–vapor interface of each pore is a function

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Nomenclature

g	gravity, m/s^2
h	liquid height, m
K	permeability, m^2
m	liquid mass, kg
$\dot{m}$	liquid mass flow rate, kg/s
$\dot{m}_e$	evaporation flux from the surface, kg/m^2 s
m_{evp}	evaporated liquid mass, kg
m_{st}	stored liquid mass in the foam, kg
m_{tot}	total wicked liquid mass, kg
P	periphery, m
r	pore radius, m
r_{eff}	effective pore radius, m
t	time, s
T	foam thickness, m
W	foam width, m

Greek symbols

φ	porosity
μ	viscosity, Pa s
ρ	liquid density, kg/m^3
Θ	contact angle, deg.

of the pore structure and also liquid contact angle on the porous material. Therefore, effective pore radius is rather used instead of geometrical pore radius to account for the effect of liquid contact angle. According to the definition of the effective pore radius, it is related to the actual pore radius of a porous material, r, by the liquid contact angle on that material:

$$r_{eff} = \frac{r}{\cos\theta} \tag{1}$$

Effective pore radius is inversely proportional to the liquid contact angle on the solid surface. Hence, a lower liquid contact angle will result in a lower effective pore radius which in turn will increase the K/r_{eff}. Wetting property of a liquid–solid system is defined by measuring the contact angle of the liquid droplet on the solid surface. In the case of water, wettability is expressed by hydrophilic (contact angle less than 90°) and hydrophobic (contact angle more than 90°). It can be concluded that in capillary driven systems such as heat pipes and heat spreaders using water, a hydrophilic wick system is necessary to transport water [5]. It is shown that low wettability of the wicking material directly reduces the critical heat load that can be carried by a heat pipe [6]. Therefore, a good knowledge of these capillary and wetting parameters and a robust method to measure them is important.

The wetting property of a material is commonly determined by measuring the external contact angle of a droplet of liquid on that material (Sessile drop test). This method is not suitable for porous materials since the liquid wicks and disappears under the surface. Furthermore, relating the contact angle on a flat surface to a porous media of the same material can be misleading [7]. The meniscus inside the porous media experiences a complicated 3-D structure which is significantly different from the uniform roughness assumption done in the Sessile drop test. For porous media, a series of methods are available to measure capillary parameters, such as pressure drop measurement for permeability [8,9], or bubble test and rising meniscus for the effective pore radius [4]. One major drawback in these methods is their inability to deliver both K and r_{eff} parameters at the same time and in one test [10].

A potentially more informative method is based on measuring the transient rate of rise of a liquid in a porous medium by measuring its height visually or the increasing mass with a balance [11]. Unlike the rising meniscus which is a static method based on measuring the maximum height of the liquid in a sample, rate of rise method is a dynamic and time dependent method. By fitting a suitable mathematical model to the rate of rise measurements, one can extract both permeability and effective pore radius, or their ratio. This method can also be used to characterize wetting properties of a porous material (internal contact angle) by doing this test with liquids of different surface tension [7,12,13]. The rate of rise method will therefore be used in this work to extract the permeability, effective pore radius and internal contact angle.

When dealing with the transient movement of a liquid in a porous media rising against gravity (vertical sample), a balance between capillary forces wicking the liquid upwards and the opposing inertial, gravity, viscosity and evaporation-induced forces should be considered. Given the complexity of the physics involved, simplified models were initially developed to characterize wicking properties of porous media. By only balancing the viscous pressure drop with the capillary force, and neglecting the other effects, the widely used Lucas–Washburn equation will be obtained [14]. With this method, K and r_{eff} will be obtained as a ratio. To find the values of K and r_{eff} independently, one needs to find the maximum attainable height or mass. This requires fabrication of long samples which may be impractical in many cases. By adding gravitational effects to the Lucas–Washburn equation, Holley and Faghri [10] developed a different equation which permits the extraction of both K and r_{eff} directly (without finding the maximum height or mass). Evaporation taking place on the surface of the porous material will lead to a higher liquid flow rate to accommodate for the evaporated liquid. By assuming a uniform rate of evaporation over the wetted area of their samples, Fries et al. [15] developed a fully implicit solution for all the effects except for inertia, but their experimental results show a 20% difference from their modeling results. Rogacs et al. [16] considered the effects of capillarity, viscosity and evaporation for their thin (~10 μm) silicon nanowire array and obtained the K/r_{eff} ratio and internal contact angle for this porous structure. Ideally, a suitable model should include the effects of capillarity, viscosity, gravity to extract K, r_{eff}, and internal contact angle, but may also need to account for evaporation in realistic conditions.

Although ignoring the evaporation is useful to simplify the extraction of K and r_{eff}, its omission or the uncertainty on evaporation rate measurements can falsify the results. Understanding the role of evaporation in the rate of rise method is specifically important while dealing with highly volatile liquids like acetone and ethanol. These liquids, due to their low surface tensions, rise easily in copper metal foams in room ambient without the need for any surface treatment. This can alleviate the problem of rapid loss of hydrophilicity in copper-based porous materials when exposed to room ambient. Our tests show that leaving the samples more than 3 min in ambient air has quantifiable effects on the rate of rise of water in these foams. To restore the hydrophilicity, a high temperature hydrogen treatment that may take up to 7 h should be done on the samples, which is not necessary with acetone and ethanol.

Another overlooked aspect is the role of attached walls in the capillary behavior of the porous materials. In practical applications, wicking materials are not used alone and are sintered to a wall to form a two-phase cooling device such as a heat pipe or a heat spreader. A wall can change the flow pattern in the adjacent foams and hence affect the values of permeability. Moreover, the sintered