Lawrence Livermore Laboratory

Project CLEER - A Study of the Heat Transfer Characteristics of a Capillary Wetted Surface

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May 14, 1968

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Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

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May 14, 1968

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INTRODUCTION

An experimental program (Project CLEER) has been initiated for the purpose of investigating the heat transfer characteristics of a surface covered with a wick-like material and cooled by a capillary liquid. The results from this program should provide information that will be useful in the design of heat transfer equipment incorporating capillary wetting.

Data to be obtained from the CLEER program (Capillary Liquids Evaporation Experimental Research) are values of local heat transfer rates from a constant temperature flat plate cooled by capillary wetting. These data will be correlated to establish the effects of variables such as geometry and fluid properties. The final results can then be used in future applications to determine the requirements for equipment size, amount of wick required, and heat transfer rates.

The phenomenon of heat transfer from capillary wetted surfaces involves a surface containing some type of capillary structure (e.g., micro-grooves, or a covering of some kind of wick, such as cloth). A capillary liquid (e.g., water) wets the surface by flowing from some remote location through the wick by capillary pumping. If the surface is heated, the liquid will be evaporated and at the same time be replaced by new liquid via the capillary pumping. The net result is large amounts of heat can be transferred from the surface by evaporation without any mechanical work done on the liquid to get it to the surface. Also, only small quantities of liquid needed to keep the surface wet.

Nucleate pool boiling of liquids could also be improved by the addition of a capillary structure to a surface. The capillary structure would provide additional nucleation sites, thus improving the heat transfer for a given

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surface temperature. Also, the maximum heat transfer rate in nucleate boiling before transition to film boiling could be increased. The wick-like material on the heated surface could break up the vapor film that forms during film boiling and provide a means for the liquid to reach the heated surface. Thus, this application of wicking material could possibly be used to improve the operating characteristics of boilers.

The capillary wetted surface concept can be applied to examples such as the vapor convector (known also as the Grover heat pipe). Figure 1 illustrates this device which consists of a sealed chamber lined with a suitable wick and containing a small amount of some kind of capillary liquid. Heat is added to one end of the chamber and rejected at the other end causing evaporation and condensation at the respective ends. The wick directs the liquid from the condenser section back to the evaporator section thereby making a complete cycle for the fluid. If pressures do not greatly change in the chamber, temperatures should be nearly constant. Thus, the device behaves like a very high thermal conductivity material.

Another example of capillary wetting is illustrated in Figure 2. This concept is a proposed design for cooling heat sources of various shapes. In this application the heat source can be cooled without totally immersing it in a liquid, therefore only small amounts of liquid are required. Also, the wick can cover only specific areas of the heat source if desired.

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Figure 3 shows proposed methods for taking advantage of improved heat transfer by capillary wetting. The liquid is brought directly to the wick covered surface where it can be vaporized. The flow path of the liquid in the wick is shortened in this arrangement, thus allowing a higher flow rate of liquid to occur.

These examples are to illustrate only a few of the possible uses of a capillary wetted surface. There are undoubtedly many more possible applications that can be used very advantageously. The concept has come into the light of heat transfer engineering only quite recently, however there is already a great deal of interest in it. This interest is expected to develop even more in the future as additional applications are discovered.

PRELIMINARY ANALYSIS

To have some understanding about the mechanism of heat transfer in a capillary wetted surface one should examine the various types of heat transport that exist in this situation. Consider an elemental length of the heat transfer surface as shown in the accompanying sketch.

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The element length is ΔX , the wick thickness is δ , and heat is supplied from a constant temperature wall at t_w .

From the conservation of mass principle the net mass flow of both liquids and vapors in and out of the element must be zero. Consequently,

$$\left[\int_0^{\delta} \dot{m}_l dy \right]_{X = X + \Delta X} - \left[\int_0^{\delta} \dot{m}_l dy \right]_{X = X} + \dot{m}_v \Delta X = 0$$

where $\dot{m}_l$ and $\dot{m}_v$ are the mass flow rate per unit area of liquid and vapor, respectively.

Letting the length $\Delta X \rightarrow 0$ yields

$$\frac{\partial}{\partial X} \int_0^{\delta} \dot{m}_l dy + \dot{m}_v = 0$$

A conservation of energy principle requires that the net flow of energy in and out of the element must be zero for steady state flow and no internal heat sources. The flow of energy can be by mass transport of heat or by thermal conduction.

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Accounting for the heat flow through all the element faces results in the following expression:

$$\left[\int_0^{\delta} \left(\dot{m}_l e_l - k_l \frac{\partial t_l}{\partial X} \right) dy \right]_{X = X+\Delta X} - \left[\int_0^{\delta} \left(\dot{m}_l e_l - k_l \frac{\partial t_l}{\partial X} \right) dy \right]_{X = X}$$

$$+ (\dot{m}_v e_v - Q_w) \Delta X = 0$$

where e_l and e_v are liquid and vapor enthalpies, respectively, k_l is the liquid thermal conductivity, Q_w is the heat flux from the wall boundary and t_l is the liquid temperature. Letting $\Delta X \rightarrow 0$ yields

$$\frac{\partial}{\partial X} \int_0^{\delta} \left(\dot{m}_l e_l - k_l \frac{\partial t_l}{\partial X} \right) dy + \dot{m}_v e_v - Q_w = 0$$

Assume that a heat transfer coefficient can be defined as

$$h = Q_w / (t_w - t_v)$$

Using this relationship and an expression for $\dot{m}_v$ from the conservation of mass equation yields

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$$h = \frac{1}{(t_w - t_v)} \frac{\partial}{\partial X} \int_0^\delta \left(\dot{m}_l e_l - k_l \frac{\partial t_l}{\partial X} - \dot{m}_l e_v \right) dy$$

$$h = \frac{1}{(t_w - t_v)} \frac{\partial}{\partial X} \int_0^\delta \left(\dot{m}_l c_l (t_l - t_v) - \dot{m}_l e_{lv} - k_l \frac{\partial t_l}{\partial X} \right) dy$$

where c is the liquid specific heat and e_v is the heat of vaporization at t_v . Both mass flow rate and temperature profiles are not known at this point, preventing any further simplification. However, at small heat transfer rates liquid and vapor temperatures will be equivalent and liquid temperatures will not be related to X . Therefore, for this condition the foregoing equation becomes

$$h = \frac{-e_{lv}}{(t_w - t_v)} \frac{\partial}{\partial X} \int_0^\delta \dot{m}_l dy$$

or

$$h = \frac{e_{lv} \dot{m}_v}{(t_w - t_v)}$$

From an experiment, one can obtain the values of $(t_w - t_v)$ and Q_w . Then Q_w can be equated to both $h(t_w - t_v)$ and $e_{lv} \dot{m}_v$ to obtain the values of h and $\dot{m}_v$.

The dependence of Q_w on X and $(t_w - t_v)$ will be obtained from examination of the experimental results. Other quantities that should be determined are the location of wick "dry up" and the effect of wick properties.

The mechanism by which vapor bubbles (if any) are formed in the wick is not known. The magnitude of the relative cross flow of vapor and liquid should certainly effect the heat transfer rate. Until a suitable analysis of this

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phenomena can be formulated, it is best to study the problem by experiment.

EXPERIMENTAL APPARATUS

A sketch of the apparatus to be used for this experiment is shown in Fig. 4. The design is built around a flat plate about 24 by 8 inches in surface area that can be either flooded or wetted by a capillary wick. This plate is to be heated by 12 individually controlled cartridge heaters so as to keep it at a constant temperature. Special instrumentation will provide measurements of plate temperatures and heat transfer rates.

Vapors rising from the heated plate will flow to a bundle of water cooled condensing tubes. There the vapors will condense and fall into a drip pan which will carry the liquid to a reservoir. The liquid will flow either naturally or by capillary pumping back to the heated plate, thereby forming a closed cycle.

The vapor-liquid cycle is to be enclosed in a chamber for reasons of safety and cleanliness. All structural materials will be type 316 stainless steel because of high temperature strength properties and corrosion resistance to liquids like sodium and potassium. The cartridge heaters will, however, be mounted in a 1-1/4 inch thick copper block because of its high thermal conductivity.

First experiments will be with liquids such as water and alcohol. These liquids will allow operating temperatures up to approximately 400 °F. Subsequent tests with liquid potassium or sodium will allow temperatures up to 1500 °F.

Wicks for low temperature tests will probably be cotton, wool or fiberglass cloth while for the high temperatures, stainless steel cloth must be used. Other changes that will be required for high temperature measurements are

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replacing the glass level tube with a metal one and sealing the condenser flange by welding instead of using a rubber seal. Also, the entire apparatus must be placed in a controlled environment chamber during high temperatures to avoid corrosion to sensitive parts and excessive heat losses.

The measurement of local heat transfer rates will be by one of two methods presently under consideration. The first is by using an instrumented reference material. As shown in Fig. 5, a 1/4 inch thick plate of Armco alpha iron is sandwiched between the copper and stainless plates. If the surfaces of the plates are regulated to a constant temperature, the heat flow direction should be only normal to the plates. By measuring the temperature change across the iron plate with thermocouples, the heat flow can then be computed by the Fourier heat conduction equation

$$Q_w = \frac{k \Delta t}{w}$$

where k is the thermal conductivity and w is the thickness of the plate. A third thermocouple measures the temperature of the stainless steel bottom surface temperature so as to avoid errors induced by the thermal contact resistance of the iron and stainless plates. The Fourier equation can be used again to calculate the upper surface temperature of the stainless steel.

The success of this type of heat flow measurement will depend upon uniform contact resistance between the plates. It is believed this can be accomplished by making the plate surfaces flat and highly finished, and electroplating several mils of silver on them to create a low contact resistance.

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The second method under consideration is to meter the heat flow by measuring the electrical power to a small heater attached to the stainless steel surface. As illustrated in Fig. 5, the iron plate is omitted and a hole is drilled in the copper plate to accomodate the small spot heater. During operation, the power to the spot heater would be adjusted until the stainless surface temperature under the spot heater is equal to the stainless surface temperature under the copper plate. The Fourier heat conduction equation would be used as in the first case, to compute the upper surface temperature of the stainless steel plate.

These methods of heat flow measurement are being studied in a small bench experiment to establish which will be most suitable for the final experiment design. The first method is currently preferred, however, because of its simplicity in design and operation.

The temperature of the vapor in the experiment can be determined from thermodynamic properties of the fluid being tested. All that is needed to do this is a vapor pressure measurement which can be done quite easily.

EXPERIMENTAL METHOD

A very important requirement for successful operation of the experiment is extreme cleanliness. The inside surfaces will be cleaned and acid etched, then the chamber evacuated to a very low pressure before filling with a test fluid.

The first tests will be with water, followed by alcohol and perhaps another liquid such as an organic material. These liquids will allow an operating temperature range of approximately 100 to 400 °F. After completion of these tests,

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the data will be analyzed and reported. Then, whatever changes and equipment that are required for testing a liquid metal will be made. Liquid metal testing will be done last, since it is believed that the apparatus cannot be cleaned after being exposed to liquid metal vapors.

PROJECT PROGRESS

Drafting and design of the equipment has been completed. Included is the heat transfer apparatus, a support stand, the piping system for filling and evacuating and a containment chamber for high temperature testing. After the heat metering design has been verified by the preliminary tests now in progress, the drawings will be submitted for fabrication. This is expected to occur within a few weeks.

The experiment will be located in bldg. 174. This is the only available Laboratory space that could be found for conveniently supplying the 100 kw of 220 volts ac power required for the experiment.

PREVIOUS RELATED WORK

The only studies described in the literature which are related to the current project are the "heat pipe" studies by organizations such as LRL, LASL, NASA and RCA. The LRL work was done by the Space Power Group. The work of these groups has been directed towards examining the performance of "heat pipes" as a whole. The present work is, of course, concerned with local heat transfer characteristics of a capillary wetted surface, which is related to, among other things, "heat pipes." The list of references provided gives some of the more notable reports existing on "heat pipes."

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Fig. 1 A Typical Heat Convector (Heat Pipe)

Fig. 2 An Example of Capillary Cooling

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Fig. 3 Examples of Maximizing Capillary Cooling

Fig. 4 LATERAL SECTION OF HEAT TRANSFER EQUIPMENT

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stainless surface temperature
iron surface temperatures

Fig. 5 Heat Flow Measurement by Reference Material Method

stainless surface temperature

Fig. 6 Heat Flow Measurement by Power Measurement of a Heated Spot

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