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EVAPORATION-CONDENSATION HEAT TRANSFER DEVICE

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2 Sheets-Sheet 1

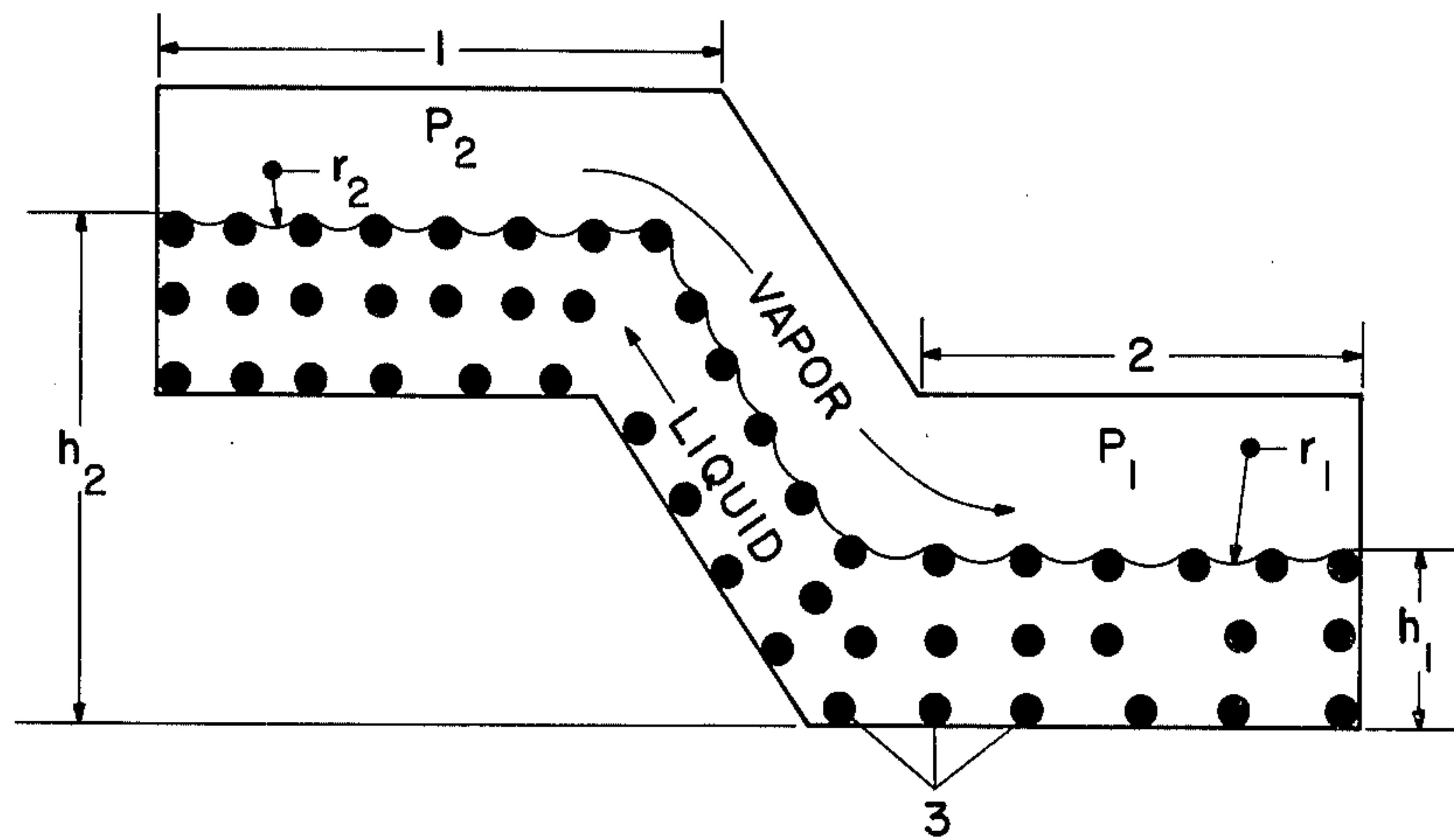


Fig. 1

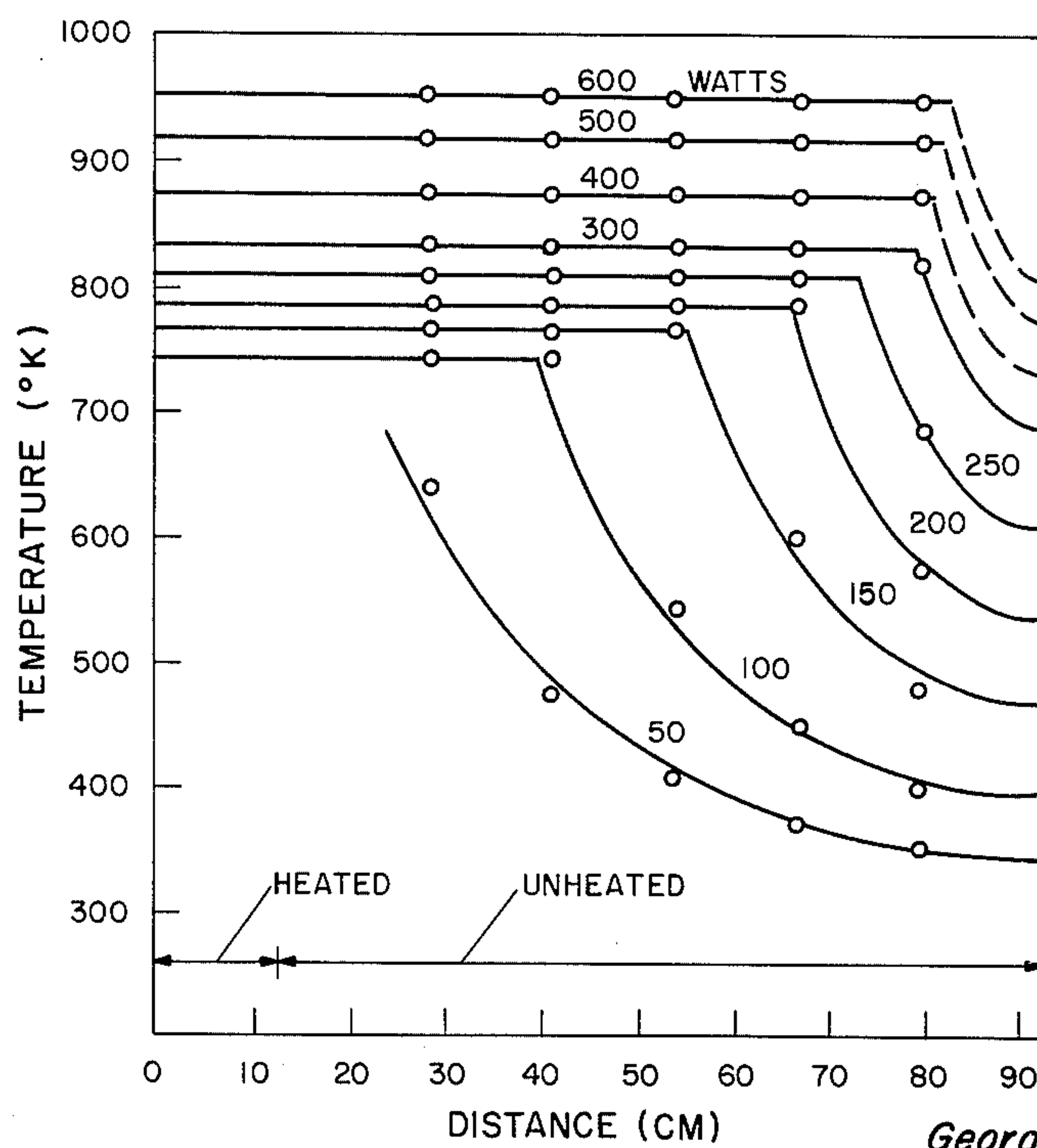


Fig. 2

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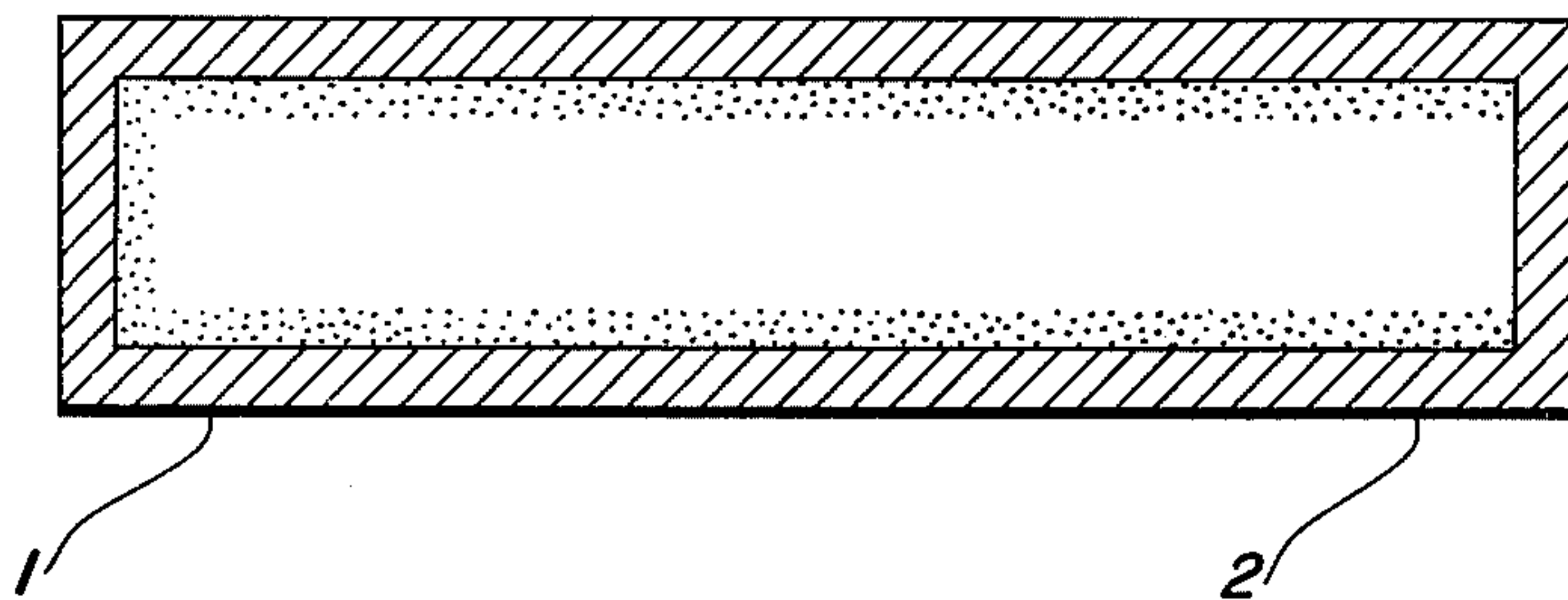


Fig. 3

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EVAPORATION-CONDENSATION HEAT TRANSFER DEVICE

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3 Claims. (Cl. 165-105)

This invention relates to structures of very high thermal conductance and, more particularly, to devices for the transfer of a large amount of heat with a small temperature drop, thereby being equivalent to a material having a thermal conductivity exceeding that of any known metal by a very large factor. The invention described herein was made in the course of, or under, a contract with the U.S. Atomic Energy Commission.

It is a desirable objective in substantially all heat transfer applications to transfer a maximum amount of heat with a minimum temperature drop. For example, if heat is to be transferred by radiation, it is desirable that the temperature at this place be as high as possible since the rate of emission of radiant energy from the surface of a body is a function of the temperature to the fourth power.

The evaporation of a liquid, transport of the vapor through a duct, and subsequent condensation is a well-known method for the transfer of a large amount of heat with a small temperature drop. In order to work continuously, the condensate must be returned to the evaporator. Ordinarily this is done by gravity or with a pump.

The present invention is a device in which this function is accomplished by a wick of suitable capillary structure. Devices of this general class will hereinafter be referred to as "heat pipes," although it should be kept in mind that the shape of the device is not a matter for concern. Within certain limitations on the manner of use, a heat pipe may be regarded as a synergistic engineering structure which is equivalent to a material having a thermal conductivity greatly exceeding that of any known metal.

Accordingly, the invention is a heat transfer device comprising a container, said container enclosing a condensable vapor and capillary means within the container capable of causing the transport of the condensed vapor from a cooler area of the container to a hotter area. The transport of the vapor through the container uses, as the driving force, the difference in vapor pressures in the high temperature zone and cold temperature zone. The liquid which condenses in the cold zone is returned to the evaporation zone by capillary action. The forces to move fluids by capillary action are, of course, derived by the system attempting to arrive at a minimum free energy configuration.

It is an object of this invention to provide heat transfer devices having thermal conductivities exceeding that of any known metal by a very large factor.

It is a further object of this invention to transfer a relatively large quantity of heat with an exceedingly low temperature gradient.

It is another object of this invention to provide heat transfer devices which will accomplish the above objectives under gravity-free conditions.

The above-mentioned and other features and objectives of this invention will become more apparent by reference to the following description taken in conjunction with the accompanying drawings in which:

FIGURE 1 is a schematic diagram of the principle of operation of a heat pipe.

FIGURE 2 represents the temperature profiles of a heat pipe representing the steady state temperatures measured at a number of input power levels.

FIGURE 3 is a cross section of an embodiment of the invention wherein the capillary material covers the entire inner surface of the container except for a portion of the condensing region.

The principle of operation of a heat pipe is shown schematically in FIGURE 1. The wick is saturated with a wetting liquid. In the steady state, the liquid temperature in the evaporator is slightly higher than in the condenser region. The resulting difference in vapor pressure, $P_2 - P_1 > 0$, drives the vapor from evaporator region 1 to condenser region 2. The depletion of liquid by evaporation causes the vapor-liquid interface in the evaporator to retreat into the wick surface where the typical meniscus has a radius of curvature, r_2 , equal to, or greater than, the largest capillary pore radius. The capillary represented in the drawing as a wire mesh is shown at 3. The pressure in the adjacent liquid will then be $P_2 - (2\gamma \cos \theta)/r_2$, where γ is the surface tension and θ the contact angle. In the condenser the typical meniscus assumes a radius, r_1 , which cannot exceed some relatively large radius determined by the geometry of the pipe. The pressure in the condenser liquid is then, $P_1 - (2\gamma \cos \theta)/r_1$. The pressure drop available to drive the liquid through the wick from the condenser to the evaporator against the viscous retarding force is

$$2\gamma(1/r_2 - 1/r_1) \cos \theta - (P_2 - P_1) - \rho g(h_2 - h_1)$$

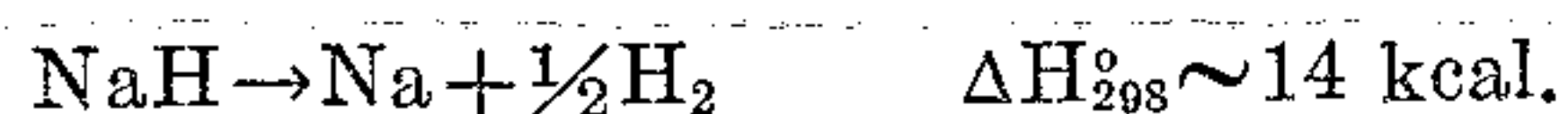
where ρ is the liquid density, g the acceleration of gravity, and h_2 and h_1 the heights of the liquid surfaces above a reference level. This pressure drop may be made positive by choosing the capillary pore size sufficiently small. The above equation can be solved for r_2 since the term $1/r_1$ is so small as to be negligible. The pore radius of the capillary material should then be selected to be smaller than r_2 . Care should be taken to not make the pore radius too much smaller than r_2 since for very small pores the increased viscous drag would interfere with the capillary return. It should be particularly noted that the possible case, $g=0$ (existent in gravity-free conditions such as space applications), is not excluded. Heat pipes will work under gravity-free conditions and even, to some extent, in opposition to gravity.

Water was used as working fluid in an initial qualitative experiment. A porous Alundum tube, 1" O.D., 3/4" I.D., and 12" long was inserted into a close-fitting Pyrex tube. Enough water was added to saturate this wick and provide a small excess. The pressure in the tube was reduced by pumping at room temperature until the resulting boiling swept out all but water vapor from the central gas space. The tube was then sealed off. An evacuated blank of identical structure containing no water was also prepared. The heat pipe and the blank were arranged vertically side by side. Within a few minutes of the beginning of heating of the top few inches of the two tubes with an infrared lamp, the bottom of the heat pipe became and remained uncomfortably hot to the touch, while the bottom of the blank continued to stay nearly at room temperature.

In order to explore the qualitative potentialities further, a liquid sodium heat pipe was made for operation at about 1100° K. The containing tube was made of 347 stainless steel, 3/4" O.D., 5/8" I.D., and 12" long, with welded end-caps. The wick was made of 100-mesh 304 stainless steel screen with 0.005" diameter wires. This was formed in a spiral of five layers and fitted closely against the inner wall of the tube, leaving an I.D. of 1/2". The pipe was loaded with 15 grams of solid sodium, evacuated to about 10⁻⁵ mm. Hg and sealed. When the top third of the pipe is heated by induction, the remarkably efficient heat transfer caused the heat pipe to be luminous almost to the cold end of the pipe. The luminous zone in the heat pipe terminates before reaching

the bottom due to the relatively low thermal conductivity of the liquid sodium sump.

A second sodium heat pipe was made similar in all respects to the first except that the length was increased to 36". The sodium charge was increased to 40 grams. This heat pipe was placed in a vacuum chamber and about 5" at one end was heated by electron bombardment from a concentric spiral filament. The data of FIGURE 2 were obtained after the pipe had been vacuum-baked at 1070° K. for two days. The vacuum baking, when using sodium as a coolant, is rather important owing to the fact that hydrogen is an impurity in sodium metal. Hydrogen is liberated in the reversible reaction



The hydrogen is swept to the unheated end of the pipe by the refluxing sodium vapor. Consequently, in the hydrogen region the heat flux is accomplished by ordinary thermal conduction, mainly by the container wall and the saturated wick. This results in a rapidly decreasing temperature profile along the heat pipe. Under the vacuum baking conditions, hydrogen diffuses fairly readily through stainless steel. However, even after baking for two days, there appears to be about 5×10^{-6} mole of hydrogen present at 100 watts, when the average temperature is near 500° K., increasing to 20×10^{-6} mole at 600 watts, when the average temperature is about 850° K. This is roughly consistent with the heat of reaction cited. Residual hydrogen occupies a volume determined jointly by the pressure of the sodium vapor in the refluxing section, and some average temperature in the non-refluxing section.

In FIGURE 2, which is a plot of the steady state temperatures measured at a number of input power levels versus the distances along the heat pipe, the region of rapidly decreasing temperature is caused by the presence of hydrogen gas. The temperature plateaus extending out from the heat region are of principal interest. This is the refluxing region. The method of measurement (five chromel-alumel thermocouples welded at intervals along the 36" pipe) was not precise enough to detect the minute temperature gradients but they do not exceed 0.05° K./cm. In the refluxing region the heat pipe is behaving in a manner equivalent to a solid bar of material having a thermal conductivity in excess of 10^3 cal./sec.-cm.-° K. A calculation, based on a detailed dynamic model of the heat pipe which will not be elaborated here, indicates that the actual temperature gradients are at least an order of magnitude less than this upper limit.

Attempts to deliver more than 30 watts/cm.² through the surface of the heated section of the pipe resulted in the appearance of local overheated areas due either to deformation or drying of the wick. This phenomenon is probably a significant limitation on the operation of heat pipes.

Obviously, when using a coolant which does not have as an impurity a gas which is non-condensable at the temperatures of interest, the non-reflux region of rapidly decreasing temperatures will not be present. The use of sodium as a coolant may also be disadvantageous in that the corrosive sodium may, after extensive operation, dissolve the container at the place of condensation and deposit the container metal at the place of evaporation. Lithium coolant in a niobium-1% zirconium alloy would be advantageous at temperatures of about 1100° C. Lithium possesses another advantage in that its heat of vaporization is approximately 5000 cal./gram as compared to about 1000 cal./gram for sodium and about 500 cal./gram for water. An experiment was carried out using lithium in niobium-1% zirconium alloy without a capillary path. The bottom portion of the pipe was immersed in a heat source. After proper operation for a short time the heat transfer rate went down very sharply. This was found to be due to the accumulation of lithium at the top of the pipe. The addition of a screen mesh along the inner

walls of the pipe to provide a capillary flow return path allowed proper operation of this heat pipe. Tantalum and silver do not form alloys and this combination of materials would be useful at temperatures of about 2000° C. A heat pipe of tantalum with a tantalum screen and with silver as the working fluid has been operated for short times at 1700° C. The lifetime at this operating temperature has not been established. It should be noted that a range of temperatures for each coolant is possible by operating at various pressures inside the container. A range of temperatures would accordingly give a range of vapor pressures and heat transfer rates. The theoretical upper limit of temperature is the critical temperature of the circulating fluid since at that temperature the surface tension goes to zero.

It should also be noted that the shape of the device is a matter of discretion. Hollow plates, rods, etc., are equally adaptable to the present inventive concept. Furthermore, there is no requirement that the pipe be heated at one end and condense at the other. For example, the pipe may be heated somewhere along its length and condense at both ends. Capillary material should be present at the point at which the heat transfer pipe is to be heated. However, it is not necessary that the capillary material cover the entire condensing region, only that the capillary material extend into the condenser region. This construction is shown in FIGURE 3 wherein 1 represents the evaporator region and the condenser region is shown at 2. The material comprising the capillary path is a matter of complete discretion. For example, glass frit, wire mesh, tubes, etc., may be utilized; the only requirement being that the pore size be sufficiently small to produce capillary action. Since capillary action is utilized to return the liquid from condenser to evaporator regions, the heat pipe will work under gravity-free conditions and even, to some extent, against the force of gravity.

Since many changes can be made in the construction of a heat pipe (some of which are mentioned above) and many apparent widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense. The invention should therefore, be limited only by the following appended claims.

What is claimed is:

1. A heat transfer device comprising a container having condenser and evaporator regions composed of niobium-1% zirconium alloy, said container enclosing a condensable vapor consisting of lithium, capillary means, said capillary means covering the entire inner surface of the container except for a portion of the condensing region, the quantity of condensable vapor present being just sufficient to saturate the capillary means when condensed and provide a small excess, said capillary means capable of causing the transport of the condensed vapor from the cooler area of the container to the hotter area.

2. A heat transfer device comprising a container having condenser and evaporator regions composed of niobium-1% zirconium alloy, the exterior portion of said container being smooth and said container enclosing a condensable vapor consisting of lithium, capillary means, said capillary means covering the entire inner surface of the container except for a portion of the condensing region, the quantity of condensable vapor present being just sufficient to saturate the capillary means when condensed and provides a small excess, said capillary means capable of causing the transport of the condensed vapor from the cooler area of the container to the hotter area.

3. A heat transfer device comprising a container having condenser and evaporator regions composed of niobium-1% zirconium alloy, the exterior portion of said container being smooth, said container enclosing a condensable vapor consisting of lithium, capillary means, said capillary means covering the entire inner surface of the

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container except for a portion of the condensing region, the quantity of condensable vapor present being just sufficient to saturate the capillary means when condensed and provide a small excess, the pore radius of the capillary material being slightly smaller than r_2 , r_2 being defined by making the expression

$$2\gamma(1/r_2)\cos\theta-(P_2-P_1)-\rho g(h_2-h_1)$$

slightly positive, where ρ is the liquid density, g the acceleration of gravity, h_2 and h_1 the heights of liquid surfaces in the evaporator and condenser regions above a reference level, γ is the surface tension, θ the contact angle, P_2 and P_1 are the vapor pressures in the evaporator and condenser regions, and r_2 the radius of curvature of a meniscus in the capillary located at the evaporator region.

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