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VARIABLE VAPOR VOLUME HEAT PIPES

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SUBJECT: Variable Vapor Volume Heat Pipes

ABSTRACT

Design of a heat pipe which provides for a vapor volume which changes or adjusts as a function of input power is discussed. An illustrative example using steam is provided. The heat pipe as a temperature transducer is suggested.

Substantially all heat pipes which are discussed in the current literature and those which have been fabricated operate on a constant volume basis. An exception is some work by RCA[1]. Thus, although the pipes are isothermal devices (by virtue of the latent heat of vaporization) they are not ones of constant internal energy since any incremental change in heat input raises or lowers pressure and internal energy and a new equilibrium point is reached at a new isotherm.

It has been observed[2] that the inadvertent inclusion of a low solubility gas (H_2) in a heat pipe causes the normally isothermal pipe to have a temperature falloff at the condensing end. This falloff is due to the hydrogen having been pumped to the end of the pipe with the vapor and being non-condensible remaining there while the condensed vapor returns to the evaporator end via the wick. The temperature drop seen is a function of the thermal conductivity of the gas. If the heat input is increased the length of the H_2 pocket is seen to decrease. Therefore there must exist a vapor/gas interface which moves as a function of the change in vapor pressure to the total pressure.

If a heat pipe is designed which purposely has a large ratio of gas volume to change in vapor volume and the gas selected is one of low thermal conductivity and low solubility then a system can be visualized which will respond to changes in input power by an appropriate change in vapor volume which will not materially raise the system total pressure because of the large gas buffer. The vapor volume change will cause the condenser surface area $\left(Q_{out}\right)$ to change to match the new load condition. The non-condensible gas will see no significant change other than a slight increase or decrease in pressure.

Three benefits should be realizable from this type of heat pipe:

1. The temperature of the heat pipe will be substantially independent of input power changes.
2. The temperature of the gas will be independent of the vapor temperature except near the interface.
3. Considering that the pressure is constant throughout the system high vapor temperatures can be ascertained (if the thermodynamic properties of the vapor are known) by reading the pressure of the gas.

For a first look at a variable vapor volume unit consider a heat pipe using H_2O as fluid and argon as the gas and assume that the system is set up to operate at 300 ^oF.

The properties of saturated steam at 300 ^oF are:

$P = 67.013$ psia

$v_{liq} = .01745\ ft^3/lb$

$v_v = 6.449\ ft^3/lb$

$\rho_{liq} = 1/v_l\ lbs/ft^3$

$\rho_v = 1/v_v\ lbs/ft^3$ (*.016 for gms/cm^3)

Latent heat of vapor. = 910.1 BTU/lb = 505 cal/gm

$\mu_{liq} = 1.2 \times 10^{-4}$ lb/ft-sec (*14.88 for gram/cm sec)

γ = 75 Dynes/cm

Consider a pipe of 1 cm I.D. of length ℓ = 50 cm using grooves and mesh as the capillary structure. The relationship of the vapor conduit cross section to the total cross section of the inside of the pipe will be taken as $\sqrt{\frac{2}{3}}$ (2). Pipe dimensions will be

r_w = .5 cm

r_v = .41 cm

b = groove height = .09 cm

The equation for a grooved heat pipe with mesh covering the grooves is:

$$\frac{2\gamma\cos\theta}{r_c} \geq \frac{4\eta\ell Q}{\pi L N \rho K^4 r_c^4} + \rho_{liq} g \ell \sin\phi + \frac{\left(1 - \frac{4}{\pi^2}\right) Q^2}{8\rho_v r_v^4 L^2} \quad (1)$$

[CAPILLARY FORCE] ≥ [PRESS DROP IN LIQUID] + [GRAV. COMP.] + [PRESSURE DROP IN VAPOR]

where

L = latent heat of vaporization dyne cm/gm

γ = surface tension dynes/cm

θ = wetting angle

r_c = capillary radius (groove half width) cm

η = viscosity gm/cm-sec

ℓ = pipe length cm

Q = heat input dyne-cm/sec

N = No. of channels

ρ = density gm/cm^3

K^4 = groove height/groove half width

r_v = radius of vapor conduit cm

r_w = radius of pipe cm

b = groove height cm

ϕ = angle of inclination

In the limit (w/o intervening wall between grooves) the maximum number of channels for capillary flow in the pipe is:

$$N = \frac{2\pi r_w}{2r_c} = \frac{\pi r_w}{r_c}$$

In his paper, "Theory of Heat Pipes", Cotter defines the term K^4 as:

$$K^4 = b/r_c$$

Making these two substitutions the equation has the form:

$$\frac{2\gamma\cos\theta}{r_c} \geq \frac{4\eta\ell Q}{b\pi^2 L\rho_{liq} r_w r_c^2} + \rho_{liq} g\ell\sin\phi + \frac{1 - \left(\frac{4}{\pi^2}\right)Q^2}{8\rho_v r_v^4 L^2} \quad \text{(1A)}$$

This equation (1A) can be expressed as:

$$AQ^2 + B + \frac{CQ_e}{r_c^2} = \frac{D}{r_c}$$

where

$$A = \frac{\left(1 - \frac{4}{\pi^2}\right)}{8\rho_v r_v^4 L^2},\ B = \rho_{liq} g\ell\sin\phi,\ C = \frac{4\eta\ell}{b\pi^2 L\rho_{liq} r_w}$$

and $D = 2\gamma\cos\theta$

Solving for Q

$$Q = \frac{-C \pm \sqrt{C^2 - 4Ar_c^{\,2}\left(Br_c^{\,2} - Dr_c\right)}}{2Ar_c^{\,2}} \qquad (2)$$

$$\frac{dQ}{dr_c} = \frac{C}{Ar_c^{\,3}}\left[C^2 - 4ABr_c^{\,4} + 4ADr_c^{\,3}\right]^{1/2} \pm \frac{C}{Ar_c^{\,3}}\left[C + \frac{ADr_c^{\,3}}{C}\right] \qquad (3)$$

Setting $dQ/dr_c = 0$ and solving for r_c the optimum r_c for max Q is:

$$\left(r_c^{\,3}\right) + \left(\frac{4B_c^{\,2}}{AD^2}\, rc\right) - \left(\frac{2C^2}{AD}\right) = 0$$

For the case where the gravity term is zero (i.e., in space or for $\phi = 0$)

$$r_{c_{opt}} = \left(\frac{2C^2}{AD}\right)^{1/3} \qquad (4)$$

and in the absence of gravity the axial power is

$$Q = \frac{-C \pm \sqrt{C^2 + 4Ar_c^{\,3}\,D}}{2Ar_c^{\,2}} \qquad (5)$$

For the special case of optimum r_c and max power

$$Q_{max} = \frac{C}{Ar_{c_{opt}}^{\,2}} \qquad (6)$$

It will now be assumed that the 50 cm long heat pipe will have the vapor/gas interface at ~37.5 cm. The remaining 12.5 cm will be used for any $+\Delta Q$ that may occur.

The volume of heat pipe used for vapor at the initial state is:

$$\pi r_v^2 \ell = 3.14 * .41^2 * 37.5 \approx 20 \text{ cm}^3$$

Assume a volume for the argon equal to 10x the vapor volume or 200 cc.

If the power input to the heat pipe is increased so as to raise the pressure of the vapor sufficiently to move the vapor/gas interface from 37.5 cm to 50 cm the change in volume of the vapor will be = + 6.7 cm^3 and that in the gas = - 6.7 cm^3. As a consequence of the volume change created in the gas the system pressure will be

$$P_2 = \frac{P_1 V_1}{V_2} = \frac{67 * 200}{193.3} = \underline{69.3 \text{ psia}}$$

From the thermodynamic properties of steam at 69.3 psia the saturation temperature is 302 ^oF. The temperature rise is 2 ^oF.

From equations (5) or (6) it can be seen that for small pressure or temperature changes Q is a function only of the heat pipe length ℓ. Thus the ΔQ applicable to the 2 ^oF rise in the system temperature is

$$\Delta Q = \frac{\Delta \ell}{\ell} = \frac{12.5}{37.5} = 33\%$$

Had the system been one of constant vapor volume as in a conventional heat pipe the 33% change in input power would have raised the temperature of the pipe from 300 ^oF to approximately 380 ^oF and perhaps more significantly the pressure would have changed from 67 psia to $\sim$195 psia. These values were determined from the heat pipe equation using a capillary radius which is optimum at a pipe length of 37.5 cm.

One potential use for this variable vapor volume heat pipe is in conjunction with burnup studies on fuel capsules where the capsule is placed in a reactor whose flux level at a particular location is generally not known within a factor of 3x and whose variation in flux over the test period may be

2x. If the heat pipe were used as a means of removing heat from the test capsule reasonable temperature stability of the test fuel should result. Since future tests of fuel material are contemplated at ~2000 °C the heat pipe also lends itself as a temperature measuring device using pressure pickups in the gas plenum as transducers. The gas plenum can be at a much lower temperature than the fuel capsule and be remotely and more conveniently located away from the fuel.

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REFERENCES:

1. RCA, "Development of a Heat Pipe for Automatic Temperature Control", TL-317-18-994-138.

2. Cotter, T. P., "Theory of Heat Pipes", LA-3246-MS, March 1965.

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