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Theoretical Design and Analysis of Gravity Assisted Heat Pipes

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***Abstract*— Gravity assisted heat pipes are heat transfer devices that are extensively used for heat recovery and cooling applications. This paper presents a theoretical approach to the design of gravity assisted heat pipes. The variation of the heat transport limits is plotted for different wick structures, materials, working fluids in the heat pipe and heat pipe dimensions. To obtain the best case for heat transfer in gravity assisted situations, the lowest heat transport limit is compared for different wick structures of the heat pipe.**

Keywords—Heat Pipes; Gravity Assisted; Heat Transfer Limits; Thermosyphons

I. NOMENCLATURE

A_v	Cross-sectional area of vapour space
A_w	Cross-sectional area of wick
B_o	Bond Number
ε	Porosity
d_w	Wire diameter
$f_l Re_l$	Drag coefficient
f_1, f_2, f_3	Entrainment limit factors
g	Gravitational acceleration
K	Permeability of wick
k_{eff}	Effective conductivity of wick
k_f	Thermal conductivity of fluid
k_w	Thermal conductivity of wick
L	Latent heat of vaporization of fluid
l_c	Length of condenser section
l_e	Length of evaporator section
l_{eff}	Effective length of heat pipe
l_{tot}	Total length of heat pipe
μ_l	Dynamic viscosity of fluid
μ_v	Dynamic viscosity of vapour
N	Mesh number
P_v	Vapour pressure of working fluid
σ_l	Surface tension of fluid
r_c	Capillary radius of wick
r_i	Inner radius of heat pipe wall
$r_{h,l}$	Hydraulic radius of wick
r_n	Nucleation radius
r_v	Radius of vapour space
ρ_l	Liquid density
ρ_v	Vapour density
T_v	Saturation temperature
w	Width of groove
w_f	Width of fin (groove)

II. INTRODUCTION

Heat pipes are two-phase heat transfer devices with an effective thermal conductance about thousand times higher than that of copper. Heat pipes operate on an evaporation-condensation cycle. Heat pipes have found broad applications in many areas such as energy conservation, thermal management of spacecraft, electric and electronic cooling, heat recovery systems, refrigeration and HVAC systems.

Heat pipe transports heat over relatively large distances via latent heat of vaporization of the working fluid. The amount of heat transported through the use of latent heat is typically of several orders of magnitude than that of sensible heat of a similar geometrical system. Also no external power is required for fluid circulation because of the capillary force generated by the wick structure or because of the gravitational force.

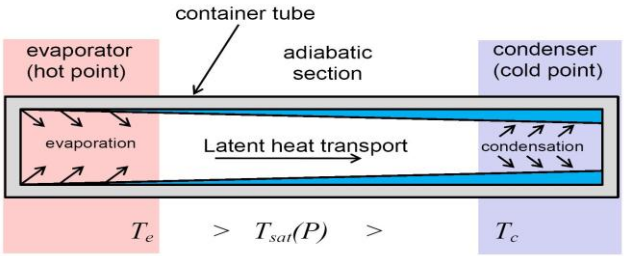

Fig. 1. Heat Pipe Working

Fig. 1. schematically shows the operation of a heat pipe. Supplying heat to the evaporator section of heat pipe causes the operating liquid to vaporize. The vapour then flows from the hotter evaporator section due to higher vapour pressure to the colder section of the heat pipe, where it is condensed. The liquid condensate returns to the evaporator section from the condenser section with the assistance of gravity or capillary action of the wick. Since the latent heat of vaporization is very large, high heat transfer rates can be achieved with a small temperature difference between the evaporator and condenser sections.

The type of wick structure used in a heat pipe determines the amount of capillary force generated and the permeability of the liquid passage. Permeability is a measure of the resistance provided by the wick to the axial flow of liquid. The capillary force generated by the wick assists the condensed fluid to return to the evaporator section again and complete the cyclic process. Some of the wick structures are:

1. Mesh
2. Grooved
3. Sintered
4. Annular

They can also be a combination of the above mentioned types.

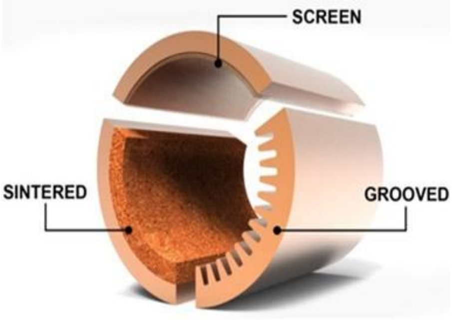

Fig. 2. Wick Structures

The material selected for the wick structure and heat pipe body should be compatible with the working fluid. Some of the working fluids generally used are ammonia, methanol, acetone, water or metals like potassium, sodium etc.

The maximum heat transport capacity of a heat pipe is governed by several heat transfer limits like Sonic Limit, Viscous Limit, Entrainment Limit, Capillary Limit and Boiling Limit; that are calculated for different cases of heat pipe operation.

III. LITERATURE REVIEW

The thermodynamic properties of the working fluid govern the operating characteristics of a heat pipe. The heat transfer capacity of a heat pipe is directly proportional to the latent heat of vaporization of the fluid. Whereas other properties like density, viscosity and surface tension determine the flow characteristics of the working fluid. A.K. Mozumder et al [1] presented in 2010, The Performance of Heat pipes for Different Working Fluids and Fill ratios. Fill ratio is the volume occupied by the liquid to the total volume of the evaporator section. He compared the fluids - water, methanol and acetone for fill ratios of 35%, 55%, 85% and 100% in the heat pipe. Acetone showed minimum temperature difference at all fill ratios and also the highest heat transfer coefficients. The heat pipe performed best with water at 85% fill ratio and with acetone at 100% fill ratio.

Ammonia is another fluid which was widely used in cooling circuits to transfer heat. But for safety reasons, the toxicity of ammonia precludes its use in manned environments. An account of this was published by NASA [2] in a paper on Ammonia-charged Aluminium Heat Pipes with Extruded Wicks. It also highlighted that the purity of fluid used in a heat pipe had to be at least 99.99 percent and any traces of water in ammonia could lead to formation of hydrogen gas. To ensure that the heat pipe is leak proof, further importance was laid on X-ray verification of all welds and testing of the heat pipe at twice the maximum expected operating pressure.

The characteristics of heat transfer in a heat pipe were discussed by A. K. Mozumder et al [4] in a research article in 2011. The heat pipe was tested with and without the working fluid; also considering whether phase change occurs or not. The operating temperature of heat pipe was found to govern the vaporization of the working fluid. The heat pipe seemed to work efficiently only when phase change occurred. Also 85% fill ratio was found to be the most optimum amount for the three working fluids, Acetone, Methanol and Water.

Along with the material and the working fluid; the dimensions, wick structure and orientation of the heat pipe also have a major effect on the heat transfer limits. Qpedia eMagazine [3] discusses the impact of orientation and wick structures on the thermal performance of a heat pipe. Grooved, mesh and sintered wicks were tested at different angles of inclination for the diameters 4 mm, 5 mm and 6 mm. The sintered wick heat pipe showed the least variation with change in the angle of inclination and was most effective when used against gravity. Grooved wick on the other hand performed best in gravity assisted situations. Also the wicks were tested for different loads and operating temperatures. As expected the heat pipes performed better at higher temperatures.

IV. THERMAL DESIGN PROCEDURE

The first step of the design procedure is the selection of the working fluid used in the heat pipe. One major restriction to the selection of the working fluid is the operating temperature range. Very low temperatures can prevent vaporization of the fluid, whereas at high temperatures there is a possibility of thermal degradation of the working fluid. A good thermal stability is necessary for the working fluid over its operating temperature range.

TABLE I. OPERATING RANGE OF SOME WORKING FLUIDS

Working Fluid	Useful range
Ammonia, Pentane	-40˚C to 110˚C
Acetone, Methanol, Ethanol, Heptane	0˚C to 130˚C
Water, Toluene	30˚C to 200˚C
Sodium	600˚C to 1200˚C

Generally the operating range for the heat pipes is between 0°C and 100°C. Based on this following fluids were shortlisted – Ammonia, Pentane, Acetone, Methanol, Ethanol and distilled Water. The working fluid must be without any impurities for effective working of the heat pipe. The next property to be considered is the Merit Number which is a measure of the heat transfer capability of the working fluid. Water has the highest merit number because of its high latent heat of vaporization and thus performs better than other working fluids.

$$Merit\ Number = \frac{L * \rho_l * \sigma_l}{\mu_l} \tag{1}$$

The second step is selection of material for wick structure and body of the heat pipe. The material selected must be compatible with the working fluid and in no way react to form non-condensable gases inside the heat pipe. It should also be compatible with the external environment. The strength to weight ratio of the material should also be considered. Copper and Aluminium are the most common materials used in heat pipes.

TABLE II. MATERIAL AND WORKING FLUID COMPATIBILITY

Material	Compatible Fluid
Copper	Water, Acetone, Methanol
Aluminium	Ammonia, Acetone

Copper has a very high thermal conductivity but it also has a high density. Aluminium on the other hand is cheaper and has a much lower density. But water is not compatible with aluminium because hydrogen gas is formed during its operation which blocks the condenser section volume. Hence acetone is used with aluminium. The type of wick structure is determined based on the wicking limit requirement. As in this application the heat pipe is gravity assisted so there is no need for any capillary force. Grooved wicks have high permeability and are expected to perform better than mesh or sintered wicks in gravity assisted situations. But grooved wick also has a large thermal resistance, so thermosyphon was also considered for comparison.

The final step was calculations of the heat flux limits that restrict the working of heat pipe at different temperatures range. The limits were:

1. Sonic limit: Heat flux at which the vapour velocity reaches sonic limitation. The evaporator cannot respond to further decrease in pressure in condenser section so vapour flow is choked.
2. Viscous limit: The heat flux for which the viscous forces are no longer dominant in the vapour section.
3. Entrainment limit: The maximum heat flux after which the rising vapour starts to entrain the returning condensed fluid. It may lead to dry out of the evaporator section.
4. Capillary limit: The heat transfer capacity based on ability of wick to pump the liquid back to the evaporator section. This limit depends on the wick permeability and properties of working fluid.
5. Boiling limit: Maximum heat flux after which nucleate boiling starts and bubble formation takes place in the evaporator section. The bubbles formed during evaporation may block the vapour flow. Bubble formation limits the heat transfer from the heat pipe wall to the working fluid which is by conduction only.

The minimum of the above mentioned heat flux limits is considered as the maximum permissible amount of heat (Q_{max}) a particular heat pipe can transfer.

$$Q_{max} = \min(Q_{sonic}, Q_{viscous}, Q_{entrainment}, Q_{boiling}) \tag{2}$$

A. *Thermosyphons*

Thermosyphons are wickless heat pipes. They rely on gravity for returning the liquid from the condenser to the evaporator and can only be used in gravity assisted situations where the condenser section lies above the evaporator. Due to the absence of capillary force of wick entrainment is prominent in thermosyphons as they have no wick to separate the vapour flushing through the evaporator section from the returning condensate.

The sonic and viscous limits for thermosyphons are calculated as in [7].

$$Q_{sonic} = 0.474 * A_v * L * (\rho_v * P_v)^{0.5} \tag{3}$$

$$Q_{viscous} = \frac{A_v * r_v^2 * L * \rho_v * P_v}{16 * \mu_v * l_{eff}} \tag{4}$$

Calculation of the entrainment limit, as in [5] requires the value of Bond Number (Bo) and a parameter K_p.

$$B_o = D_i * \left[\frac{g * (\rho_l - \rho_v)}{\sigma_l}\right]^{0.5} \tag{5}$$

$$K_p = \frac{P_v}{[g * \sigma_l * (\rho_l - \rho_v)]^{0.5}} \tag{6}$$

The entrainment limit and boiling limit is derived from the following empirical relationship, as in [5].

$$Q_{entrainment} = A_v * L * f_1 * f_2 * f_3 * \rho_v^{0.5} * (g * \sigma_l * (\rho_l - \rho_v))^{0.25} \tag{7}$$

$$Q_{boiling} = 0.12 * L * \rho_v^{0.5} * (g * \sigma_l * (\rho_l - \rho_v))^{0.25} \tag{8}$$

B. *Wicked heat pipes*

The primary factor in wick selection is the capillary force generated by the wick. But in gravity assisted heat pipes the necessary force required for returning the condensate back to the evaporator is provided by gravity. Hence other parameters like the porosity (ε), permeability (K) and effective thermal conductivity (k_{eff}) of the wick play a greater role than the wicking limit. The calculations for wicked heat pipes were performed as in [6].

1. Screen (Mesh) Wick:

$$\varepsilon = 1 - \left(\frac{\pi * N * d_w}{4}\right) \tag{9}$$

$$K = \frac{d_w^2 * \varepsilon^3}{122 * (1 - \varepsilon)^2} \tag{10}$$

$$k_{eff} = \frac{k_l[k_l + k_w - (1 - \varepsilon)(k_l - k_w)]}{k_l + k_w + (1 - \varepsilon)(k_l - k_w)} \tag{11}$$

2. Grooved Wick:

$$\varepsilon = \frac{w}{w + w_f} \tag{12}$$

$$K = \frac{2 * \varepsilon * r_{h,l}^2}{(f_l * Re_l)} \tag{13}$$

$$k_{eff} = k_w * \left[1 - \varepsilon\left(\frac{k_l}{k_w}\right)\right] \tag{14}$$

3. Annular Wick:

$$\varepsilon = 1 \tag{15}$$

$$K = \frac{2 * \varepsilon * r_{h,l}^2}{(f_l * Re_l)} \tag{16}$$

$$k_{eff} = k_l \tag{17}$$

Arterial wicks and sintered wicks are only used in heat pipes working against gravity and hence both are not considered for gravity assisted applications. The equations for sonic and viscous limits remain the same for wicked heat pipes. The boiling and entrainment limits change due to the introduction of wick structure.

$$Q_{entrainment} = L * \sqrt{\frac{\sigma_l * \rho_v}{2 * r_c}} \tag{18}$$

$$Q_{boiling} = \left(\frac{4 * \pi * l_{eff} * k_{eff} * T_v * \sigma}{L * \rho_v * \ln(r_i/r_v)}\right) * \left(\frac{1}{r_n} - \frac{1}{r_c}\right) \tag{19}$$

V. RESULTS & DISCUSSIONS

The heat transfer limits were calculated using the above mentioned steps for a heat pipe using the following data.

TABLE III. DESIGN PARAMETERS

Parameter	Value
l_{tot}	350 mm
l_e	150 mm
l_c	200 mm
d_w	0.1 mm
N	5000 m^{-1}
w	0.2 mm
w_f	1 mm
δ	0.25 mm

The results of this theoretical analysis showed which combination of wick and working fluid worked best in certain gravity assisted situations. The variation of the heat transport limits was studied for the diameters ranging from 3 mm to 12 mm and temperatures ranging from 290 K to 350 K.

Fig. 3, shows the variation of the maximum heat transport limit of a heat pipe (Q_{max}) with change in the diameter (D_o) of a copper heat pipe with water as the working fluid.

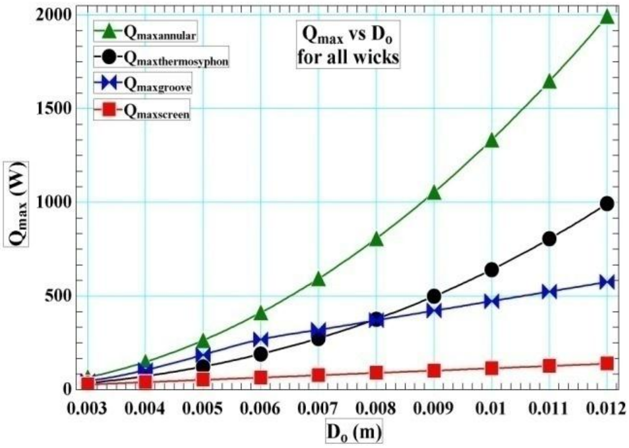

Fig. 3. Q_{max} vs D_o for different wicks at 350 K

As seen from Fig. 3, the heat transport limit of a heat pipe increases with an increase in diameter. A heat pipe with an annular wick shows the highest heat transfer capacity because of the high porosity of the annulus and the separation of the vapour and liquid passage by the meshed screen. Whereas a heat pipe with a screen wick shows the minimum heat transfer limit due to low permeability of the screen wick which provides resistance to the flow of the returning condensate. A grooved wick shows a higher heat transport limit than a thermosyphons at smaller diameters as the wick prevents the entrainment of the condensate. But for larger diameters, entrainment is very less and hence a thermosyphon performs better than a grooved wick heat pipe.

Fig. 4, 5 and 6 show the variation of Q_{max} with temperature (T) for heat pipes with acetone, methanol and water as the working fluid respectively.

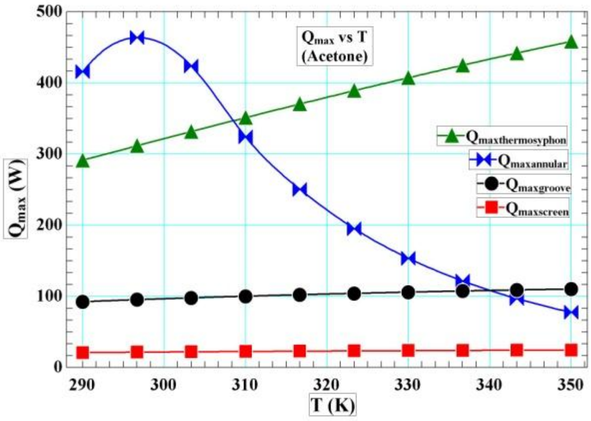

Fig. 4.Q_{max} vs T for acetone as working fluid

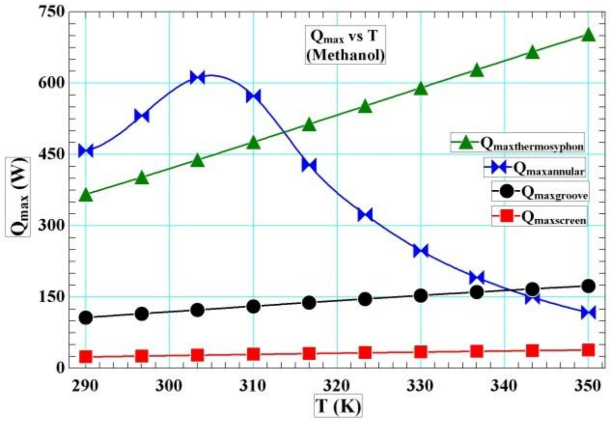

Fig. 5. Q_{max} vs T for methanol as working fluid

It is seen in Fig. 4 and 5 that a heat pipe with annular wick has greater heat transport limit than a thermosyphon at temperatures below 310 K. This is because the entrainment limit of an annular wick is higher than that of a thermosyphon. But at temperatures above 310 K, boiling limit becomes the deciding factor for heat pipes with annular wicks and hence their heat transfer capacity goes on decreasing with increase in temperature.

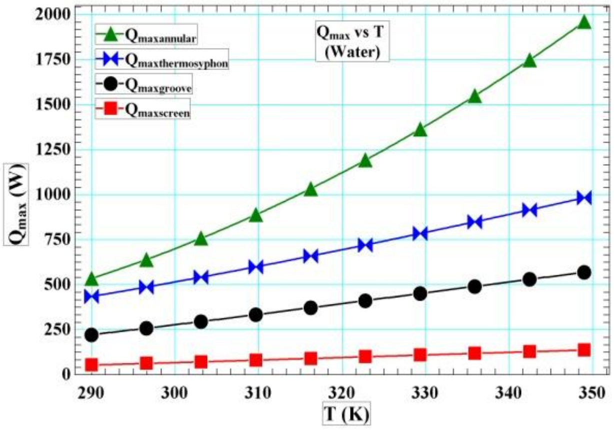

Fig. 6. Q_{max} vs T for water as working fluid

When water is used as working fluid in a copper heat pipe, the heat transfer capacity of the annular wick is no longer governed by its boiling limit. Hence due to its high wick permeability and lower entrainment, an annular wick shows the highest heat transport limit.

VI. CONCLUSION

1. Capillary action of a wick is not required in gravity assisted situations and entrainment decides the heat transport limits.
2. The heat transfer capacities increase with increase in the heat pipe diameter. Also entrainment decreases with increase in diameter. Therefore thermosyphons perform better than grooved heat pipes at higher diameters.
3. Thermosyphons and grooved heat pipes showed higher heat transport capacities with acetone and methanol as the working fluids. But with water as the working fluid, heat pipes with annular wicks show much greater heat transport capacity.

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