EFFECT OF VARIOUS GROOVE CROSS SECTIONS ON PERFORMANCE OF AXIALLY GROOVED HEAT PIPE

¹Venkatesha M, ²Dr. M.S. Rajagopal, ³D. Raghunath

¹M-tech student, ²Professor and Head of the department, ³Director Department of mechanical engineering, Global academy of technology, Bengaluru, India

Abstract— Heat pipe design is based on operating temperature range, selection of fluid and compatibility with container material and wick structure for cooling the medium heat flux electronic devices. This paper deals about, heat pipe design procedure and optimization. Theoretical analysis has been carried to find out the optimum wick cross section for axially grooved heat pipe for space application. Effect of the groove section on the performance of axially grooved heat pipe is analysed and for one particular cross section, results are compared with experimental results. Parametric studies are carried out to determine the effect of wick cross section on heat pipe transfer capacity, effective axial thermal conductivity, amount of fluid, and mass of heat pipe with regard to specific testing conditions.

IndexTerms— axially grooved heat pipe, wick cross section

1. INTRODUCTION

It is believed that heat pipe is new era technology for controlling thermal loads, but since 1800 they were being use in application of transferring thermal load. During 1892, Angier March Perkin and W.E buck conducted experiments on these devices and hold patent. The following figure shows the experimental setup of their work. It consists of furnace chamber, coil tube, water tank, and furnace bed and heat interceptor. Tube exposed to furnace bed turns liquid into vapor. Due to the expansion of vapor, vapor travels towards the cold end. At the cold end vapor turns into liquid by giving up latent heat.



Figure 1: Drawing of Perkin's Tube, a simple thermo-siphon whose purpose it was to heat a baker's oven.

In the above heat transfer equipment fluid used travels with the help of gravity, which is named as Thermosyphon. Work expressed level of utilization and conductivity is more than any solid metal conductivity. These ideas led for designing and developing of a new thermal managing system for space application and succeeded.

2. DESIGN CONSIDERATION

Design consideration have to be done very carefully for space application, and have to investigate the effect of factors considered on the performance of heat pipe. For a particular case, the material selection is the major factor. Materials in pipes fundamentally incorporate the working liquid, wick, and container.

- Depending upon the operating temperature range at which working fluid should operate.
- Compatibility of working fluid with container material.
- Wick structure for pumping fluid with capillary action.

2.1 Selection of working fluid

Working liquid in the device serves as a media exchanging heat through phase changes. Basically, working fluid is chosen on their chemical and physical properties. In the first place, the liquid must have a good chemical stability. It should not disintegrate inside the pipe working temperature range. Likewise, the working liquid should not respond with the pipe and wick materials under any circumstances. For the physical properties, the working liquid should to have high latent heat, high conductivity, high surface tension and low viscosity. The general considerations which necessary to select the liquids are:

- 1) Working temperature range
- 2) Liquid transport factor
- 3) Properties of vapour
- 4) Wicking capability
- 5) Thermal conductivity
- 6) Fluid operating pressure
- 7) Fluid compatibility with container material

2.2 Wick design

Wicks in the system give the capacity of pumping the working liquid to the dissipation area. The primary condition for wicks is high pumping limit. The pumping limit is an important activity coming about because of the wick capillarity and porousness. Capillarity is controlled by the physical and geometric properties. At a given temperature, the fluid has a higher surface tension would cross section bigger droplet, along these lines permitting a vast wick channel size. For a lower surface tension fluid, a littler size channel is required to prevent the fluid framing droplets. To choose the right wick material, we have to consider the decision of the working liquid. Other than capillarity, wicks additionally require a decent conductivity, and great manufacturability.

Table.1: Characteristics of different wick structure

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Wick type	Pumping capability	Permeability	Thermal conductivity
Grooved	Low	High	Average
Mesh	High	Low	Low average
Sintered	High	Average	Low average

3. HEAT PIPE PROCESSING

The processing and fabrication of a heat pipe includes cleaning inner section by evacuation and fluid charging methods.

3.1 Cleaning

The container gets needs essential cleaning after some operations have been finished. Machining is carried to obtain required dimensions and preparing it for welding. A variety of contaminants, for example, chips, oil, dampness can be normal in the process of machining. Metal chips may trap inside wick and can harm the inner surface while Subsequent wick insertion. Presence of water can bring about erosion and damages both aluminium envelope and wick if unique materials are utilized. Contaminants may clog, reduce the area of device, but also which may affect properties of liquid and the wick, Presence of chemicals would generate the inert gases. These would react while consequent assembling situations, the wick, and the working liquid.

Cleaning of aluminium tubes

This procedure is prescribed for 6061 and 6063 aluminium pivotally furrowed or circumferentially strung envelopes.

a) Clean in chilly tri-choloro ethane with swarm brush or wire expansion

- b) Trichloro ethane is flushed through the tube and air is passed through the tube to dry the inner surface
- c) Anti acid is flushed for a small duration through the pipe
- d) Tube is rinsed with water for small duration and submerged in chromate deoxidizer
- e) Again the tube is rinsed by water for small duration

f) After removing the moisture from tube, Tube has to be washed by anhydrous isopropyl solvent

g) At 160° F dry nitrogen is used to clean the inner surface of the tube. This closes the top channel and is washed with isopropyl liquor and dried

h) If appropriate, vacuum outgas tube/wick get together at hoisted temperature in the wake of welding.

- i) If heat treating is required in the wake of welding:
- a) At 600° F tube is evacuated and checking the spots.

b) End closures are welded.

c) Processing to heat treatment operations.

4. PERFORMANCE EVALUATION

The following equations [5] are used to calculate the maximum heat carrying capacity of axially grooved heat pipe with trapezoidal wick structure and an equation which varies for other wick structure are tabulated, fluid properties to be considered at operating temperature.

4.1 Maximum heat capacity (trapezoidal groove)

The maximum heat carrying capacity of axially grooved heat pipe by the wick is the ratio of maximum capillary pressure difference to the sum of liquid pressure drop in wick structure and vapour pressure drop in vapour space. The equation is as follows.

$$QL_{c,max} = \frac{\Delta P_{c,max}}{F_l + F_v} inWm...eq.no 1$$

The above equation is only applicable for axially grooved heat pipe.

4.2 Maximum capillary pressure difference (▲ Pc, max).

Maximum capillary pressure difference is value of fluid pressure difference occurs between evaporator and condenser section which drive the fluid from condenser section to evaporator. The following equation is for calculating maximum capillary pressure difference. If right hand term is eliminated that gives the value at zero gravity condition. Including the terms gives the value in gravity condition.

$$\Delta P_{c,max} = \frac{2\sigma}{r_{eff}} - \rho glsin \emptyset in N/m^2 \dots eq.no 2$$
$$\sin \emptyset = \frac{h}{l} \dots eq.no 3$$

4.3 Liquid friction co-efficient F₁

Liquid friction co-efficient is pressure drop of fluid flowing through wick due to various factor. Liquid pressure drop will be less if the permeability is high. The equation is as follows

$$F_l = \frac{\mu}{\rho K N A_w L} i n N / m^3 W \dots \text{eq.no } 4$$

a) <u>Permeability</u>

It's the ability of wick structure which allows the fluid to flow with low resistance. This is inversely proportional to liquid pressure drop. Therefore, high heat transport capability.

$$K = \frac{D_h^2 \varphi}{2(f, R_{e,h})} m^2 \dots \text{eq.no } S$$

 $(f,R_{e,h})$ =friction co-efficient for laminar flow (from graph w.r.t groove angle & ratio of w/D_g).

b) Hydraulic diameter D_h

Hydraulic diameter is a average diameter available for flow of fluid with respect to the individual wick, which effects the capillary pumping.

$$D_h = 4\left(\frac{D_g(w+D_g/\tan\theta)}{w+2D_g(1/\tan\theta+\frac{1}{\sin\theta})}\right) m\dots \text{eq.no } 6$$

c) <u>Porosity</u>

It is also similar to the permeability which allows the average space available in wick structure for the flow of fluid with minimum pressure drop. Its dependent on wick geometrical parameter and independent from the fluid properties.

$$\boldsymbol{\varphi} = \frac{(w+D_g/\tan\theta)}{s}$$
...eq.no 7

$$S = (w + t) \dots eq.no 8$$

4.4 Vapour friction co-efficient F_v

It is vapour friction co-efficient is vapour pressure drop occurs in vapour space. While traveling from evaporator to condenser section.

$$F_{v} = \frac{(fR_{e,z,v})\mu}{2(r_{v}^{2})A_{v}\rho L} in \frac{N}{m^{3}W} \dots \text{eq.no } 9$$

4.5 Effective length of heat pipe

For a heat pipe effective length is only considered. Because it is assumed that fluid is not completely saturated at half of the length of evaporator and condenser region. The equation is as follows,

$$\boldsymbol{L_{eff}} = \frac{l_e + l_c}{2} + \boldsymbol{l_a} \boldsymbol{inm} \dots \text{eq.no } 10$$

4.6 Effective thermal conductivity K_{eff}

Thermal conductivity is one of the principle on which heat pipe operates. It plays major role at evaporator and condenser for absorbing and dissipating the heat.

$$K_{eff} = \varphi k_l + (1 - \varphi) k_s W / m K \dots$$
eq.no 11

4.7 Calculation of amount of fluid

The proper amount of fluid is also affects the heat transport capability. Less amount of fluid results in dry out point at evaporator before the average value of heat load. Excess amount would reduce the rate of condensation at condenser by forming pool of fluid increasing the resistance. For calculating amount of fluid for axially groove heat pipe the equation is as follows.

4.8 Mass of liquid ammonia

Amount of liquid ammonia for wick structure is calculated by following equation.

4.9 Mass of vapour ammonia:-

Amount of vapour ammonia for vapour space is calculated by following equation.

$$m_{va} = V_{vs} * \rho_{va} ingrams...eq.no 13$$

 $m_{la} = V_w * \rho_{la} * Ningrams...$ eq.no 12

Calculation of mass of heat pipe:-

Varying cross section of wick structure is also effects on the mass of heat pipe. The equations are as follows.

Total mass of operating heat pipe is difference between total mass of solid heat pipe and sum of mass occupied by wick and vapour space. The equation is as follows.

$$M_{hp} = M_t - (M_w + M_{vs})...$$
eq.no 14

5. TEST SETUP OF HEAT PIPE

The heat pipe testing set up consist of heat input system, heater pad, radiator, chilling pad, thermo couple and temperature display. Heater pads and chiller pads are made in contact with evaporator and condenser section respectively; inside the chilling pad a coolant will be circulated to absorb the heat. The thermocouples are connected between heat pipe and temperature display. Performance test will be carried out by maintaining constant temperature throughout the heat pipe, which is similar to the operating condition. The heat input is continuously increased till when the temperature at evaporator section is starts increasing than the maintained temperature, that point is called burn out point. The heat input at which burn out occurs is maximum heat capacity of heat pipe. A similar setup, but much more sophisticated with all possible measurements is already available at M/s. Avasarala Technologies where the experiments have been carried out. However, because of extreme confidentiality, the experimental results have not been published in this work. Only for circular grooved heat pipe heat capacity data is made available for validation.



6. RESULTS AND DISCUSSION

The effect of wick cross section like trapezoidal, circular, rectangular and triangular on heat pipe performance parameters such as heat transfer capacity, effective thermal conductivity and mass of fluid are detailed and discussed below.

6.1 Effect of cross section on heat capacity



Fig 3: Heat capacity for different wick cross section

The above graph shows the heat capacity versus cross section of wick section. The above results are obtained by keeping the outer diameter of heat pipe, area of wick constant and varying the cross section of the wick. The theoretical results of trapezoidal groove wick structure are matching with experimental results and results of circular groove wick structure are matching with the results shown in fig.4.apart from that it can be seen that triangular groove structure has low heat transport capability and circular groove structure has high heat transport capability because of high maximum capillary difference, low liquid and vapour pressure drop. Heat capacity of rectangular groove structure is 20% lower than trapezoidal wick structure and circular groove wick structure has 54% higher than the trapezoidal wick structure. As already mentioned heat pipe performance is measured with heat transport capability and effective thermal conductivity, so designer has decide the heat pipe based on requirement.

In the figure 4.shows the values of heat transport capability of axially groove heat pipe of circular wick structure at different temperature. The theoretical results of my work are matching with brown line (3rd curve from bottom) at temperature of 60 in graph.



6.2 Effect of cross section on effective thermal conductivity



Fig 5: Effective thermal conductivity for different wick cross section

The above graph shows the variation in the effective thermal conductivity versus cross section of wick structure. Effective thermal conductivity decreases following from triangular, rectangular, trapezoidal and circular grooves. The triangular groove has high effective thermal conductivity whereas circular groove has low effective thermal conductivity. The effective thermal conductivity depends upon the depth of groove, higher the depth more is the values, that is what happened in following case. At the end designer has to compare the values between various cross section and has to pick the required cross section of groove structure for manufacturing.

6.3 Effect of cross section on mass of fluid

The following graph shows the variation of mass of fluid versus cross section of groove structure. Even though the area is constant, because of change in the number of grooves varies the mass of fluid using for heat pipe. The amount of fluid should saturate the heat pipe, excess or less amount of fluid affects the heat capacity of heat pipe. From the above graph it can be observed that trapezoidal groove consumes more amount of fluid comparing to other groove structure followed by rectangular, triangular and circular. From the results it can be say that amount of fluid is for proper functioning of heat pipe and that will not affect the heat transport capability.



Fig 6: Mass of fluid for different wick cross section

6.4 Effect of cross section on mass of heat pipe

The below graph is drawn for the mass of heat pipe versus cross section of wick structure. From the graph it can be observed that triangular groove structure heat pipe has more mass and trapezoidal wick structure has less compared to other heat pipes. Mass of heat pipe is also becoming a major factor because the shuttle programs spends certain amount per gram and also reduces the mass on shuttle. Mass of heat pipe mentioned here including the mass of fluid. Whereas at final heat transport capability and effective thermal conductivity are the major deciding factors for the performance of heat pipe.



Fig 7: Mass of heat pipe for different wick cross section

6. CONCLUSION

The following conclusion is drawn from results obtained from experimental and theoretical method.

- 1) Temperature at which fluid has high latent heat is to be maintained inside the system for best performance.
- 2) Groove should have geometry which produces,
 - a. Capillary pressure more than pressure drop of liquid and vapour in system.
 - b. Higher permeability, porosity for fluid path with minimum pressure drop.
 - c. Higher conductivity.
- 3) Results shows circular groove exhibits high heat carrying capacity followed by the trapezoidal, rectangular and triangular cross sectional grooves.
- 4) Designer has to bargain between the heat transfer and conductivity rate of groove to decide optimum structure for system.

FUTURE SCOPE

At present heat pipe is major equipment for maintaining thermal loads and researches are conducting for improvement. But the processing and experimenting of this is costlier and time consuming. And still developments are under process in CFD for analysing it, because tool is not sufficient to obtain satisfying results. So work has to be carried out in CFD simulation, Coding to analyse this system. If that happens that will be major breakthrough in CFD and Heat pipe technology.

ACKNOWLEDGEMENT

I sincerely thank M/s. Avasarala Technologies for permitting to use their facility to carry out the experimental work. I also would like to thank Mechanical Engineering Department staff and Principal, Global Academe of Technology for their invaluable support.

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Nomenclature

= Maximum heat carrying capacity's in ρ=Vapour density kg/m³ $(Q L)_{c,max}$ A_v =Area of vapour space m² Wm d_v=Diameter of vapour space in m ▲ Pc, max = Maximum capillary pressure difference L_{eff} = Effective length of heat pipe in m in N/m² F_1 = Liquid friction co-efficient in N/m³W l_e =Evaporator length in m $F_v =$ Vapour friction co-efficient in N/m³W = Adiabatic length in m 1. σ = Surface tension of a liquid in N/m = Condenser length in m 1 R_{eff =}w=Effective pore radius in m $\phi = Porosity$ P=Density of liquid in kg/m³ k_1 =Thermal conductivity of liquid in W/mK. g=Gravity constant in m/s² k_s=Thermal conductivity of solid (T6 6063 aluminium) in = 200 W/mK. L=Length of heat pipe in m m_{la}=Mass of liquid ammonia in g h=Tilt height in m V_w=Volume of wick in m³ Sin ø=Angle of inclination μ =Viscosity of liquid in Ns/m² ρ_1 =Density of liquid ammonia in kg/m³ ρ = Density of liquid in kg/m³ N=Number of grooves K=Permeability in m² m_{va}=Mass of vapour ammonia in gms A_w=Area of wick in m² V_{vs} =Volume of vapour space in m³ ρ_v =Density of vapour ammonia in kg/m³ L=Latent heat in kJ/kg D_g=Depth of groove m M_t=Mass of solid heat pipe in grams w=Width of groove m ρ_{al} =Density of aluminium in Kg/m³ Tan θ =Angle of groove V_{hp} =Volume of heat pipe in m³ Sin θ = Angle of groove M_w=Mass occupied by wick space in heat pipe in grams ρ_{al} =Density of aluminium in Kg/m³ a_d = Adjacent in m $V_w = Volume of wick space in m^3$ b=Breadth of groove in m M_{vs}=Mass occupied by wick space in heat pipe in grams w=Width of groove in m ρ_{al} =Density of aluminium in Kg/m³ t=Thickness of fin in m V_{vs} =Volume of wick space in m³ S=Pitch in m $(fR_{e,z,v})$ = Laminar flow in circular flow constant.=16 M_t=Mass of solid heat pipe in grams. $\mu_v =$ Vapour viscosity in Ns/m² M_w=Mass occupied by wick space in heat pipe in grams. $r_{v} = (d_{v}/2) = Vapour space radius in m$ M_{vs}=Mass occupied by vapour space in heat pipe in grams