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Research Article

DESIGN, MODELING AND ANALYSIS OF HEAT PIPE FOR SPACE APPLICATION

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ABSTRACT

Heat pipe is a thermo mechanical device which is employed to get thermal equilibrium where huge no of electronic equipments are present like in space ship, satellite etc. which is very necessary to temperature to certain predetermined level unless which there may a higher chances of malfunctioning of system. Heat pipes are very good at maintaining thermal equilibrium, transferring heat from one point to other in large acceptable distance with a small heat drop. Heat pipes(HP) are somewhat comparatively not complicated for design, fabrication and controlling them can be done effectively with adequate knowledge of heat pipe, also they can be arranged in any direction which is an added advantage. Here some design aspects, modeling of heat pipe, analysis is done to effective and optimum fabrication of heat pipe for space applications.

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INTRODUCTION

Power generators like engines, turbines etc. electrical modules like motherboards, IC chips, programmable chips etc. generally use atmospheric air to cool it or to maintain thermal equilibrium. In some situations liquid water is unavailable and atmospheric air temperature is high which makes it impossible to cool heated surfaces by using this ambient conditions, during this case a specialized device called heat pipe is a promising technology which can be used as an alternative method of maintaining the thermal equilibrium over 130kW when thermal gradient reaches more than 6-8kW/K. Thus heat pipes (Thermosyphon) are employed to create heat exchange surface with the object of getting thermal equilibrium so that the system will work actively without any failure.

Removing heat from heated surface is a continuous process in heat pipe which involves vaporization followed by condensation. This thermosyphon (HP) is designed to have a wick structure inside, adiabatic line, evaporator and condenser. Inside which a working fluid is filled and provided with partial vacuum, when heat is received at evaporator side the fluid inside gets evaporated and this vapor due to wick moves to the cooler space in heat pipe i.e. condenser where heat is rejected and these vapors are condensed, this condensate moves further by capillary action to evaporator region and this whole process repeats continuously till the goal is achieved. The main advantage of heat pipes are, their high heat transfer capabilities

over large distance, high heat recovery effectiveness, compactness, no movable parts, less denser, economy, no external power to operate Grooten, (January 2007).

The concept of heat pipe originally comes in the year 1944 by scientist Gaugler and following his idea by Trefethen in the year 1962. Subsequently the concept and its idea developed and practically proved and demonstrated by the scientist Groover and his friends.

Heat pipe basic elements and operation

The heat pipe is thermo mechanical equipment which has higher thermal conductance which is employed with an objective of thermal equilibrium of electronic equipments or heat sources.

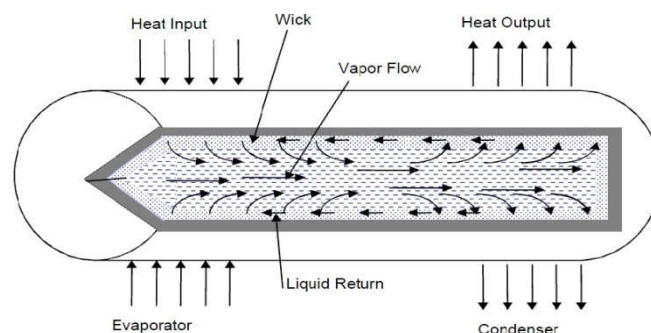


Figure 1 Conceptual working of heat pipe [Source: Jentung Ku, 2015]

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Figure 1 represents a typical diagram of a standard thermosyphon which consists of basic elements like Evaporator (heat receiver), Adiabatic and Condenser (heat rejecter). When heat is received in evaporator section the operating fluid inside converted into vapor and by capillary action these vapors are pumped towards condenser section where temperature is lower and here rejection of heat from vapors takes place there by converting these vapors to condensate, this condensate further moves towards evaporator where high temperature is observed and this process repeats continuously.

Operating fluid

The conceptual idea of development of heat pipe with proper design and analysis initially comes up with the selection of correct working fluid. For selection of operating fluid, we must consider the many of factors which plays predominant role Prashanth H.K. (May 2017).

- Operating fluid have consenting agreement with the wick, tube material used
- Good and appreciable thermal stability for effective operation
- Wetting of wick, wall material during operation
- Adequate vapor pressure over working temperature range in operation
- Good latent heat capacity for better operation etc.
- If heat pipe to be in operation in practical conditions, its wick should be saturated by operating fluid. The working substance from cryogenic fluids to liquid metals have already been developed, based on this heat pipes can be clasified into cryogenic, medium temperature (-240F or 122K), fluid metal heat pipes (670F or 628K) these are logical since
- The normal boiling point of working gases such as H₂, neon, N₂, O, and CH₄ lies below the -240F/122K.
- Metals working fluids like potassium, sodium, cesium, lithium and silver lies mercury, greater than 670F/628K.
- Refrigerants and liquid as water, ammonia, Freon and methanol all boils less than one standard atmospheric pressure at temperature of -240F/122K.

Wick

It is a layer developed to produce the action of Capillarity to overcome the force of gravitation in space since it is a celestial area where we cannot come across gravity.

- To provide path of passage to return condensate during operation.
- To provide pores at the surfaces for establishment of capillary pumping pressure at liquid-vapor interface.
- To create the heat flow passage in between the container inner wall and liquid vapor interface
- Some materials used as wick include mesh screen, fiberglass and sintered porous metal etc Prashanth H.K. (May 2017).

Table 1 shows acceptable values for different properties of working fluids

Table 1 Properties difference of cryogenic, moderate-temperature and fluid metal heat pipes at normal boiling conditions Robert D. Karan, (1998).

Properties	Fluids		
	Nitrogen	Ammonia	Sodium
Normal boiling temperature, F (K)	-321 (77)	-28 (240)	1621 (1156)
Liquid density, lbm/ft ³ (kg/m ³)	50.61 (811)	42.5 (681)	46.1 (739)
Liquid surface tension, lbf/ft(N/m)	6.1 x 10 ⁻⁴ (8.9 x 10 ⁻³)	2.3 x 10 ⁻³ (3.36 x 10 ⁻²)	7.9 x 10 ⁻³ (1.15 x 10 ⁻¹)
Liquid viscosity lbm/ft-hr(kg/m-sec)	0.38 (1.57 x 10 ⁻⁴)	0.65 (2.69 x 10 ⁻⁴)	0.42 (1.74 x 10 ⁻⁴)
Liquid thermal conductivity, Btu/lbm(J/kg)	0.080 (0.138)	0.32 (0.554)	31.8 (55)
Vapor density, lbm/ft ³ (kg/m ³)	0.288 (4.61)	0.056 (0.90)	0.017 (0.27)

Satellite Thermal Management

If motions of two bodies are considered in an inertial frame for reference, solely due to the mutual force of gravitation between two bodies, the path of one body is relative to other is a conic section (circle, ellipse, parabola, or hyperbola). The first body, relative to which the motion of the second body is considered, is called the primary body and the secondary body is called a satellite (of the primary body).

The equation of motion of a two-body probe is given as

$$\ddot{\mathbf{r}} = -\frac{\mu}{r^3} \mathbf{r}$$

Where,

$$\mu = G(m_1 + m_2)$$

And is called as the gravitational parameter, G refers to universal gravitational constant and m₁ and m₂ are masses of two bodies where r is the position vector.

The primary body lies at one of foci of the conic section that describes the path of the secondary body (satellite) relative to the primary body. The path of the secondary body is called an orbit.

The most "obvious" examples of one body orbiting another are Sun-Earth system and Earth-Moon system. In both cases, the orbiting body, Earth in the former and Moon in the latter, are called natural satellites. Objects or bodies placed into orbits around natural heavenly bodies by human beings are called artificial satellites. In present work, the word "satellite" refers to an artificial satellite unless otherwise specified Robert D. Karan, (1998).

Maximum priming height which can obtain by a capillary is expressed by equation.

$$h + h_c = \sigma_1 \frac{\cos\theta}{(\rho_l - \rho_v)g} * \left(\frac{1}{r_{p1}} + \frac{1}{r_{p2}} \right)$$

Where, h = vertical height to the base of the artery, h_c = vertical height to the top of the artery, r_{p1} = first principal radius of curvature of the priming meniscus, r_{p2} = second principal radius of curvature of the priming meniscus.

The maximum heat transfer due to the entrainment limit can be obtained from

$$Q = \pi r_v^2 L \sqrt{2\pi\rho_v\sigma_1/z}$$

Where z = characteristic dimension of the liquid-vapor interface

The degree of superheat to result nucleation expressed by

$$\Delta T = \frac{3.06\sigma_1 T_{sat}}{\rho_v L \delta}$$

Where δ = Thermal layer thickness, ΔT = elevated temperature at 85°C

To find minimum flow area, we can equate the maximum capillary pressure to the sum of the liquid and gravitational pressure drops as follows

$$\Delta P_c = \Delta P_l + \Delta P_g$$

Thermal conductivity of the wick can be found and used in the steady state conduction.

$$k_{wick} = \left(\frac{\beta - \epsilon}{\beta + \epsilon} \right) k_1$$

Also thermal conductivity of the wick is approximated employing the relation

$$k_{wick} = (1 - \epsilon)k_{wall} + \epsilon k_f$$

Where k_f is the thermal conductivity of the working substance. The wick-wall interface equivalent heat transfer coefficient is evaluated using

$$h = \frac{k_{wick}}{k_{wall} r_w \log \left(\frac{r_w}{r_v} \right)}$$

Pressure loss in the condenser and evaporator is expressed by $\Delta P_{loss} = K_l * l_{eff} Q / 2KA_c$

Where, l_{eff} = effective circumferential flow which is equal to $\pi r_w / 4$

Capillary pressure generated is given by Marcus, B.D (April 1972)

$$\Delta P_c = 2\sigma_1 \cos\theta / r_c$$

Need

If the temperature limits of the satellite is maintained to a limit which it was designed and assembled for, then the operation of the satellite will be better and thus the performance of the satellite also. Thus for this the thermal management of the satellite system is very important. Thus satellite thermal management must start with establishing thermal specifications in which the satellite present in its various stages of its life for overcoming the obstacle of thermal control after which can be proceeded further.

Heat pipes in satellite

The only mode of heat rejection in a satellite is by radiation to deep space (2.73K). Heat dissipating components on a satellite are placed on thermal radiators that can reject heat by radiation.

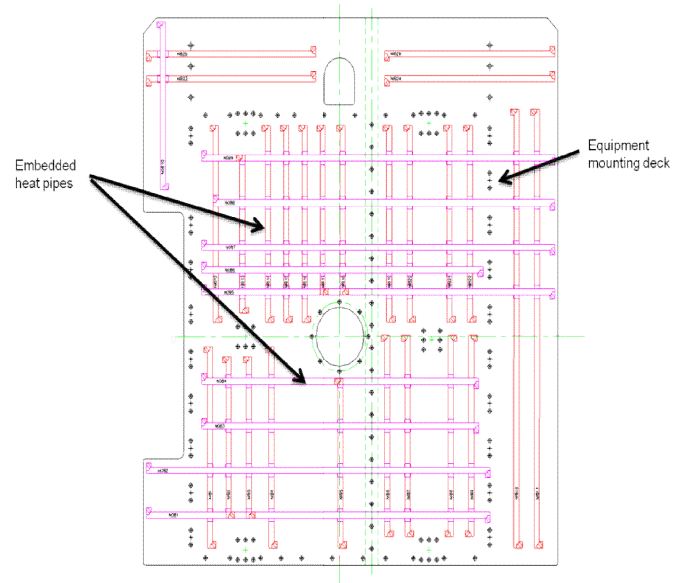


Figure 2 Embedded heat pipes in satellite

Figure 2. Indicates equipment deck of heat pipe in satellite with an objective of removing heat from satellite electronic source.

Thermal Modeling and Analysis

Three principal heat pipes and six spreader heat pipes are considered for design and analysis. Each main heat pipe has two electronics units mounted on one side. The heat dissipation in electronics 1 is 50W and in electronics 2 it is 25 W. The overall size of the deck is 1m x 0.5 m. This configuration of the deck is shown in figure 3.

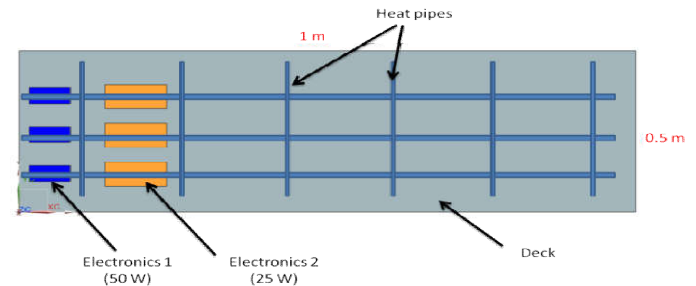


Figure 3 Equipment deck

Thermal radiator area of size 950 mm x 500 mm is provided on the other end of the deck. The remaining portion of the deck is provided with multi-layer super-insulation to prevent any heat losses if so.

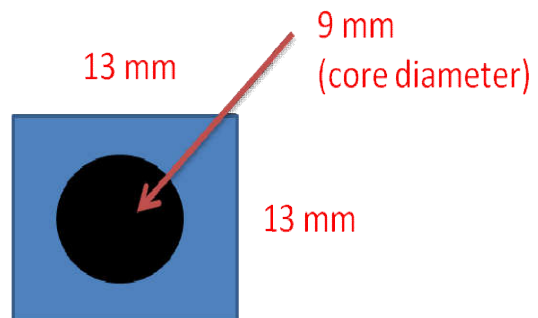


Figure 4 Heat pipe dimensions

A thermal model domain is developed by using in Siemens NX 8.5 and steady-state thermal analysis is done to estimate the temperatures and temperature balance of the heat pipe zone.

Table 2 Input parameters for analysis

Parameter	Value
Deck size	1.50 m x 0.50 m
Deck thickness	13 mm
Deck skin thickness	0.3 mm
Deck material	Aluminium alloy
Deck out of plane conductivity	1.5 W/m K
Heat pipe cross section	13 mm x 13 mm
Heat pipe type & casing material	Axially grooved ammonia heat pipe, aluminium alloy
Length of heat pipe	1.5 m
Electronics 1 heat dissipation	50 W
Electronics 2 heat dissipation	25 W
Radiator emittance	0.88
Sink temperature	2.73 K

The parametric values selected for analysis is given in table 2. This uses aluminum alloy as deck material and ammonia as an operating fluid.

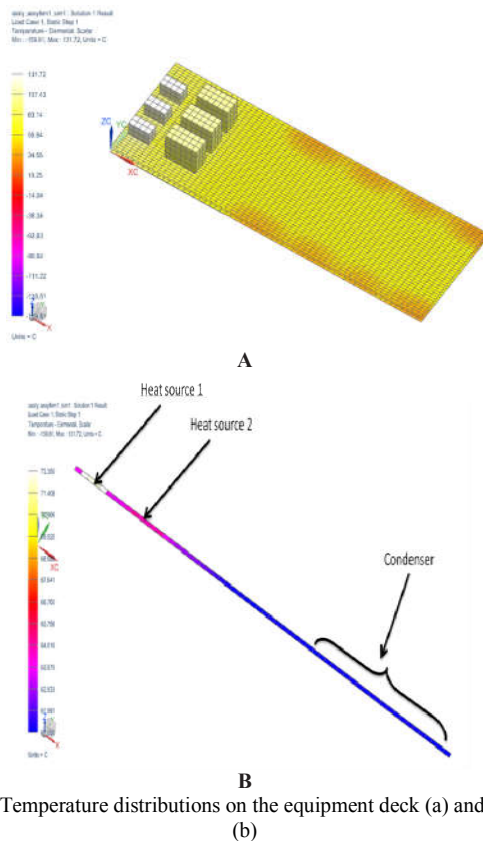


Figure 5 Temperature distributions on the equipment deck (a) and Heat pipe (b)

Temperature distribution of the heat pipe and deck is shown in figure 5(a) and 5(b) respectively. Above figures shows the distribution of the temperature on the heat pipe where major concentration of this analysis goes towards the evaporator and condenser section, as we can see there is a large quantity of temperature is concentrated at the heat source 1 and 2(evaporator) and least quantity of temperature in the condenser region.

The equations were solved in SCILAB for n=0 to 200. The heat pipe length is subdivided in 10 equal nodes for the ease of analysis.

Temperature of wall distribution from the system level Analytical model analysis is shown in figure 6.

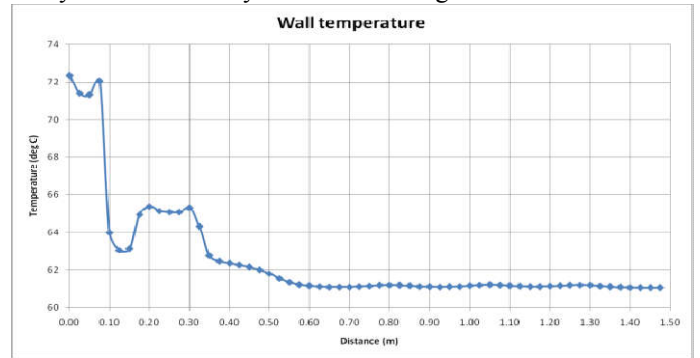


Figure 6 Temperature distribution at wall from analytical model of heat pipe

The above figure shows and it is clear that the temperatures are higher at heat source 1(50W) and heat source 2 (25W) and the slope decreases gradually as the temperature decreases and reaches the minimum i.e. at the condenser section.

CONCLUSION

A technical approach is done for developing model of heat pipe with two heat input sources which is used in thermal radiator of satellite which is discussed here in with. Results for analytical model are developed for in comparison with the system level model. The present work uses idea of mathematical model presented by Shabgard and Faghri to estimate the operating condition of the heat pipe under steady-state operation.

According to the model developed, analysis done, this model can be used in optimal way for effective thermal management for space applications like satellite, space ships, celestial technical objects etc.

Scope of Future Work

In future continuation of the present work, liquid and vapor flows have to be modeled in addition to temperature profiles to get a complete understanding of the processes taking place in the heat pipe, Further, several other models available in literature can be applied to analyze the operating condition of heat pipes in similar applications. Further, experimental validation of the results obtained by analysis can be carried out.

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