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CFD Study on flow and heat transfer characteristics of heat pipe with axial "Ω"-shaped microgrooves

Engineering

KEYWORDS:

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ABSTRACT

Advanced thermal devices, such as spacecraft thermal control systems and themicroelectronic cooling system requires cooling beyond the capability of metallic sinks. This can be met by the heat pipes with axial 'Ω'-shaped microgrooves heat pipe. These axial'Ω'-shaped microgrooves heat pipe has high heat transfer capability and provide ahigh degree of temperature uniformity.

A COMPUTATIONAL FLUID DYNAMICS (CFD) analysis is carried out for heat pipe to determine the surfaceand vapor temperature transient conditions for four different input powers in the evaporator section and cooling the condenser section by air by using ANSYS Fluent software. For geometric modeling of theheatpipe, ANSYS Design Modeller is used. For CFD meshing, ANSYS Meshing Software is used. A comparison study is made with and without grooves and also compared with available experimental data.

INTRODUCTION

All electronic components generate heat and rejection of this heat are necessary for their optimum and reliable operation. As electronic design allows higher throughput in smaller packages, dissipating the heat load becomes a critical design factor. Since the mid-1960's heat pipes have been available.

The purpose of this article is to explain basic heat pipe operation, review key heat pipe design issues and to discuss current heat pipe electronic cooling applications.

Designing of a heat pipe is based on many factors. These are as follows- compatibility of materials, operating temperature range, diameter, power limitations, thermal resistances and operating orientation.

Copper/water heat pipes have been selected for cooling electronics. The design issues are reduced to two major considerations. These considerations are the amount of power the heat pipe is capable of carrying and its effective thermal resistance. Typical, heat pipe working principle and components is shown in Fig 1.

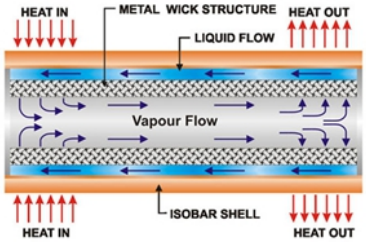


Fig. 1Heat Pipe

Heat pipes are two- phase heat transfer devices with high effective thermal conductivity. These heat pipes can be cylindrical or planar in structure.

Some of the important studies carried out by the researchers on low-temperature heat pipe are summarized in this section.

Faghri et al.[1] conducted the study on the effect of axial conduction in the fluid and the pipe wall of the heat pipe for forced convective laminar flow with blowing and suction at the impermeable wall. Faghri et al. [2] conducted astudy on the effect of conjugate heat transfer, vapor compressibility and viscous dissipation for thecompressible and incompressible model. Chen et al. [3] conducted a coupled analysis of the wall, wick and vapor region. The study was conducted on both single and multiple heat sources in a 2D axisymmetric cylindrical heat pipe. The working fluid considered were both sodium and water. For the considered operating conditions, the solutions were compared against the experimental results for the vapor and wall temperature at high and low temperatures. It was found that the compressibility effects were important. Faghri et al. [4] made an observation on the overall performance of the concentric annular heat pipe. An emphasis was given to the increase in the heat transport capacity when compared to the conventional heat pipe. The prediction of the capillary limitation in a concentric annular heat pipe was made theoretically. Cao et al. [5] investigated the transient response of heat pipe to a pulsed heat input mathematically. Chang [6] developed the mathematical model to derive the effective thermal conductivity and porosity of the copper screened wick. Pruzan et al. [7] developed a model for predicting peak steady- state heat flux limit as a function of wick structure parameters and capillary pumping requirements. Faghri et al. [8] through experiments determined the capillary limit for single and multiple evaporators operating modes. Cao et al. [9] numerical analysis on the transient and steady state temperature distribution of leading edge heat pipe with uniform and on- uniform heat distribution. Cao et al. [10] did a numerical prediction of the dynamics of the heat pipe from the frozen state to the steady- state operation.

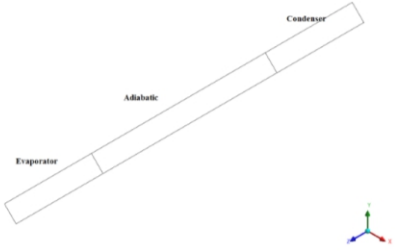
Schmalhofer et al. [11] determined the transient and steady- state temperature in the wall and the vapor region. For this purpose, step heat input of 50W and 150W were applied respectively. Also, prediction of the capillary limit for circumferentially and block heated heat pipe was made analytically. El- Genk et al. [12] conducted an experimental investigation on the vapor temperature and the effective power throughput as afunction of the electric power input and the water mass flow rate in the cooling jacket of the condenser section. Tournier et al. [13] developed a heat pipe transient analysis model theoretically. Comparison of the calculated transient and steady- state values was done with the experimental results. Kim et al. [14] experimentally and analytically investigated the entrainment phenomenon in the capillary – driven heat pipe. Also, theoretical

investigation of the capillary limitation as a function of vapor temperature for three different mesh number was done. Harley et al. [15] conducted the numerical analysis of the transient and steady-state temperature distribution in the wall and the wick with pulsed heat input. Also, astudy on the vapor dynamics of gas-loaded heat pipe was conducted by him. Ma et al. [16] conducted an experimental investigation on the heat transport and maximum unit effective area heat transport in triangular grooves. Peterson et al. [17] made a mathematical prediction of the maximum heat transport in micro heat pipes. Ma et al. [18] made a prediction on the minimum meniscus radius and the maximum capillary heat transport limit in micro heat pipes. Thomas et al. [19] made an examination on the steady- state performance of a helically grooved copper – ethanol heat pipe under various heat inputs and transverse body force field.

In the present work, numerical investigation of a water heat pipe for two different values of surface heat flux given in the evaporator section of the heat pipe and cooling in the condenser section by atmospheric air is done. A detailed study on the transient surface and vapor temperature distribution along the length of the heat pipe is done. The comparison of with and without grooves heat pipe was carried out in a transient computational fluid dynamics (CFD) analysis.

2. MODELLING AND CFD ANALYSIS

The configuration of the heat pipe modeled for the present study is shown in Fig.



Along the axial direction, the heat pipe consists of three sections namely evaporator section, transport section (adiabatic), and thecondenser section. Along the radial direction, there are three regions namely vapor region, wick region, and the wall region. In the wick region, the working fluid is in thevapor phase.

For analysis, the heat pipe with axial "Ω"-shaped microgrooves is charged with theappropriate amount of working fluid. In the evaporator section, theheat flux is applied in order to vaporize the liquid. At the condenser section, thevapor condenses and releases the latent heat. The microgrooves create the capillary pressure. This capillary pressure drives the condensate from the condenser back to the evaporator. After the release of the latent heat to the environment through the outer surface of the condenser, in the condenser region, it returns to the wick region as asaturated liquid.

For the construction of a two- dimensional axisymmetric model ANSYS Design Modeller pre-processor software was used. After the construction of geometry, the mesh generation process was carried out by defining the grid points on each edge. In order to create quadrilateral elements on the model – faces "Mapped Mesh" scheme was used using ANSYS Meshing as shown in Fig 2.

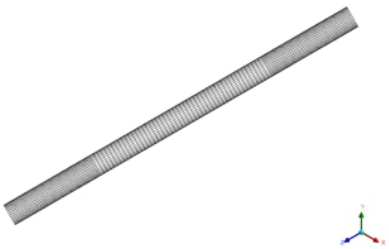
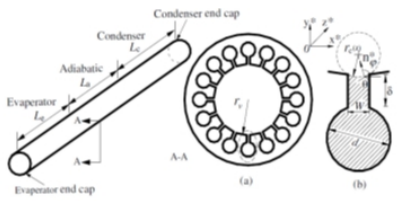


Fig. 2Geometric Model and Meshing of Heat Pipe



Number of groove N	Outside diameter d_o (mm)	Vapor core radius r_v (mm)
16	4.5	1.40
Wick slot width W (mm) 0.12	Evaporator length L_e (cm) 10	Condenser length L_c (cm) 10
Working temperature T_{work} (K) 293	Working fluid Ammonia	Solid material Aluminum alloy

Wick diameter D (mm)	Wick slot height δ (mm)
0.36	0.18
Adiabatic length L_a (cm) 8.5	Contact angle θ (°) 45.6

Fig. 3 Schematic of heat pipe with axial ""-shaped grooves (a) Cross-section (no interconnection among microgrooves at both ends) (b) Geometric shape of a "Ω"-shaped groove

The continuous domain was discretized by creating nodes. The total numbers of nodes created for the model were 45000.

A partial vacuum was created in the pipe. Due to this vapor starts to vaporize at the temperature less than that at ambient pressure. An assumption considered for the analysis is that the working temperature of the pipe is 338K. According to water vapor thermodynamic tables, the working pressure at 300K is 25030Pascal. At this pressure, the thermophysical properties of the liquid in both phases were used for the ANSYS-FLUENT software. Heat load input to the evaporator was 30 to 60 watt. The material of the heat pipe container and the wick was selected as copper.

Geometric model of groove heat pipe is shown in Fig 4.

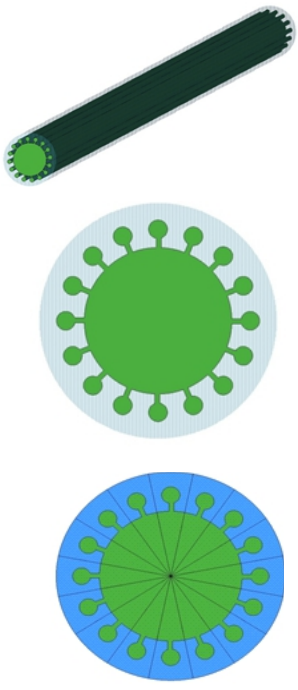


Fig. 4 Geometric Model of Groove Heat Pipe

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Due to the cyclic sector of the model, only one sector of the heat pipe is considered for the simulation. This is done so in order to reduce the computational time of the simulation.

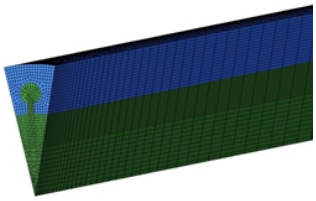

Fig. 5Sector CFD Mesh of Grooved Heat Pipe

3. RESULTS AND DISCUSSIONS

Teand Tc are defined as the average values of temperature at the evaporator and the condenser sections. Heat supplied to the heat pipe is denoted by Q. From all the figures, it can be concluded that for grooved heat pipe the performance is increased.

Fig 6, shows the temperature contours at 45 and 90 minutes.

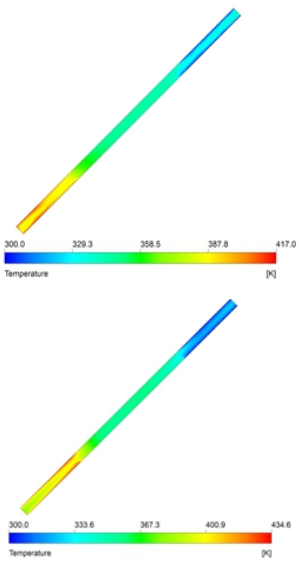

Fig. 6 Temperature contours at 45 and 90 min

Fig 7, 8, 9 shows the velocity vectors in evaporator, adiabatic and condenser section.

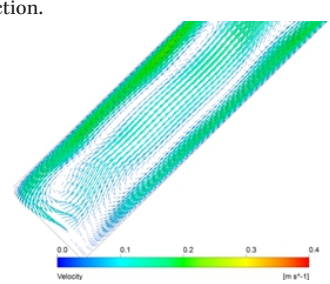

Fig. 7Velocity vectors at Evaporator section

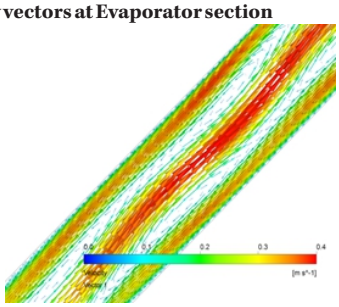

Fig. 8 Velocity vectors at adiabatic section

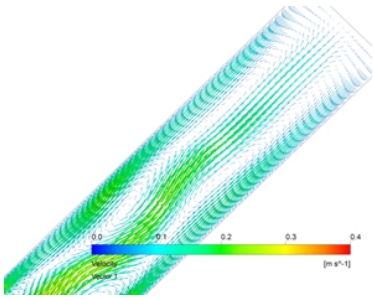

Fig. 9 Velocity vectors at condenser section

It can be concluded that velocity remains constant in adiabatic section, compared to other sections. Fig11. shows the temperature difference between the evaporator and the condenser for various heat loads.

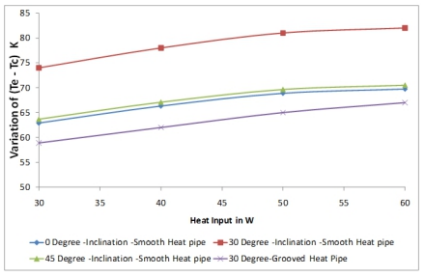

Fig. 11 Variation of (Te - Tc) for smooth and grooved heat pipe

It can be concluded from the graphs that for increasing values of heat input, the temperature difference between evaporator and the condenser increases.

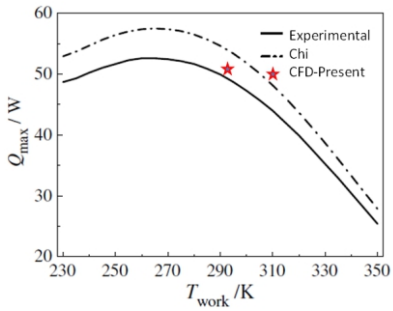

Fig. 12 shows the maximum heat transport capability of grooved

Heat pipe with respect to the operation temperature, in which the present result is plotted in the star and what from Chi [27] is plotted in the dash-dotted line. As shown in Fig12, for the case study in this work, the peak point of the maximum heat transport capability appears at 300K, and the heat transfer performance matches well with the experimental data.

4. CONCLUSIONS

CFD simulation of fluid flow and heat transfer in a heat pipe with axial "Ω" -shaped grooves is developed. It has been solved numerically to obtain the heat pipe performance and maximum heat transport capability using CFD package FLUENT 13.0.

It is observed that the temperature difference between the evaporator and the condenser increases for increasing values of heat input. For grooved heat pipe, the performance is increased further.

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