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DEVELOPMENT AND TESTING OF FLEXIBLE HEAT PIPES

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ABSTRACT

The paper describes the ongoing design and development of a flexible heat pipe system which couples heat transfer function along with its inherent flexibility, so that the evaporator section of the heat pipe, which is connected to the heat load does not get stressed or deformed under the mounting conditions. Providing this flexibility will prevent damage to the heat pipe and the system on which it is mounted. The flexibility has been incorporated in the adiabatic section of the heat pipe by using a flexible metallic bellow to allow relative movement between the two ends of the heat pipe. The primary technological challenge faced during the execution of this project is to integrate the capillary wick along with the flexible bellow sub-system and ensure proper thermal operation. A stainless steel bellow has been used as the flexible element and has been brazed to pipes on both sides to form the outer casing. In the present study, the flexible heat pipe has been tested in 'vertical heater-down position' and 'for horizontal position'. Its thermal resistance is reported under straight and bent configurations of the heat pipe; detailed study is presently underway. As per the required specifications, the heat pipe is expected to cater to about 100 W of thermal load dissipation, in the operating range of 10°C to 100°C. The heat pipe has an internal diameter of 10 mm and is 270 mm long.

Keywords: Heat pipes, metallic bellows, capillary limit, thermal performance testing

NOMENCLATURE

T_a	average adiabatic section temperature (ºC)
T_e	average evaporator section temperature (ºC)
$\dot{Q}$	input heat power (W)
R_{th}	thermal resistance (K/W)
V	input voltage (V)
I	electric current (A)
δR_{th}	uncertainty in thermal resistance (K/W)
δQ	uncertainty in measurement of heat input (W)
δT	uncertainty in measurement of temperature (K)
δV	uncertainty in input voltage (V)
δI	uncertainty in input current (A)

INTRODUCTION

Two-phase passive devices are proven present day solutions which can cater to a large variety of thermal management problems at various levels. Conventional heat pipe technology has been successfully applied in the last forty years for the thermal management of a variety of applications like heat exchangers, economizers, space applications, and electronics cooling.

In general, typical heat pipes utilize the continuous evaporation / condensation of a suitable working fluid for two-phase heat transport utilizing latent heat in a closed system. A typical heat pipe consists of three sections: evaporator, adiabatic section and condenser [1-3].

The present study describes the design and development of a wicked flexible heat pipe system, which performs the heat transfer function while not getting stressed or deformed under the mounting conditions [4-5]. These mounting forces are likely to be generated while attaching the heat pipe to the heat source as well as to the condenser. Providing this flexibility is aimed at preventing the heat producing element from damage. These mounting forces and vibrations affect the thermal performance and reliability of the heat pipes [6-9]. The heat pipe is designed for a nominal heat carrying capacity of 100W at operating temperature range of 10°C to 100°C.

MANUFACTURING OF FLEXIBLE HEAT PIPE

The proposed heat pipe has a flexible structure that is formed on the metal pipe, such that the heat pipe can be bent/ gets bent if external loads are experienced. In addition, the woven mesh and the support element can be bent together with the heat pipe without a risk of being broken, such that the woven mesh can be maintained in contact with the internal wall of the metal pipe to allow the working fluid to flow smoothly in the woven mesh and to maintain a good heat dissipating effect.

A flexible heat pipe comprising of the following is manufactured [10-11]:

a. a metal pipe;
b. a flexible structure which is essentially a stainless steel bellow;
c. a wick consisting of multiple layer of phosphor bronze screen mesh, disposed inside the metal pipe;
d. a working fluid (water), filled inside the metal pipe and attached onto the woven mesh; and
e. a support element, passed into the interior of the woven mesh, abutted against the woven mesh, and attached onto an internal wall of the metal pipe.

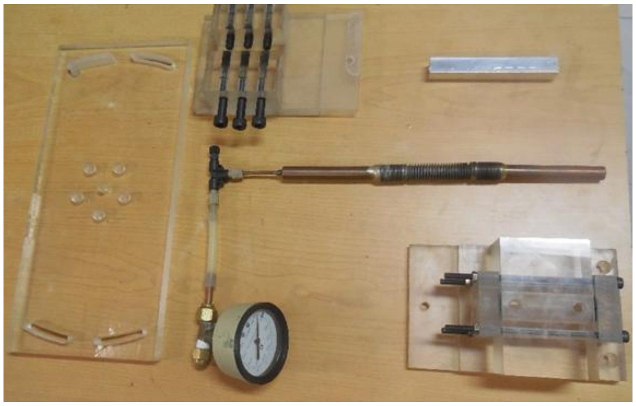


FIGURE 1: The developed flexible heat pipe and the components manufactured for its testing.

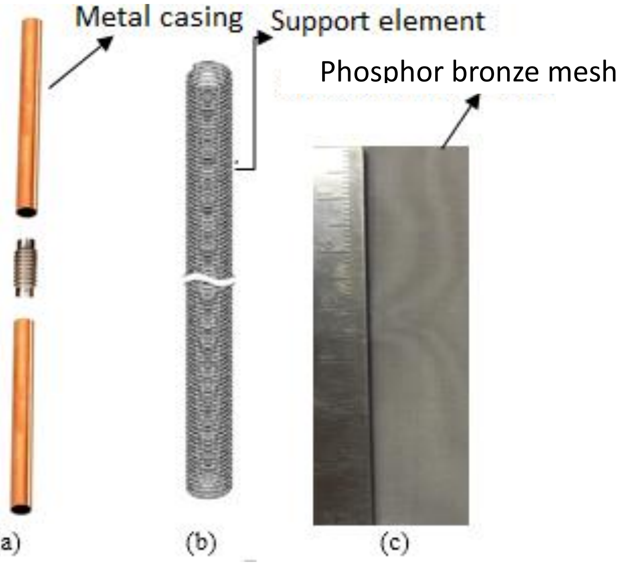


FIGURE 2: **(a)** Components of metal casing **(b)** support element **(c)** mesh used for the wick structure.

An exploded view of the flexible heat pipe is shown in Fig. 2. The total heat pipe length is about 270 mm, with the container pipe having ID of 10 mm.

A stainless steel bellow with pressure rating of 5 bars is used as the flexible element and is joined to copper pipes on both ends to form the metal casing of the heat pipe. Three layers of phosphor bronze mesh with a composite mesh design are inserted in the metal casing. These layers function as a wick of the heat pipe. The inner layers are loosely wound and press the outer layers against the metal casing thus acting as the support element and helping maintain good thermal contact.

Vacuum is created in the heat pipe using a rougher pump, in tandem with a turbo-molecular pump and then the heat pipe is charged with about 10.0 ml of deionized and degassed water (working fluid) through a micro-metering valve. The amount water needed is optimized for efficient operation. In long term plan of development, water is to be replaced with other suitable fluids, as per the need of the application. Initial tests reported here are with water as the working fluid.

EXPERIMENTAL SETUP AND METHODOLOGY

The setup to hold the heat pipe and test it under different operating conditions is machined from a 50 mm thick acrylic sheet. The heater and condenser holders are two separate units connected by a pin joint at the centre in such a way that we can give desired deformation to the heat pipe mounted on this setup, as shown in Fig. 3. This is useful while recording thermal performance of heat pipe in deformed configuration.

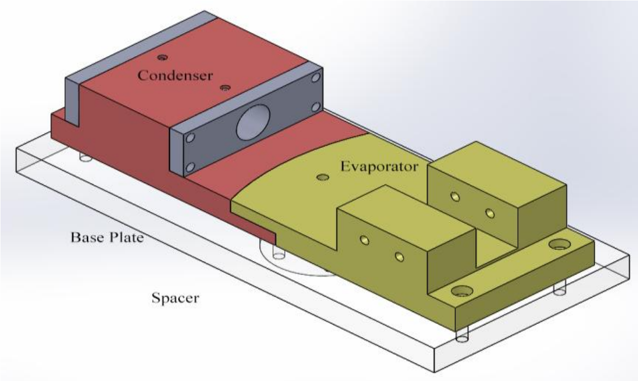


FIGURE 3: Experimental setup – framework for holding, bending and testing the heat pipe assembly.

Figure 4 shows the experimental test bench to test the thermal performance of the flexible heat pipe. The evaporator section of the heat pipe is inserted in an aluminum block of square cross section which is heated by two flat surface mountable silicon heaters (Minco®), which are powered by dual DC power supply source. The condenser section of the heat pipe is continuously cooled by water flowing at desired temperature from a constant temperature water bath circulator (Haake® – K20). The temperature at various locations is measured by using micro thermocouples (0.3 mm bead diameter; Omeg®). The temperature profile of adiabatic section is observed by using an infrared camera (FLIR® -ThermaCAM).

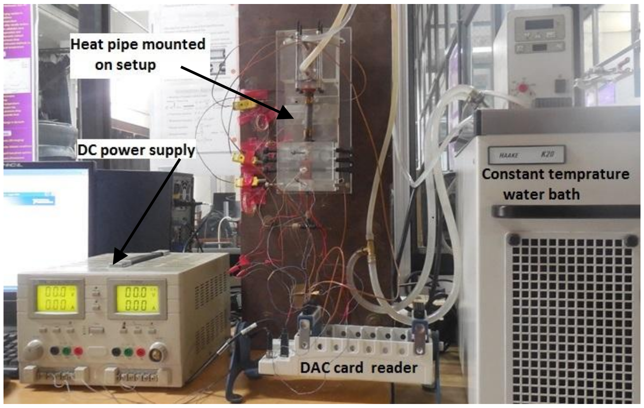


FIGURE 4: Photograph of the experimental test bench.

CAPILLARY LIMIT CALCULATION

The theoretical capillary limit for the manufactured flexible heat pipe at various working temperatures with water as a working fluid is calculated and plotted in Fig. 5. The following graph is based on the theoretical equations, obtained by equating the net dissipative pressure drop with the capillary pumping potential of the developed wick structure.

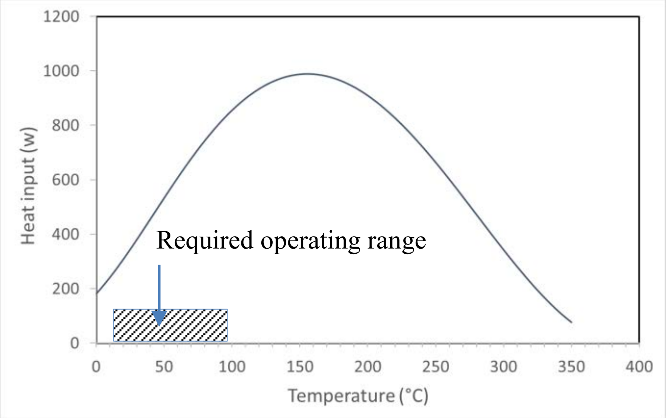


FIGURE 5: Theoretical capillary limit vs the working/ operating temperature of tested heat pipe.

As it can be observed from Fig. 5, the theoretical capillary limit for gravity assisted working, at desired range of working temperature, is much higher than 100 W for which we have designed the heat pipe. The theoretical values of capillary limit could not be verified due to constraints on heaters' input power capacity and condenser's heat removal capacity.

UNCERTAINTY ANALYSIS

Although the experiments have been repeated many number of times, statistical methods can certainly not be applied to get the error in the thermal resistance. Therefore, single-sample uncertainty analysis, as has been proposed by Kline and McClintock [12] and Moffat [13], is applied for present analysis.

The following equations have been used to calculate the error in thermal resistance, which is tabulated in Tab. 1 and Tab. 2. The maximum error in thermal resistance is calculated as following

Error in heat input: $$\frac{\delta Q}{Q} = \left\{\left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta I}{I}\right)^2\right\}^{1/2} \quad (1)$$

Error in temperature: $$\delta(\Delta T) = \{(\delta Ta)^2 + (\delta Te)^2\}^{1/2} \quad (2)$$

Error in resistance: $$\frac{\delta Rth}{Rth} = \left\{\left(\frac{\delta \Delta T}{\Delta T}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2\right\}^{1/2} \quad (3)$$

Here,
$\delta V = 0.01$ V;
$\delta I = 0.01$ A;
$\delta T_a = \delta T_e = 0.2$ K

Following the above procedure the maximum uncertainty in the thermal resistance comes to be about 0.02 K/W.

RESULTS AND DISCUSSION

Experiments are carried out to calculate the thermal resistance of heat pipe in straight and deformed configurations, respectively, to characterize performance of heat pipe in the desired operating range. The heat pipe is positioned vertically with evaporator kept downwards. Proper insulation is applied, wherever necessary. Insulation is removed temporarily to take IR images, as and when required. Power input is increased in steps, both in the forward and reverse directions. All experiments reported here are repeated, at least three times. The thermal resistance of a heat pipe is calculated as:

$$R_{th} = \frac{T_e - T_a}{\dot{Q}} \tag{4}$$

At present, we report essentially the thermal resistance of the evaporator, due to limitations of instrumentation in the condenser sub-section. The temperature in the adiabatic section, the temperature in the evaporator section, thermal resistance (between the evaporator section and the adiabatic section) and uncertainty in thermal resistance for the heat pipe, under different power inputs, is summarized Tab. 1. During this trial, the heat pipe is kept in straight configuration with coolant flowing through the condenser at 20°C.

The temperature profile of the adiabatic section (practically the bellow section) is observed by the infrared camera (IR) and is shown in Fig 6.

TABLE 1: Thermal resistance in straight configuration

Sr no	$\dot{Q}$ (in W)	I (in A)	T_a (in °C)	T_e (in °C)	R_{th} (in K/W)	δR_{th} (in K/W)
1	30	1.52	47	51.7	0.156	0.014
2	40	1.75	52.2	58.1	0.147	0.01
3	50	1.96	57.5	64.4	0.139	0.008
4	60	2.15	61.4	70.1	0.146	0.007
5	70	2.32	64.4	74.6	0.146	0.006
6	80	2.48	66	77.4	0.143	0.005
7	90	2.63	64.8	78.3	0.151	0.005
8	100	2.77	66.3	80.4	0.142	0.004
9	110	2.91	67.8	82.2	0.131	0.004

The corresponding data for the trial in which the heat pipe was deformed by 5° to the vertical, is tabulated in Tab. 2.

TABLE 2: Thermal resistance in deformed configuration

Sr no	$\dot{Q}$ (in W)	I (in A)	T_a (in °C)	T_e (in °C)	R_{th} (in K/W)	δR_{th} (in K/W)
1	30	1.52	48	52.2	0.141	0.014
2	40	1.75	52.9	58.8	0.148	0.01
3	50	1.96	56.9	64.1	0.146	0.008
4	60	2.15	60.8	69.6	0.147	0.007
5	70	2.32	63.7	73.7	0.144	0.006
6	80	2.48	65.1	77.1	0.15	0.005
7	90	2.63	66.2	79.8	0.151	0.005
8	100	2.77	66.3	82.2	0.159	0.004
9	110	2.91	67.3	84	0.152	0.004

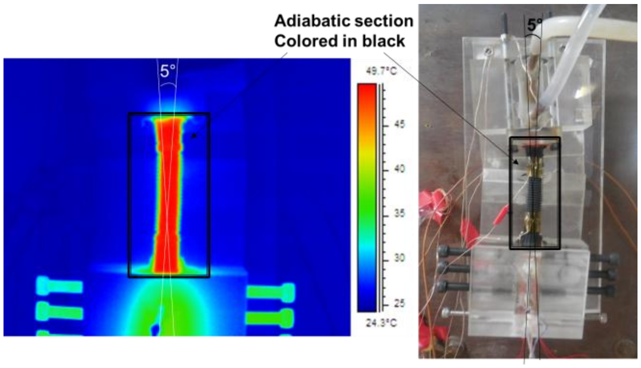
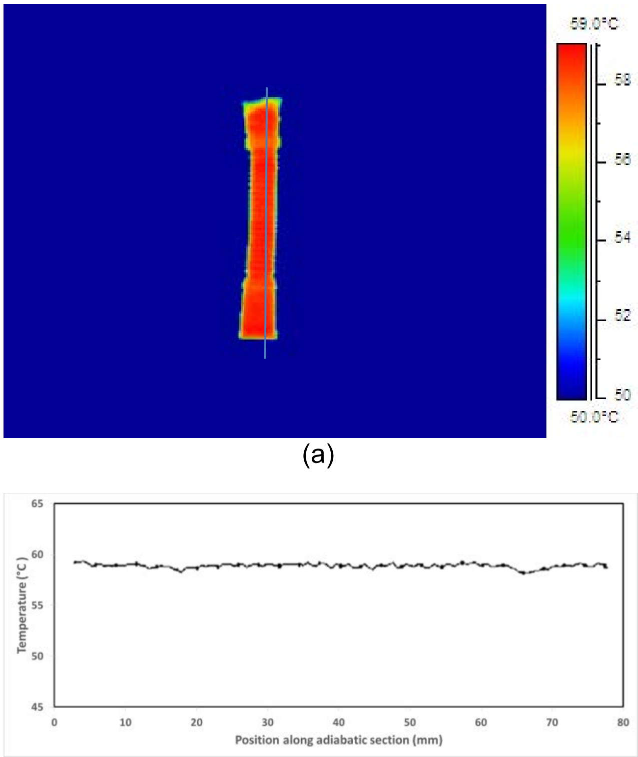


FIGURE 6: Deformed heat pipe IR image at heat input of 30 W and coolant temperature of 25°C.

IR images of adiabatic section shown in Fig. 7 and Fig. 8 depict that the temperature of the adiabatic section is almost constant i.e. 58°C for 60W heat input and 64°C for 90W heat input. This clearly indicates that the heat pipe is functioning quite satisfactorily, keeping the adiabatic temperature nearly constant, which is also reflected from its operating thermal resistance, in both vertical and 5º bent configuration. Bending the heat pipe also does not change its thermal performance, as seen in Fig. 9 and Fig. 10.



(a)

(b)

FIGURE 7: (a) IR image of adiabatic section **(b)** Graph showing Temperature values recorded by IR camera along the length of adiabatic section of the deformed heat pipe at heat input of 60 W and coolant temperature of 25°C.

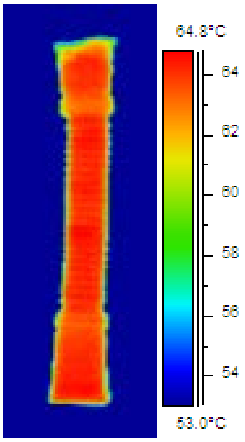


FIGURE 8: IR image of adiabatic section of the deformed heat pipe at vertical position at heat input of 90 W and coolant temperature of 25°C.

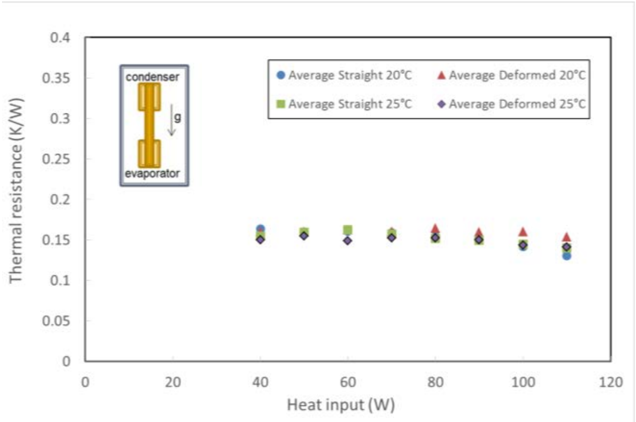


FIGURE 9: Comparing the averaged data of R_{th}, at coolant temperature of 20°C and 25°C for vertical positioning of heat pipe.

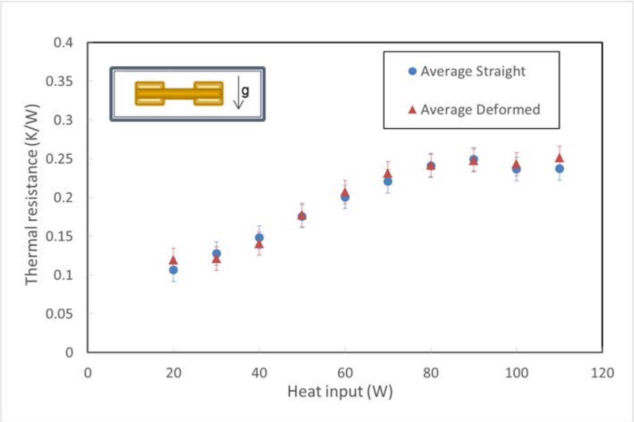


FIGURE 10: Comparing straight and deformed configuration at horizontal positioning of heat pipe at coolant temperature of 25°C.

Figure 10 shows the average thermal resistance for horizontal working condition of the heat pipe. As expected the overall thermal resistance has increased than the gravity assisted working. The substantial rise in thermal resistance in horizontal conditions is due to partial dry out which has started at some locations in the heat pipe.

To verify whether the heat pipe performs properly and stabilizes under a sudden step heat input, experiments were conducted by giving step inputs of 50 W, 60 W and 90 W, the results of which are shown in Fig. 11. It proves the fact that the design is tolerant to step inputs with no change in average thermal performance. Fig. 12 shows the stability of the heat pipe for sudden change in orientations and it is observed that steady state operating performance is restored after sudden change. Moreover at an angle of 33° with horizontal the performance is similar to that of gravity assisted working (90°).

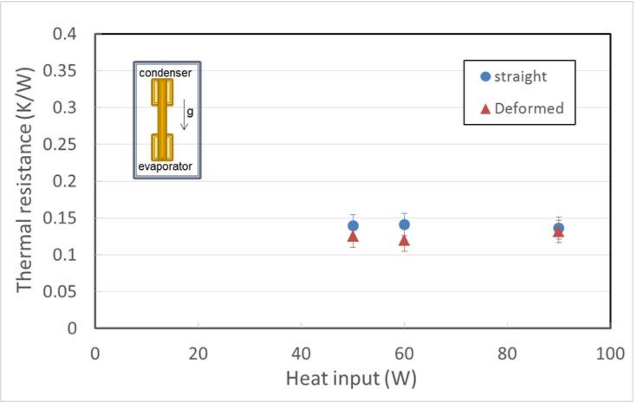


FIGURE 11: Trend for straight and deformed configuration for sudden input at vertical position at coolant temperature of 25°C.

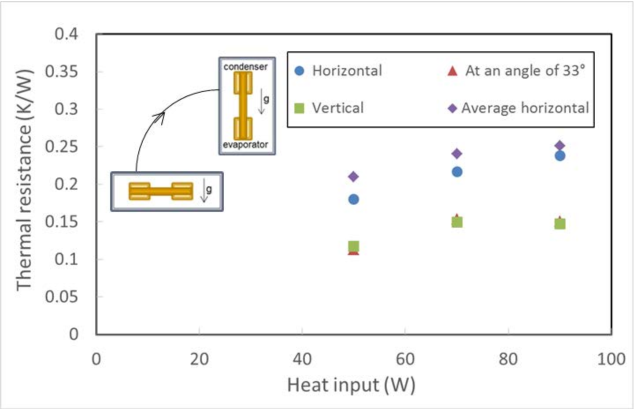


FIGURE 12: Stabilization of heat pipe while change in orientation from horizontal to vertical deformed at 7° angle at coolant temperature of 25°C.

SUMMARY AND CONCLUSIONS

The developed flexible heat pipe performs well in deformed configuration as is evident from the IR image of the adiabatic section in this configuration, which shows uniform temperature across the adiabatic section. Thermal resistance is in range of 0.1 K/W to 0.2 K/W in the operating range of heat pipe for gravity assisted working and 0.2 K/W to 0.25K/W for horizontal working, which is very low as is desired for good thermal management. It is also observed that the heat pipe can cope with sudden power inputs and position change.

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REFERENCES

[1] Dunn P.D., Reay D.A., 1976, “Heat Pipes”, Pergamon Press, Oxford,

[2] Faghri, A., 1995, “Heat Pipe Science and Technology”, Taylor & Francis.

[3] Chi S.W., 1976, “Heat Pipe Theory and Practice”, a sourcebook, Hemisphere Publishing Corporation.

[4] Hsieh S.-S., Yang Y.-R., 2013, Design, fabrication and performance tests for a polymer-based flexible flat heat pipe, Energy Conversion and Management 70 pp 10–19.

[5] Chao Yang, Chengyi Song, Wen Shang, Peng Tao, Tao Deng, 2015, Flexible heat pipes with integrated bioinspired design, Progress in Natural Science: Materials International, Volume 25(1), pp 51–57.

[6] Lü, Q., Hu, J., Cheng, D., Liu, J., Jiang, Y., 2014, Experimental study of airborne heat pipe cold plate under vibration and acceleration conditions, Journal of Nanjing University of Aeronautics and Astronautics, 46 (2), pp. 316-321.

[7] Alaei, A., Kafshgari, M.H., Rahimi, S.K., 2013, A vertical heat pipe: An experimental and statistical study of the thermal performance in the presence of low-frequency vibrations, Heat and Mass Transfer, 49 (2), pp. 285-290.

[8] Chen, R.-H., Lin, Y.-J., Lai, C.-M., 2013, The influence of horizontal longitudinal vibrations and the condensation section temperature on the heat transfer performance of a heat pipe, Heat Transfer Engineering, 34 (1), pp. 45-53.

[9] Oh, H.-U., 2011, Performance investigation of spaceborne micro-vibration isolation system combined with heat pipe cooling system, Proceedings of the International Astronautical Congress, IAC, 7, pp. 5680-5686.

[10] United States Patent US2011/0088874 by Meyer IV, 2011, titled “Heat pipe with a flexible structure”.

[11] United States Patent US2011/0220328 by Huang, 2011 titled “Flexible heat pipe and manufacturing method thereof”.

[12] Kline S.J. and McClintok F.A., 1953, Describing uncertainties in single sample experiments, Mechanical Engineering, pp. 3-8.

[13] Moffat R.J., 1982, Contributions to the theory of single sample uncertainty analysis, Tran. ASME, Journal of Fluids Engineering, Vol. 104, pp. 250-260.