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Directional sensitivity of a heat pipe under periodic thermal loading

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Abstract

Experiments were conducted on a model of a flat curved heat pipe with the purpose of investigating its performance response upon changing the pipe plane from vertical to horizontal and under periodic thermal loading applied at the evaporator side. The model consisted of a commercial laptop heat pipe firmly mounted on one end to a copper block ("Core") supplying heat by means of an electrical resistance (simulating the laptop CPU released heat) and on the other end to the cooling system of fins and centrifugal cooling fan ("Fan"). The whole system was thermally insulated in an enclosure and equipped with thermocouples monitoring the Core external wall temperature and the exhaust air temperature of the Fan. Measurements were also carried out along the heat pipe curved surface at the wall with an infrared video camera and in that case only an appropriate narrow slot was opened in the enclosure. It was found that with the same steady heat load Horizontal positioning resulted in significantly higher Core and Fan temperatures compared to Vertical positioning. Two types of unsteady tests were tried: The first, Heat On from cold, followed by Cool Down and vice versa for very long time so that steady state conditions would be reached. The time constants τ of the temperature process at the Core and the Fan were computed from those tests. In the second series of experiments square wave type periodic thermal loading was applied to the Core with periods ranging from minutes to hours. It appeared that the response resembled that of a 1st order system, including the heat pipe, and that τ increased with decreasing the cooling rate and with Horizontal layout.

1 Introduction

Heat transfer by heat pipe technology is currently present in many industrial applications where reliability, low thermal resistance, high conductivity, simplicity, compactness and space limitation indeed matter, as in spacecraft, laptop and smartphone cooling. Flat and / or bent types positively contribute to the last requirement of space limitation, Wang (2009). Accurate thermal management in transient operation is crucial in some cases like: a) die casting and injection molding industry where the controlled removal of heat with time contributes to the product quality, b) innovative hybrid starter-alternator technology in cars where the electronics components are subjected to high current cycles with fluxes in the range 60-400 W/cm^2, Harmand et al (2011), Wang and Vafai (2000), El_Genk and Huang (1993). A common feature of heat pipes is the existence of two phase flow which is working along with capillary phenomena, usually by means of a wick, and is thus affected by many factors such as gravity, surface tension and molecular properties of the working medium. Vertical orientation, with the evaporator below the condenser is generally more efficient than the horizontal orientation because the flow is gravity assisted. Modeling and experimental work have greatly contributed to the understanding and improved design of heat pipes over the last decades, Zhang (2017), Wang et al (2013), Xiao and Faghri (2008), Chao and Faghri (1992) In an effort to overcome problems in the capillary flow associated with the wick structure, the concept of Oscillating or Pulsed Heat Pipes has been introduced in the early nineties, Akachi et al (1996). In the absence of a wick, the temperature gradient between the heated and cooled ends generates a capillary slug flow.

Although the physics have not been yet well understood, research has indicated that improvements in the performance could be accomplished by selecting appropriate geometries and specialized materials for example iron oxide nanoparticles added to kerosene as a working fluid with operation under magnetic field, Goshayeshi et al (2015). They found that better performance and lower thermal resistance was attained at inclinations about 15^0 from the vertical direction. In many studies for transient operation and heat pipe plane inclination, the focus is on the behavior of the vapor inside the heat pipe El-Genk and Huang (1993). The time constants for the vapor temperature are much smaller than the time constants of the metal wall temperature of the heat pipe and generally decrease as the coolant flow rate at the condenser side increases. In the *present work* an attempt is made to *experimentally* investigate the behavior of a flat heat pipe in transient conditions and in Vertical and Horizontal inclinations, focusing attention into the temperatures of the external wall of the heat pipe and to the temperature of the exhaust air from the cooling fan, a topic which is thought to have some practical interest.

2 Experimental Set Up and Procedures

The heat pipe used was taken from a laptop. It was of bent type Rob 78C 6G, flat 7.6x3.4 mm, with evaporator length 30 mm, condenser length 72 mm, adiabatic length 110 mm, made out of copper and had water as the working medium. Heat was applied to the evaporator side via an electric resistance of power 48 W, 36 W and 24 W. The resistance was imbedded into a copper block and the heat pipe end was tightly mounted onto the block for optimum conduction of heat. A cooling fan was firmly mounted on the other end, at the condenser side, operated at flow rates Q = 2.2, 2.9, 3.7 and 4.2 l/s, removing most of the heat fed via the resistance. Thermocouples were installed on evaporator edge and the fan exit central region and their indications monitored in time would be called hereafter Θ_C or Θ_{CORE} and Θ_F or Θ_{FAN} . An enclosure made out of wood and insulating material (simulating the laptop) housed the heat pipe assembly. The system was thus thermally insulated and the energy balance was expected to hold i.e. the electrical power input to be equal to the total heat flux rate over the whole fan exit area. For the purpose of examining the heat pipe wall surface temperature distribution along the pipe length via an infrared Flir S45 video camera, a small slot opening was created having the almost a quarter sector shape of the heat pipe, which was painted black for that purpose. Measurement of the temperatures Θ_C and Θ_F with the slot opened and sealed in steady state conditions, showed differences of less than 2%, therefore the infrared temperature readings could be considered as fairly well representing the wall temperature distributions on the heat pipe of the completely insulated system, without appreciable losses. Θ_C and Θ_F were monitored with Labview platform along with two reference synchronizing time signals, when transient tests were performed. The ambient temperature Θ_{amb} was taken into account and usually temperature differences are presented.
The plane of the heat pipe was first set in the Vertical (V) direction for both steady state and transient experiments and then set to the Horizontal (H) position for similar tests. Steady state thermal equilibrium was reached either from the cool state after heat was applied for sufficiently long time, “Heat up” experiments, or from the fully heated steady state to the completely cooled down state when the heat was switched off, “Cool down” experiments. The time period during heating up or cooling down is considered as a transient, step type thermal loading. A periodic, square wave type, thermal loading was applied by switching on and off the power of the electrical resistance. The period was T and the circular frequency was $\omega = 2\pi f$ rad/s, where f is the frequency in Hz. A synchronized electrical signal was simultaneously recorded with the temperatures in order to secure phase locking of the time series for later processing.

3 Effect of Orientation on Mean Temperatures

Fig. 1 is an example of the Heat on , Steady, Cool down process. It has the classical exponential shape also encountered in similar experiments, e.g. Wang and Vafai (2000) for outside wall surface temperatures but also in Saad et al (2012), El-Genk and Huang (1993) in which the vapor temperature is examined, with time constants much smaller than those of the outside wall temperatures. Fig. 2 is a steady state image of the IR camera with the temperature scale on the right and the selected spots for the axial temperature readings through the slot. Heat is applied to the bottom right evaporator, top on the right is the fan motor location. The temperature variations with time along the selected spot locations are depicted in Fig. 3. During the

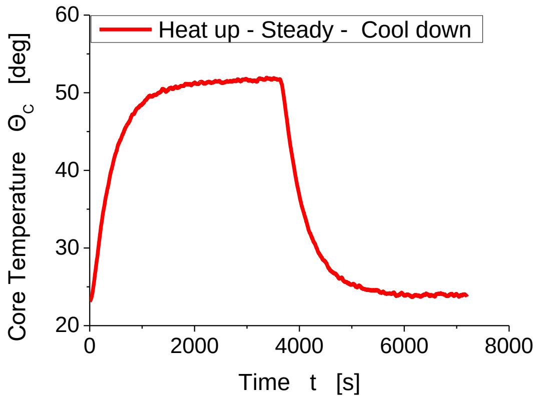


Figure 1: Heat on-Steady-Cool down process

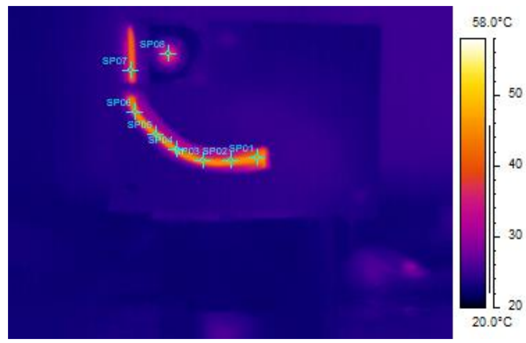


Figure 2: Spot locations, + , for IR camera readings

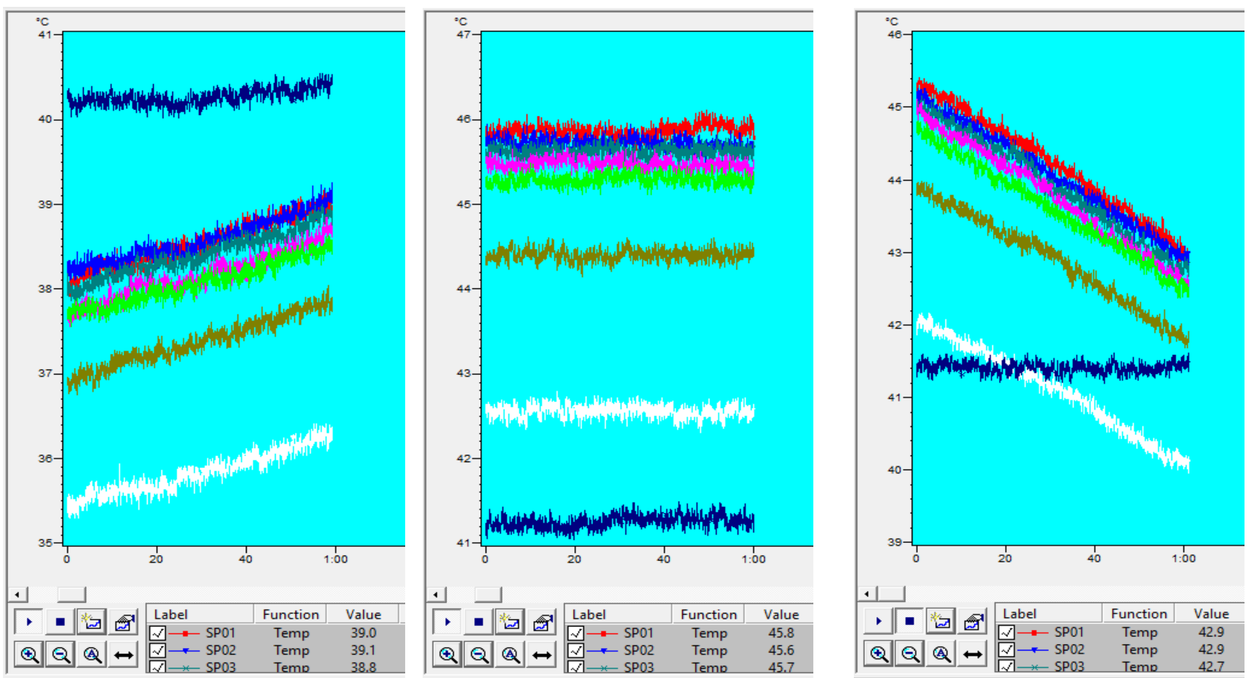
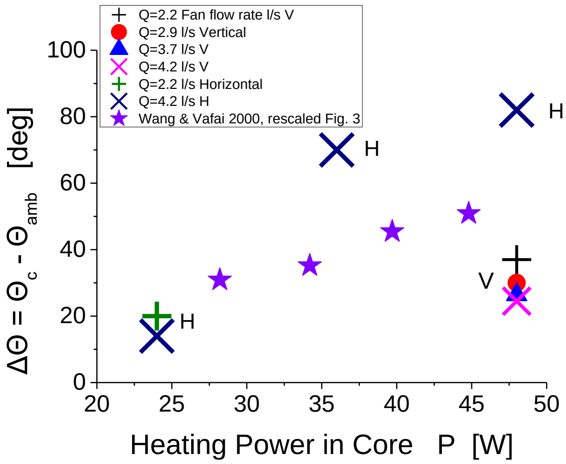


Figure 3: Temperatures on the surface along the + spots for Heat up (left), Steady (middle) and Cool down (right)

heating up stage it appears that the evaporator temperature (red color) and its closest neighbor have almost the same temperature, while at the steady state stage, with the heating power still on, and in the cool down stage when the power is switched off, there is clearly a negative axial temperature gradient along the heat pipe. The temperature of the motor of the cooling fan stays more or less at a constant temperature (deep blue line). The effect of variations in the heat power level P (W) and of tilting the heat pipe plane from Vertical (V) to Horizontal (H) on the Core temperature Θ_C is demonstrated in Fig. 4, with parameter the flow rate of the cooling fan. It is observed that the temperature of the core drops as the flow rate increases



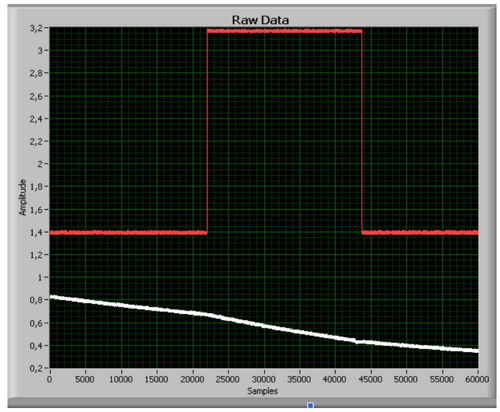


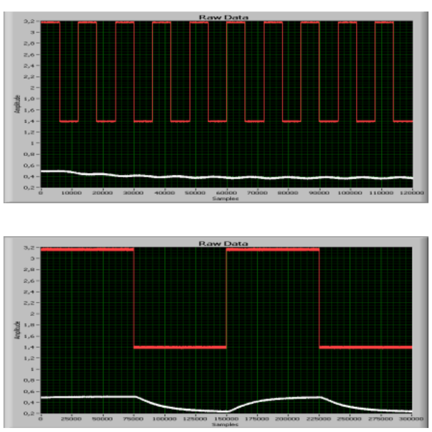
Figure 4: Effect of heating power and inclination on Θ_c

Figure 5: Cooling rate vs time in Horizontal position (left , right) and in Vertical position (middle)

indicating that the heat pipe and the fan perform as they should, for example in a real laptop with roughly the same power dissipated from its CPU. There is a dramatic increase in Θ_C when the plane is in the horizontal position, reaching unaceptable high values for a real machine, showin also that the heat pipe and the fan cannot cooperate properly. $\Delta\Theta$ is seen to increase with P as also realized in data from other workers e.g. Wang and Vafai (2000) in rescaled form. The effect of orientation in the transient phase of cooling down is also clear in Fig. 5 where the vertical V orientation in the middle of the figure exhibits the steepest temperature decline with time, as opposed to the horizontal H setting, in the left and right of Fig. 5.

4 Effect of Orientation and Periodic Thermal Loading

Fig. 6 shows raw data of core temperature time records (white lines, bottom) when the power is switched on and off periodically, the period shown by the red square wave signal on the top. Fig. 7 illustrates the



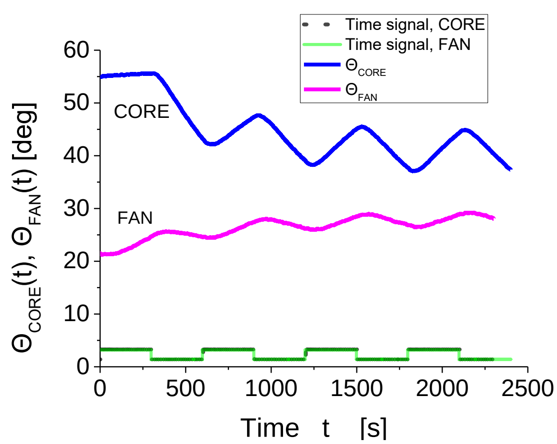


Figure 6: Θ_C vs time under periodic loading. Top, period T = 240 s, bottom, period T = 3000 s

Figure 7: Simultaneous variation of Core and Fan temperatures under periodic loading

simultaneous variation of Core and Fan temperatures Θ_{CORE} , Θ_{FAN}. High value of the red reference signal means heat is on, low value means heat is turned off, allowing the heat pipe to cool down. The test was initiated from the fully heated steady state position (left side with maximum temperature). As it occurs in a first order system responding to periodic excitation, there is an initial aperiodic behavior where the temperature decreases, followed by a periodic variation of temperature with period matching that of the excitation but of amplitude and phase depending on T (or $\omega = 2\pi/T$). If the system were intrinsically 1st order and the excitation was purely sinusoidal, then the *reduction* in amplitude, given in non-dimensional form as $F(\omega\tau)=[\Theta_{c\ top}-\Theta_{c\ bot})]/[\Theta_{c\ steady})-\Theta_{c\ in})]$, would have been $1/\sqrt{[\ 1+(\omega\tau)2\ ]}$ and the *phase difference* between the excitation and the response $\Delta\varphi$ would have been $-\arctan(\omega\tau)$. Here *top*, *bot* signify the maximum and minimum values of the response, *steady* the steady state temperature with heat on an *in* the final steady state temperature when the system is allowed to fully cool down ("initial condition"). The time constant τ was computed from temperature time records of Θ_C like those in Fig. 1. The same procedure was followed for processing the data of the temperature of air at the center of the cooling fan, and the corresponding temperatures were $\Theta_{f\ top}$, $\Theta_{f\ bot}$ etc. $F(\omega\tau)$ and $\Delta\varphi$ for Θ_{CORE} are given in Fig. 8, the reduction factor $F(\omega\tau)$ for Θ_{FAN} in Fig. 9 and the phase difference between Θ_{CORE} and Θ_{FAN} in Fig. 10. Remarks can be made :

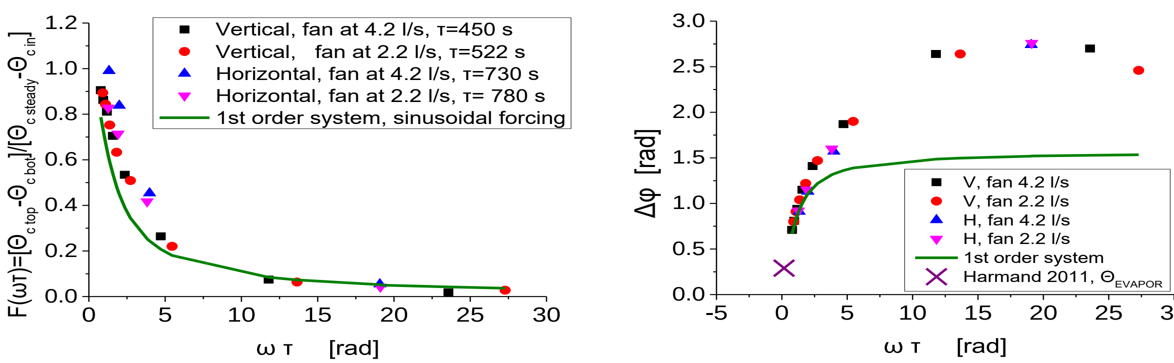
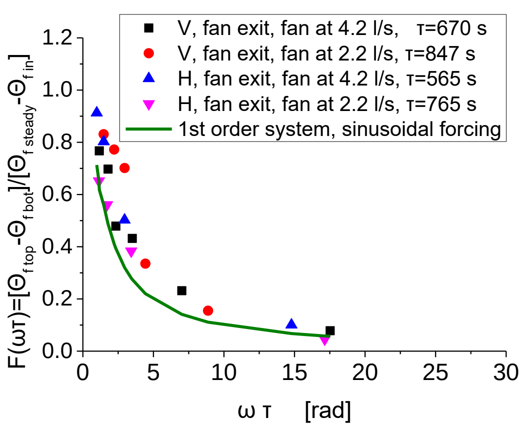


Figure 8: Core temperature amplitude reduction, left, and phase difference, right, under periodic thermal loading



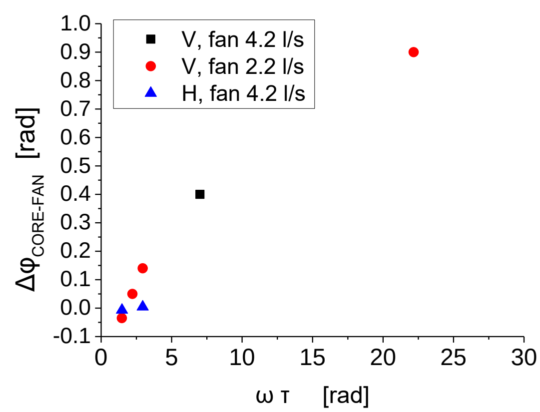


Figure 9: Fan temperature reduction with periodic load   Fig. 10: Phase difference Θ_{CORE}-Θ_{FAN} with periodic load

As the frequency $\omega\tau$ of the thermal periodic loading increases, the dynamic amplitude F of the thermal response, be it that of the Core (Fig.8) or of the Fan (Fig. 9) monotonically decreases, following fairly closely the behavior of a 1st order system in sinusoidal excitation (green solid line). The absolute value of the temperature variation difference ($\Theta_{top} - \Theta_{bot}$) is greater in the Core than in the Fan sections, Fig. 7, and is also greater for lower cooling fan flow rates (Figs 8,9). The phase difference $\Delta\varphi$ between the heat load P and the Core or Fan temperature increases with $\omega\tau$, being close to the "theoretical" value only for small $\omega\tau$, less than 5, thereafter being significantly greater, Fig.8. Literature data for comparison are only available for evaporator temperatures, such as those of Harmand et al (2011) showing similarity to our $\Delta\varphi$ variation in Fig. 8, for very low $\omega\tau$, and for the difference between the evaporator and condenser temperatures (Figs 5 and 6 of their paper), exhibiting an experimental decrease at the condenser section by about 20%. The period in their experiments is very small, 3 s, but their time constants are also very low. For Vertical orientation, the time constants τ increase with decrease in the cooling flow rate, both in the core and in the fan Figs 8, 9, as also found in El-Genk and Huang (1993). Horizontal operation causes significant increase in τ only in Θ_{CORE}, Fig.8, and also increases in $F(\omega\tau)$ for both Core and Fan areas. Finally the phase difference between the Θ_C and the Θ_F temperatures increases as $\omega\tau$ increases due to thermal inertia, Fig.10.

5 Conclusion

From a practical point of view, the present results show that cooling by means of a flat heat pipe with the evaporator below the condenser works out much better in the vertical than in the horizontal positioning of the heat pipe plane. Periodic temperature variations in the *heated end* reach the *cooling end* where the fan operates with a delay, or phase lag, which increases as the frequency of excitation increases, closely to the behavior of a 1st order system. Time constants increase with decreasing cooling flow rate. The amplitude of temperature fluctuations are greater in the horizontal layout, but they generally decrease with increasing frequency of thermal loading at the heated end.

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