# FEM Study of Velocity Profile of Flattening Heat Pipe with Multiple Heat Sources

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## Abstract

A heat pipe is a simple device that can transfer large quantities of heat over fairly long distances at nearly a constant temperature. The application of heat pipes in thermal management of electronics has increased enormously in recent years due to the limited space existing on printed circuit board (PCBs) and increasing power density. Formerly, a single heat pipe designed is used for heat transfer from both a central processing unit (CPU) and a graphics processor unit (GPU). Normally, because of the limited space for cooling, flattened heat pipes have been widely used, but the problem is that as heat pipes become thinner the heat transfer rate is reduced making it difficult to cope with smaller, thinner equipment. Thus, in this research, we numerically study the effect pipe flattening on heat transfer characteristics of miniature sintered porous media heat pipe with multiple heat sources by using Finite Element Method (FEM). The governing equations, i.e. continuity, momentum, and energy equations, and boundary conditions, were solved by using the Finite Element Method (FEM), while matrices were derived from these equations using the Galerkin approach. In the mathematical model, vapor flows are assumed to be steady, laminar flow and incompressible. The wick is assumed isotropic and saturated with the working liquid. The final flattened thickness was 2.5, 3 and 4 mm when the original diameter of the heat pipe was 6 mm. Total length of heat pipe was 200 mm. The operating temperature was 60 ºC. The model of the flattened heat pipe was composed of the evaporator section with two heaters which have distance between the heat sources were 0, 25, 50, and 75 mm, respectively. The ratios of heat input power were controlled at 10W:10W, 20W:10W and 30W:10W. It was noted that, when power input of first heater was increased from 10W to 30W, the vapor velocity increased from 21.93 to 44.24 m/s at the end of the second evaporator section due to the mass transfer of vapor was the highest. When the tubular heat pipe is flattened to 4, 3 and 2.5 mm, the vapor velocity profile highest increased were 30.16 m/s, 43.87 m/s, and 75.91 m/s, respectively. Due to the cross section area of vapor core was smaller. And, when the first evaporator section overlapped with second evaporator section (distance 0 mm), the vapor velocity increases to 42.43 m/s due to the heat accumulated from both heat sources.

**Keywords:** finite element method, flattened heat pipe, final thickness, multiple heat sources

## Introduction

The heat pipe is a simple device of very high thermal conductance. It can transmit heat at high rate over considerable distances with extremely small temperature drop. The decreasing size of electronic devices and their increasing power has led to the need for higher heat fluxes to be dissipated in a small space. Heat pipes are also attracting more and more attention as promising devices to meet electronic cooling requirements. This is due to the ability of heat pipes to transfer large amounts of heat over long distances at low temperature drops[1]. Recently, most electronic equipment tends to be thinner and lighter, so a heat pipe, which is used as thermal solution to cool down heat source, needs to be thinner and lighter too. But heat pipes have unfavorable features that thermal performance becomes worse when heat pipe is flattened. When heat pipe is flattened, pressure drop originated in vapor and liquid flow are increased remark-

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ably because of narrow space for vapor and liquid flow[2-3]. Conventionally, heat pipe has been installed on each heater individually. However recently, only one heat pipe may be installed on multiple heaters[1,4].

Many studies for heat pipe with multiple heat sources have been performed by Chen and Faghri[5] they investigated the behavior of heat pipe with two heat sources. Faghri and Buchko[6] studied the dry-out condition of the heat pipe with four heat sources. In reviews of above literature, researches were mostly limited to fixed multiple heat sources and could not even cover the heat source on flattened heat pipe. In this research, we studied the Velocity Profile of Flattening Heat Pipe with Multiple Heat Sources using the Finite Element Method (FEM).

## Materials and Methods

In this study, the mathematical model of heat pipe was established by using the finite element method. Assumptions of mathematical model simulation were shown as follows, to find vapor velocity, pressure and temperature.

- The working fluid was Newtonian fluid.
- Wick was saturated with liquid.
- The vapor was incompressible and had laminar flow
- Flow and heat transfer were at a steady state.

### 1. Governing equations

The governing equations in the vapor core region include the conservation of mass, momentum and energy equations as follows :

Conservation of mass equation:

$$\frac{\partial u_v}{\partial x} + \frac{\partial u_v}{\partial y} + \frac{\partial u_v}{\partial z} = 0 \qquad (2)$$

Momentum equation:

$$0 = -\frac{\partial P_v}{\partial x} + 2\mu_v \frac{\partial^2 u_v}{\partial x^2} + \mu_v \left( \frac{\partial^2 u_v}{\partial y^2} + \frac{\partial^2 u_v}{\partial z^2} + \frac{\partial^2 v_v}{\partial x \partial y^2} + \frac{\partial^2 w_v}{\partial x \partial z^2} \right) \qquad (2)$$

$$0 = -\frac{\partial P_v}{\partial y} + 2\mu_v \frac{\partial^2 v_v}{\partial y^2} + \mu_v \left( \frac{\partial^2 u_v}{\partial x \partial y^2} + \frac{\partial^2 v_v}{\partial y \partial z^2} + \frac{\partial^2 v_v}{\partial x^2} + \frac{\partial^2 w_v}{\partial y^2} \right) \qquad (3)$$

$$0 = -\frac{\partial P_v}{\partial z} + 2\mu_v \frac{\partial^2 w_v}{\partial z^2} + \mu_v \left( \frac{\partial^2 u_v}{\partial x \partial z^2} + \frac{\partial^2 v_v}{\partial y \partial z^2} + \frac{\partial^2 w_v}{\partial x^2} + \frac{\partial^2 w_v}{\partial y^2} \right) \qquad (4)$$

Conservation of energy includes conductive and convective heat transfer of fluid flow.

In vapor core:

$$\rho_v C_{v,v} \left( u_v \frac{\partial T_v}{\partial x} + v_v \frac{\partial T_v}{\partial y} + w_v + \frac{\partial T_v}{\partial z} \right) = k_v \left[ \frac{\partial^2 T_v}{\partial x^2} + \frac{\partial^2 T_v}{\partial y^2} + \frac{\partial^2 T_v}{\partial z^2} \right] \qquad (5)$$

In wick and wall:

$$0 = k_{eff} \left[ \frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} + \frac{\partial^2 T_s}{\partial z^2} \right] \qquad (6)$$

The governing equations in wick and wall regions were the steady state heat conduction equations. Therefore, the convective heat transfer was neglected in the wick region.

### 2. Boundary conditions

The boundary conditions of the vapor flow in flattened heat pipe were observed that at the liquid-vapor interface, a non-slip condition $(u_v = v_v = w_v = 0)$ was assumed. The heat input of each heater was received by evaporation at liquid-vapor interface in each evaporation section. Total heat output $(Q_{HT1}, Q_{HT2})$ was released by condensation at liquid-vapor interface in the condenser section. Then, the average vapor velocity of flattened heat pipe with double heat sources was given as follows:

Evaporator section:

$$v_{e,1} = \frac{Q_{HT1}}{\rho_v \times W_s \times L_{e,1} \times h_{fg}} \tag{7}$$

$$v_{e,2} = \frac{Q_{HT2}}{\rho_v \times W_s \times L_{e,2} \times h_{fg}} \tag{8}$$

Condenser section:

$$v_c = \frac{Q_{HT1} + Q_{HT2}}{\rho_v \times W_s \times L_c \times h_{fg}} \tag{9}$$

Where:

$Q_{HT1}, Q_{HT2}$ = Heat power input, W

$v_{e,1}, v_{e,2}$ = Average vapor velocity at evaporator section, m/s

$v_e$ *= Average vapor velocity at condenser section, m/s*

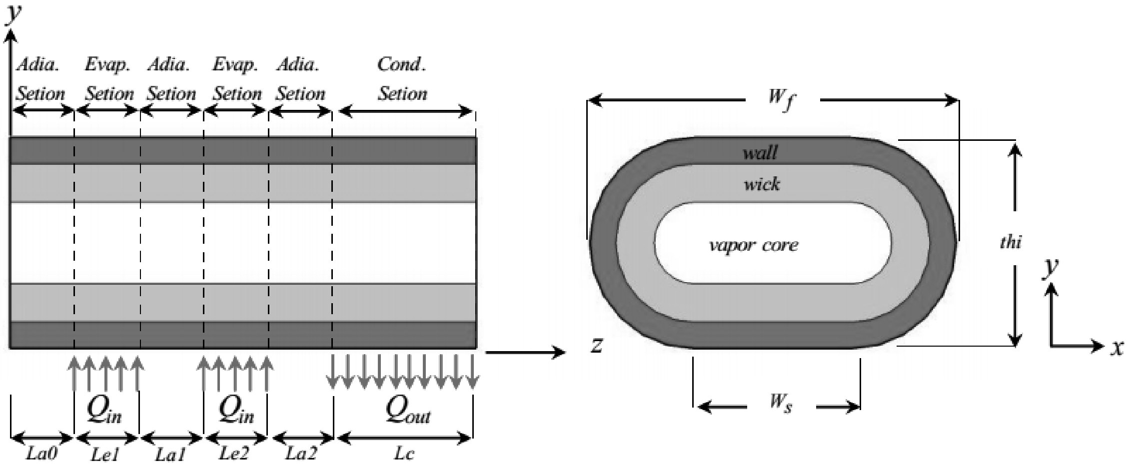


**Figure 1** Schematic of a flattened heat pipe and the coordinate system

The specifications of the heat pipes used are shown in (Table 1.) the outside diameter and the total length of the heat pipe were 6 mm and 200 mm, respectively. The lengths of the evaporator section, and condenser section, were 15 mm, and 70 mm respectively. Water is chosen as the working medium. The wick and wall are made of copper. The wick porosity of 0.57 with the voids being saturated with water. The thickness of the wick is 0.70 mm. The thickness of the wall is 0.30 mm. The effective thermal conductivities of the composite wick and copper are 5.97 W/mK and 400 W/mK, respectively. The operating temperature is controlled at 60 °C. $W_f$ is the wide of flattened heat pipe, this is the final thickness of flattened heat pipe, $W_s$ is the width of surface that contacted the heat source or heat sink. In this study, the final thickness of flattening heat pipe was 2.5, 3 and 4 mm. The method for solving equations started from generating the grids of domains. Next, the governing equations are solved by using the FEM. The conservation of mass, and momentum energy equations in equation (1) to equation (4) are solved in the vapor core region. Finally, the vapor velocity distribution of the flattening heat pipe is obtained.

**Table 1** Specifications of heat pipe used for model verification.

| Specification | value |
|---|---|
| Container material | Copper |
| Wick material | Copper |
| Wick type | Groove + Powder sintered wick |
| Working fluid | Water |
| Total length | 200 mm |
| Outside diameter | 6 mm |
| Number of heaters | 2 |
| Evaporator length | 15 mm |
| Condenser length | 70 mm |
| Wick porosity | 0.57 |
| Wick thickness | 0.70 mm |
| Wall thickness | 0.30 mm |
| Effective thermal conductivity of wick | 5.97 W $m^{-1}K^{-1}$ |
| Effective thermal conductivity of copper | 400 W $m^{-1}K^{-1}$ |
| Operating temperature | 60 °C |

The uniform temperature condition $(T_v=T_l)$ was assumed at the liquid-vapor interface, in both the evaporator and condenser sections. The temperature at this interface is equal to the saturated temperature of vapor pressure $(T_v=T_l=T_{sat@Pv})$. At both pipe ends, the insulatedboundary condition was assumed $(\partial T_v / \partial n=\partial T_l / \partial n=\partial T_s / \partial n)$ and the fluid velocity wasequal to zero $(u_v = u_l = v_v = v_l)$. The end of the evaporator section was defined to be a reference by setting the reference temperature to be equal to the operating temperature of the heat pipe.

The reference pressure was also assumed to be equal to the saturated pressure at the operating temperature $(p_v=P_{sat@Tv})$. At the wick-wall interface, the non-slip boundary condition was assumed $(u_v= v_v = 0)$, and the following energy balance was at the interface, $k_s(\partial T/\partial n)|_{wall} = k_{eff}(\partial T/\partial n)|_{wick}$. At the outer wall of heat pipe, the evaporator section was uniformly heated and the condenser section was cooled by heat sink with fan. Then, the boundary condition at the outer wall in the evaporator, the adiabatic, and the condenser section can be given by $q_{in} = k_s(\partial T/\partial n)|_{wall}, (\partial T/\partial n)|_{wall} = 0 \text{ and } q_{out} = k_s(\partial T/\partial n)|_{wall}$, respectively.

## 3. The numerical procedure

The numerical procedure is illustrated in (Figure 2). The conservation equations and conditions were solved using the FEM, while matrices were derived from these equations using the Galerkin approach. The overall numerical procedure for the investigated problem is:

1. Specify geometric dimensions, thermo-physical properties, initial conditions, and boundary conditions in the interfaces.
2. The simulation program generated the grids.
3. The pressure and the velocity distributions in the vapor core were then calculated from the equation of continuity and the momentum equations.

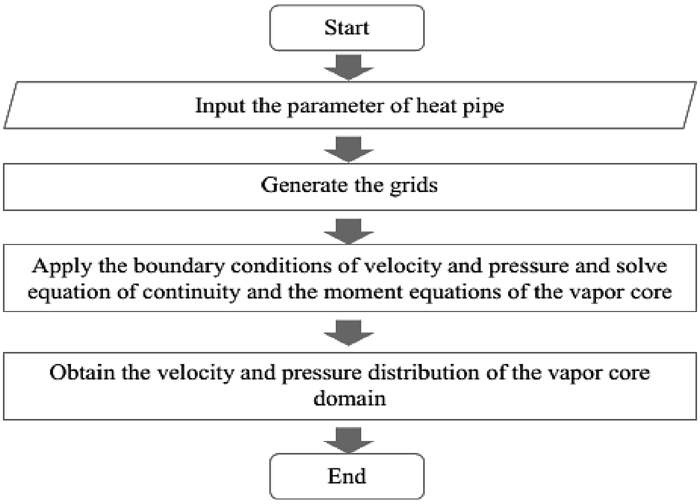


**Figure 2** Schematic diagram of the numerical procdure

## Results and Discussion

### 1. Effect of power input patterns on velocity

The effect of power input pattern is obtained by setting two different heater inputs at different positions. Vapor velocity profile in vapor core of three different power input patterns, i.e., 10W:10W, 20W:10W, and 30W:10W, (Heater 2 is fixed at 10W) is shown in (Figure 3) The vapor velocity was zero at the end of the heat pipe before entering the evaporator section. And the vapor velocity was increased through the first evaporator section. Vapor velocity was constant at the adiabatic section. The speed was increased again when entering the second evaporator section until it reached the end of this evaporator section and the highest vapor velocity was found in this position. After that, vapor velocity was maintained along the adiabatic section. Then, vapor flows to the condenser section resulting in vapor velocity being reduced to zero at the end of the heat pipe, because of the lower temperature of the condenser section. Finally, working fluid was condensed to liquid phase.

The differences of vapor velocity in three cases, i.e., 10W:10W, 20W:10W and 30W:10W. It was note that, when power input of heater 1 was increased from 10W to 30W, the vapor velocity increased from 21.93 to 44.24 m/s at the end of the second evaporator section due to the mass transfer of vapor was the highest.

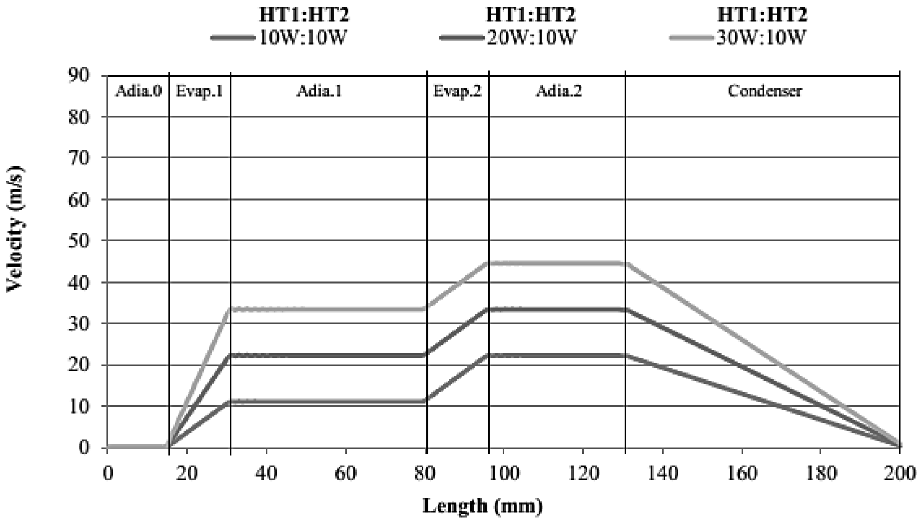


**Figure 3** Longitudinal velocity profiles at different power input patterns (distance between heaters=50 mm, final thickness=3 mm)

### 2. Effect of pipe flattening on vapor velocity

(Figure 4) shows the vapor velocity profile along the length of the heat pipe. The velocity profile was shown in three different final thickness, i.e., 4, 3 and 2.5 mm. Power input of each heater was set at 20W. Distance between heaters is 50 mm. The longitudinal vapor velocity of 2.5 mm final thickness was the highest velocity as shown in (Figure 4) It was noted that the velocity would gradually increase from the end of both heaters. The vapor velocity was both constant at the adiabatic section and gradually decreased from beginning to the end of condenser section. The maximum vapor velocity along heat pipe length was found at center vapor core of the flattened heat pipe. The maximum vapor velocity of the final thickness of 4, 3 and 2.5 mm were found to be equal to 30.16 m/s, 43.87 m/s, and 75.91 m/s, respectively. It was observed that the maximum vapor velocity within vapor core at final thickness of 2.5 mm due to the cross section area of vapor core was smaller.

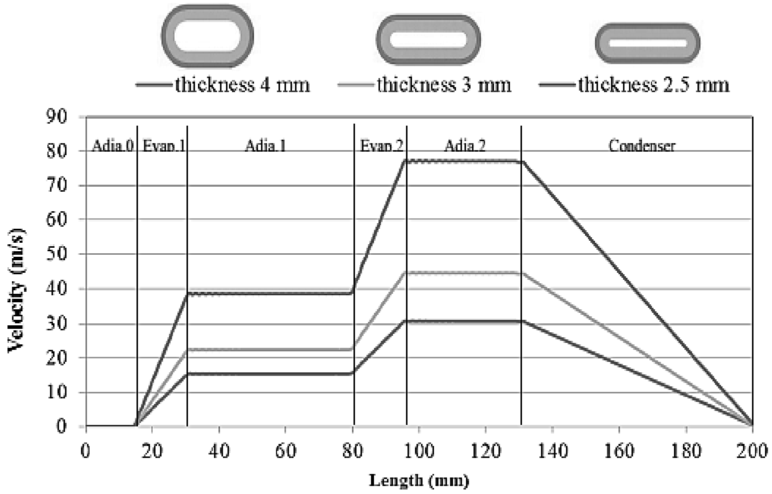


**Figure 4** Longitudinal velocity profiles at vapor core of flattened heat pipe (power input each of heater=20 W, distance between heaters=50 mm)

### 3. Effect of distance between two heaters on velocity

(Figure 5) shows the vapor velocity at longitudinal position of different distance between heaters. The vapor velocity profile was shown in four different distances between two heaters, i.e., 0, 25, 50 and 75 mm. Power input of each heater was set at 20 W. It was found that, when first evaporator section overlapped with second evaporator section (distance 0 mm), the vapor velocity increases to 42.43 m/s due to the heat accumulated from both heat sources. When distance between two heater increased from 0 to 75 mm. Maximum speed within the vapor core at about 44.43 m / s due to the amount of power supplied to the constant. As a result, the highest vapor velocity of each case was also approximately 44 m/s at the center of a vapor core.

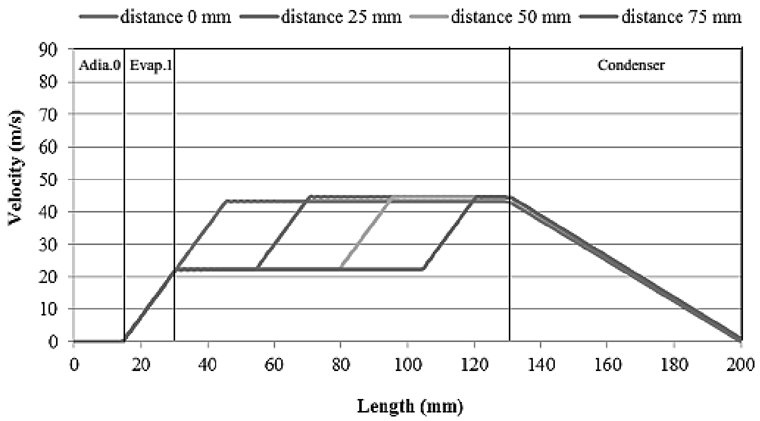
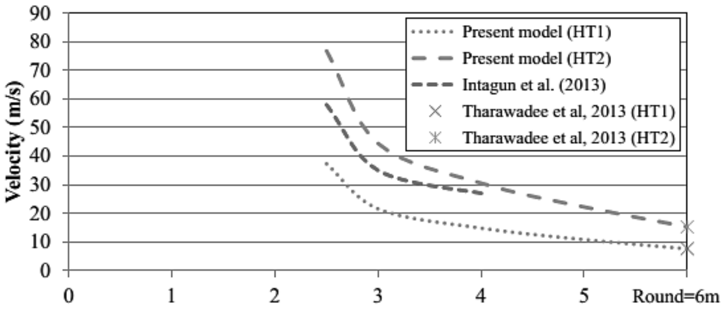


**Figure 5** Vapor velocity profiles at various distances between two heaters (power input each of heater=20 W, final thickness=3 mm)

4. **Comparison of Present Model Results**



Flattened thickness (mm)

**Figure 6** Vapor velocity profiles at various distances between two heaters (power input each of heater=20 W, distance between heaters=50 mm)

From (Figure 6), the x-axis is the flattened thickness and the y-axis is the velocity. Power input of each heater was set at 20 W. Distance between heaters is 50 mm. It was noted that, when the flattened thickness was increased from 2.5 mm to 6 mm, the velocity was decreased due to when the cross-section area of heat pipe was increased, heat load easily transferred to the condenser section because of the larger size of vapor core. The trend of velocity profile from this present model agreed with Tharawadee *et al*.[7] and Intagun *et al*.[3]

## Conclusion

The conclusions of this research are as follows.

- The mathematical model using the Finite Element Method to predict velocity have been established.
- Power input of heater 1 increases had been increased from 0 to 30 W; the vapor velocity increased from 21.93 to 44.24 m/s at the end of the second evaporator section.
- When heat pipe was flattened to the smaller final thickness, the cross sectional area of vapor core was reduced resulting in the highest vapor velocity along heat pipe length. The highest vapor velocity of the final thickness of 2.5 mm were approximately 75.91 m/s, which it was higher than final thickness of 4 and 3 mm.
- When the distance between heaters increases from 0 to 75 mm, the vapor velocity will slightly increases was approximately 44 m/s at the end of the second evaporator section.

The trend of vapor velocity from this mathematical model agreed with Tharawadee et al,$^{7}$.

## Acknowledgement

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