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Full Length Research Paper

Experimental determination of entropy generation in flat heat pipes

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Heat pipe is a thermodynamic device which transfers heat over considerable distances with a very small temperature drop. Entropy generation can be considered as a significant parameter on heat pipe performance. Major reasons for entropy generation in a heat pipe system are temperature difference between cold and hot reservoirs, frictional losses in the working fluid flows and vapor temperature/pressure drop along heat pipe. The present objective is to estimate the entropy generation in a two dimensional flat heat pipe. An experimental set up is fabricated for the analysis of the transient operation of a flat heat pipe. The entropy generation depends on both temperature and velocity distributions. The analysis involves the measurement of vapor temperature and vapor velocity and using the obtained temperature and velocity distributions, entropy generation rate is calculated.

Key words: Heat pipe, entropy generation, transient analysis, second law of thermodynamics.

INTRODUCTION

A heat pipe is a simple device of very high thermal conductance. It can transmit heat at high rate over considerable distance with extremely small temperature drop (Bejan, 1982). The design of heat pipes is simple and it is easy to manufacture. Its maintenance is also easy. Heat pipes have found various applications including energy conversion systems, cooling of nuclear reactors and electronic components, etc.

A conventional heat pipe has three sections; (1) the evaporator where heat is added to the system, (2) the condenser where heat is rejected from the system and (3) the adiabatic section which connects the evaporator and condenser, serving as a flow channel. The working fluid inside the heat pipe undergoes a thermodynamic cycle which generates entropy. The entropy generation in a heat pipe is due to frictional losses in the flow of working fluid and heat transfer across a finite temperature difference. The entropy generation rate can be used to quantify the irreversibility of the system which is directly related to the lost work during any process.

A large number of theoretical and experimental studies on heat pipes have been reported over past few decades. Cotter (1965) analyzed the laminar, steady, incompressible one-dimensional vapor flow in a cylindrical heat pipe. Bankston and Smith (1973) presented the solutions for the axisymmetric Navier-Stokes equations for steady laminar vapor flow in circular heat pipes with various evaporator and condenser lengths. Numerical calculations of the vapor flow in a flat heat pipe were presented by Van Ooijen and Hoogendoon (1981). The pressure profiles along the vapor channel of a flat heat pipe were experimentally found by Van Ooijen and Hoogendoon (1981). Numerical analysis of the vapor flow in a double walled concentric heat pipe was presented by Faghri (1986). Chen and Faghri (1990) studied the overall performance of the heat pipe with single or multiple sources of heat. A transient two dimensional analysis of the vapor core and wick regions of a flat heat pipe was performed by Unnikrishnan and Sobhan (1997).

Vasilev and Konev (1990) presented a thermodynamic analysis based on the assumption of constant vapor pressure along heat pipe. Rajesh and Raveendran (1994) developed an optimum design of heat pipe using nonlinear programming technique. Khalkali et al. (1999) presented the entropy generation in a heat pipe system. They developed a thermodynamic model of conventional

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heat pipe based on the second law of thermodynamics. A detailed parametric analysis was presented in which the effects of various heat pipe parameters on entropy generation were examined.

This paper aims at finding the entropy generation developed by thermodynamic irreversibility for a two dimensional flat heat pipe. It is seen that the entropy generation can be quantified in terms of velocity and temperature distributions of both liquid and vapor flow.

The three major factors causing entropy generation in a heat pipe are (1) temperature difference between hot and cold reservoirs (attached to the evaporator and condenser outer surfaces), (2) temperature drop in the vapor flow and (3) frictional losses associated with the vapor and liquid flows of working fluid in the heat pipe.

ANALYSIS OF HEAT PIPE

The heat pipe consists of an evacuated chamber, the interior of which is lined by a capillary structure saturated with a working fluid. The heat is essentially transferred as latent heat by evaporating the liquid working substance in a heating zone called evaporator and condensing the vapor in a cooling region called condenser. The circulation is completed by the return flow of the condensate to the evaporator through the wick under the driving action of capillary forces. This process will continue as long as the flow passage for the working fluid is not blocked and a sufficient capillary pressure is maintained. Due to this heat transfer and fluid flow between the reservoirs, entropy is generated and is formulated thus.

Entropy generation

The volumetric rate of entropy generation in a convective heat transfer problem is given as:

$$S^{III}{}_{gen} = \left(\frac{K}{T^2}\right)(\nabla T)^2 + \left(\frac{\mu}{T}\right)\phi \qquad (1)$$

where the first term represents the entropy generation due to heat transfer and second term, entropy generation due to fluid flow friction.

For a two dimensional flow, the entropy generation equation becomes:

$$\mathrm{S}^{\mathrm{III}}{}_{\mathrm{gen}} = \left(\frac{\mathrm{K}}{\mathrm{T}^2}\right)\left(\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2\right) + \left(\frac{\mu}{\mathrm{T}}\right)\left\{2\left(\left(\frac{\partial \mathrm{u}}{\partial \mathrm{x}}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2\right) + \left(\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right)\right\} \qquad (2)$$

So, for obtaining the entropy generation rate, the velocity and temperature distributions of both vapor and liquid flow in a heat pipe are required.

THE PHYSICAL MODEL

An experimental model for analyzing the transient and steady state performance of a flat heat pipe system is presented. An experimental set up of heat pipe was fabricated. The experimental set up consists of two stainless steel flat plates as container material and three layers of stainless steel wire mesh as wick structure. The aim is to measure the temperature and pressure of the working fluid at different locations along the axial direction of heat pipe for different heat inputs. The temperature was measured at 10 min time interval until steady state is achieved. Experiments were carried out with water and acetone as working fluids. Other details of the tested heat pipe are: length of evaporator = 85 cm, length of adiabatic section = nil, length of condenser section = 15 cm (overall length = 100 cm) width = 5 cm and thickness = 1 cm. Calibrated thermocouples (8 numbers) are used to measure the temperature of the vapor along the axial direction of heat pipe. Heat pipe is provided with solar heating with the help of a parabolic collector. A pyranometer is employed to measure the solar radiation.

A wick porosity of 0.65 is used in the present analysis with the voids assumed to be saturated with water. The temperature and pressure characteristics of the heat pipe were obtained by using both the working fluids in the heat pipe system. Using the obtained velocity and temperature distributions, entropy generation rate due to vapor and liquid flows were estimated.

RESULTS AND DISCUSSIONS

Transient and steady state results from the experimental analysis are discussed here. The important results of analysis are the distributions of the velocity components, pressure, temperature, and entropy generation rate in the heat pipe. Figures 1, 2, 3 and 4 represent the axial distribution of vapor temperature along the centerline of vapor core at different time instants for heat inputs of 40, 50, 60 and 70 W, respectively when water is the working fluid. As expected, the temperature increases at the beginning portion of the evaporator and then decreases.

This is because the solar radiation is more concentrated on the beginning of the evaporator section. The variation of vapor temperature along the centre line of the vapor core with acetone as the working fluid for heat inputs of 50, 60 and 70 W are shown in Figures 5, 6 and 7. The nature of variation is similar to that of water but magnitude of temperature is less. Figures 8, 9, 10, 11 and 12 show the steady state vapor temperature variation for different heat inputs with water and acetone were the working fluids. Figures 13, 14, 15 and 16 represent the variation of vapor velocity along vapor core for heat inputs of 40, 50, 60 and 70 W with water as working fluid. The steep increase in velocity along the evaporator section is due to the mass addition into the vapor core. At

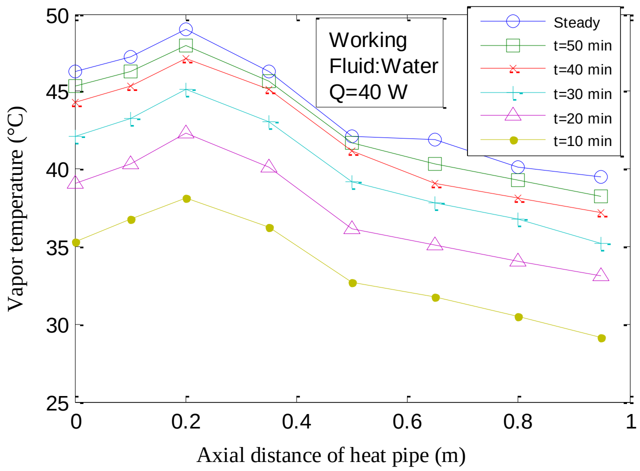

Figure 1. Variation of vapor temperature with axial length of heat pipe.

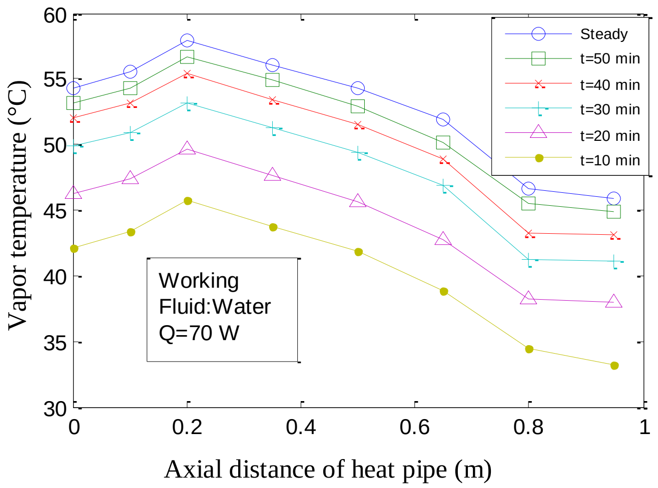

Figure 4. Variation of vapor temperature with axial length of heat pipe.

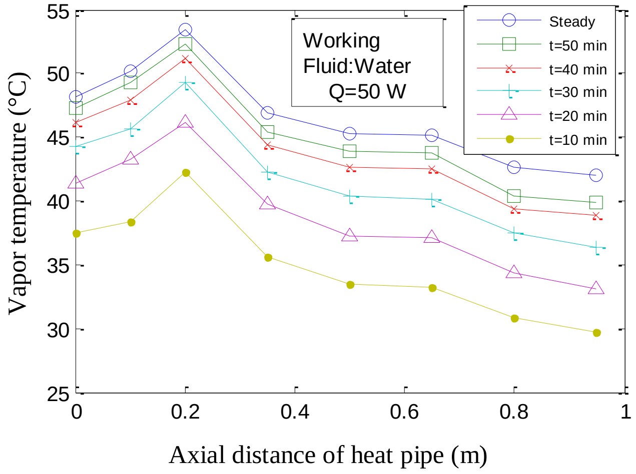

Figure 2. Variation of Vapor temperature with axial length of heat pipe.

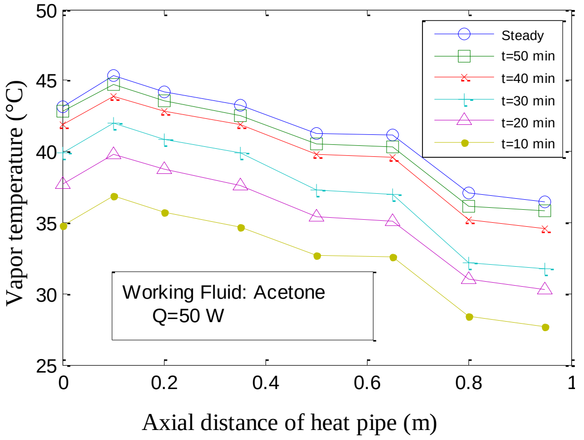

Figure 5. Variation of Vapor temperature with axial length of heat pipe.

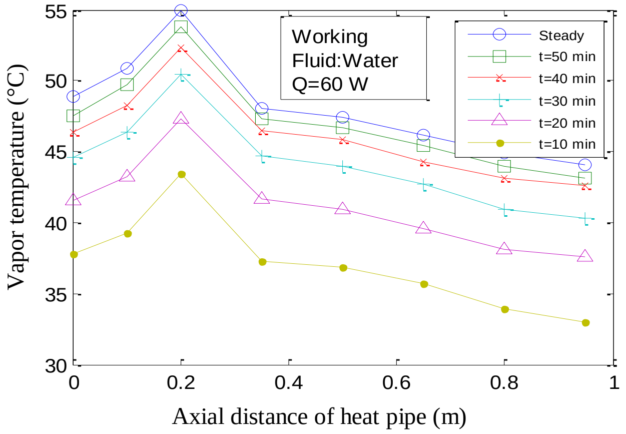

Figure 3. Variation of Vapor temperature with axial length of heat pipe.

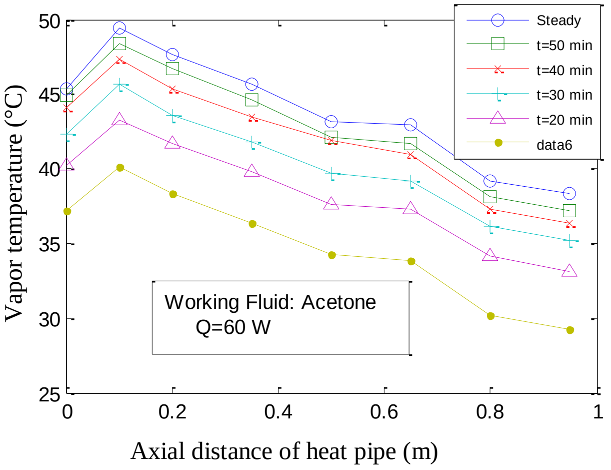

Figure 6. Variation of Vapor temperature with axial length of heat pipe.

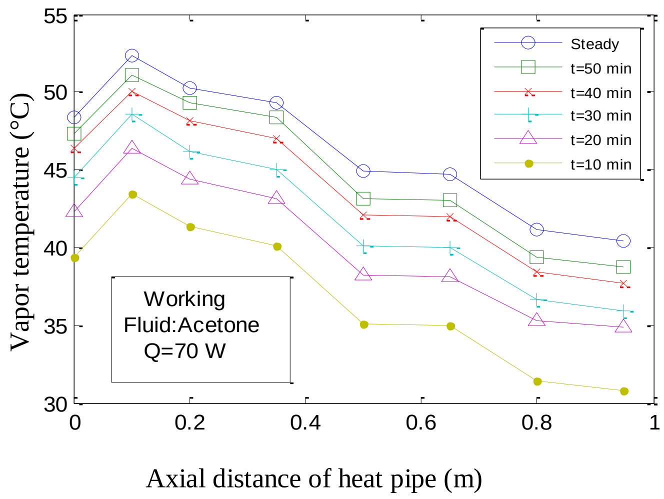

Figure 7. Variation of Vapor temperature with axial length of heat pipe.

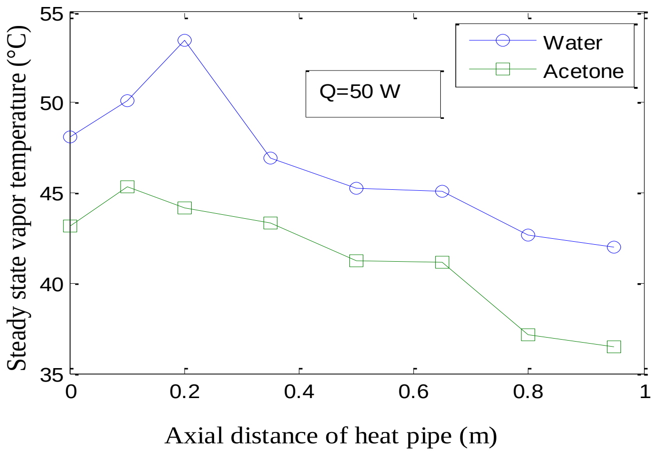

Figure 10. Variation of Steady State Vapor temperature with axial length of heat pipe.

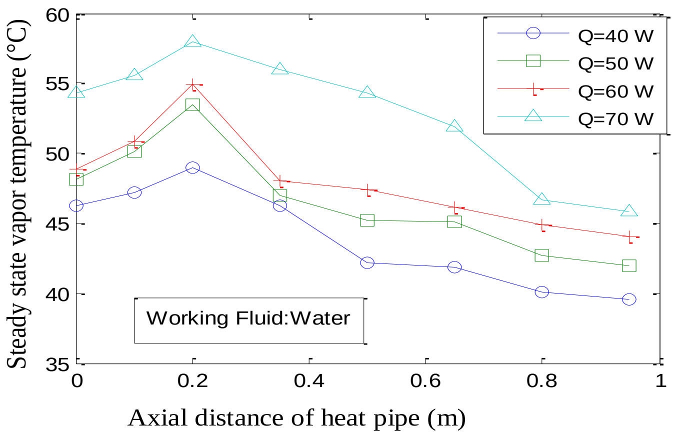

Figure 8. Variation of Steady State Vapor temperature with axial length of heat pipe.

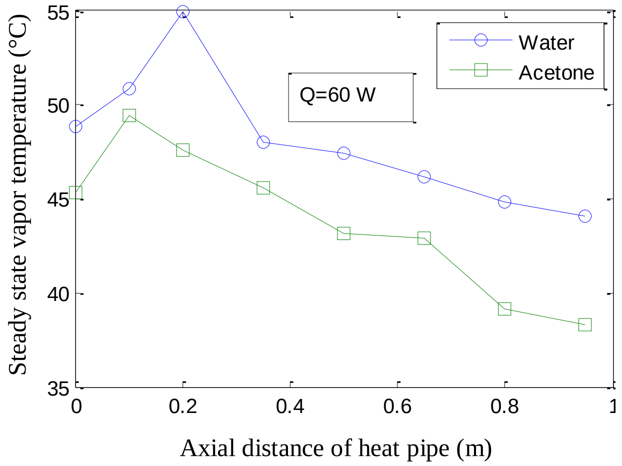

Figure 11. Variation of Steady State Vapor temperature with axial length of heat pipe.

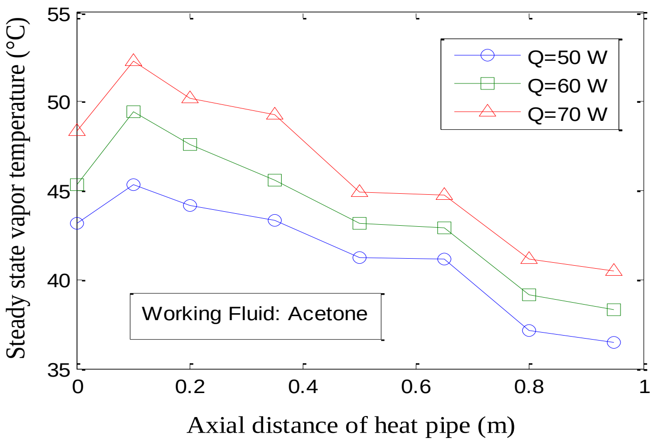

Figure 9. Variation of Steady State Vapor temperature with axial length of heat pipe

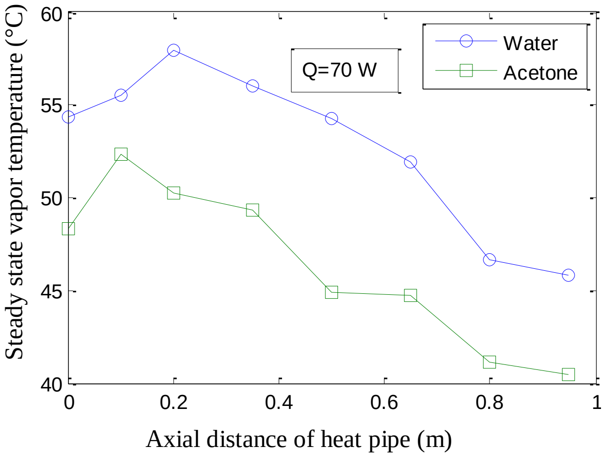

Figure 12. Variation of Steady State Vapor temperature with axial length of heat pipe.

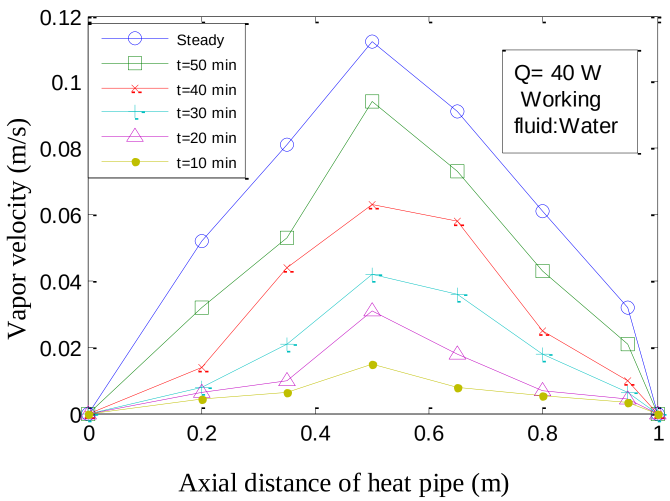

Figure 13. Variation of vapor velocity with axial length of heat pipe.

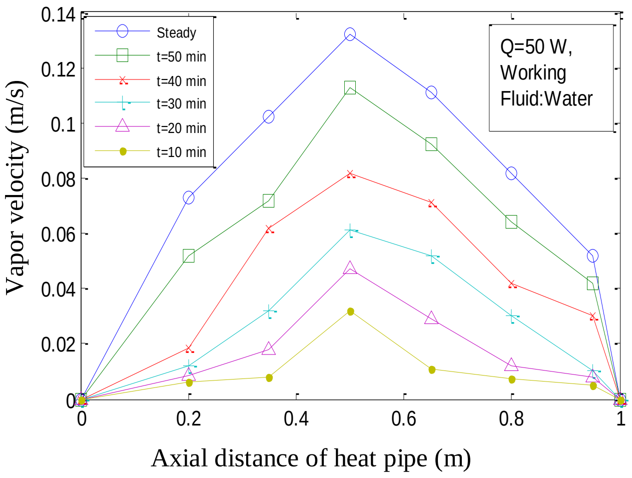

Figure 14. Variation of vapor velocity with axial length of heat pipe.

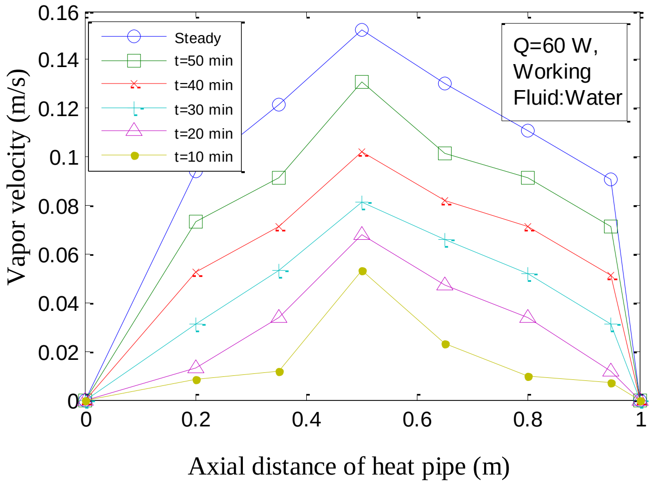

Figure 15. Variation of vapor velocity with axial length of heat pipe.

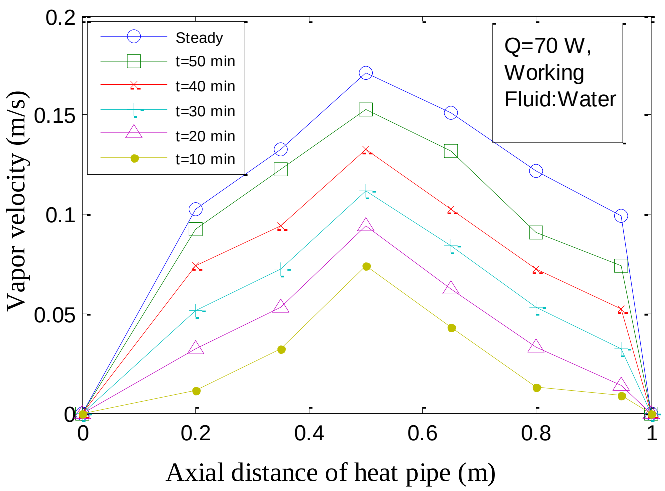

Figure 16. Variation of vapor velocity with axial length of heat pipe.

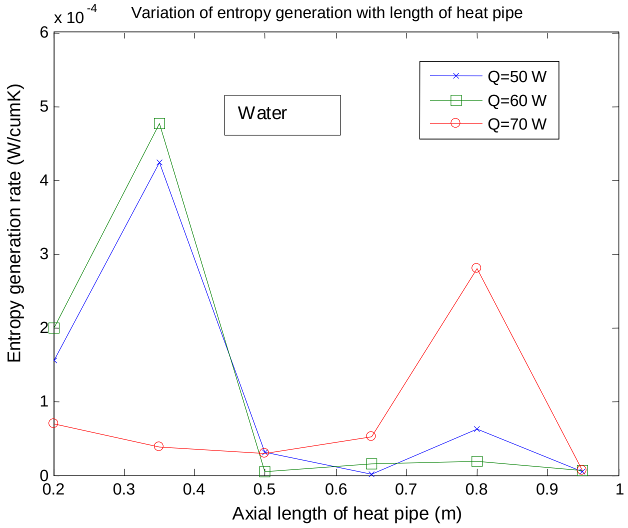

Figure 17. Variation of entropy generation rate with axial length of heat pipe.

the adiabatic and condenser sections the velocity is found to be decreasing. The rate of decrease is less at the adiabatic section. The steep decrease in velocity at the condenser section is due to high rate of mass transfer from vapor core into the wick as a result of condensation. Figures 17 and 18 show the variation of entropy generation due to vapor flow when water and acetone are the working fluids; it shows an irregular variation of entropy generation rate, since the temperature gradient along the length of the heat pipe is not varying uniformly. Figures 19 and 20 show the variation of thermal conductance with heat input for different working fluids, that is, water and acetone. It is found that the thermal conductance increases with heat load, as a result of more rate of increase in heat input compared to rate of

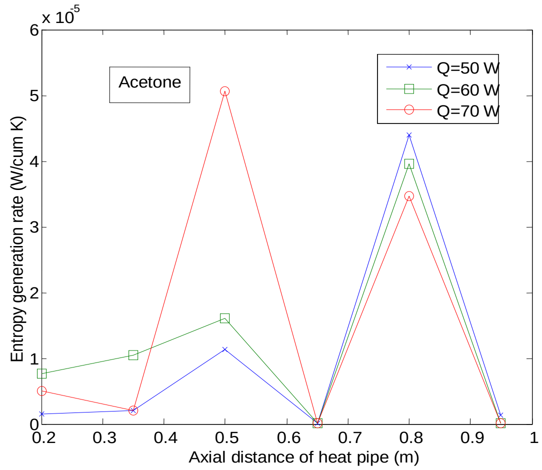

Figure 18. Variation of entropy generation rate with axial length of heat pipe.

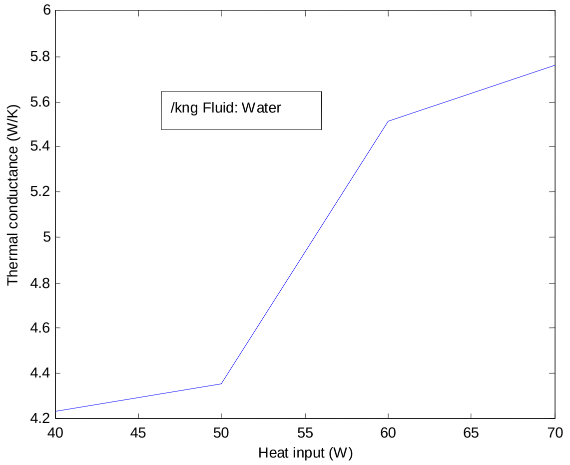

Figure 19. Variation of thermal conductance with axial length of heat pipe.

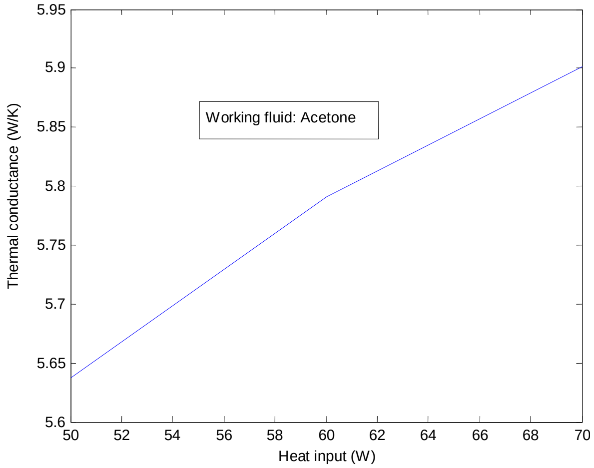

Figure 20. Variation of thermal conductance with axial length of heat pipe.

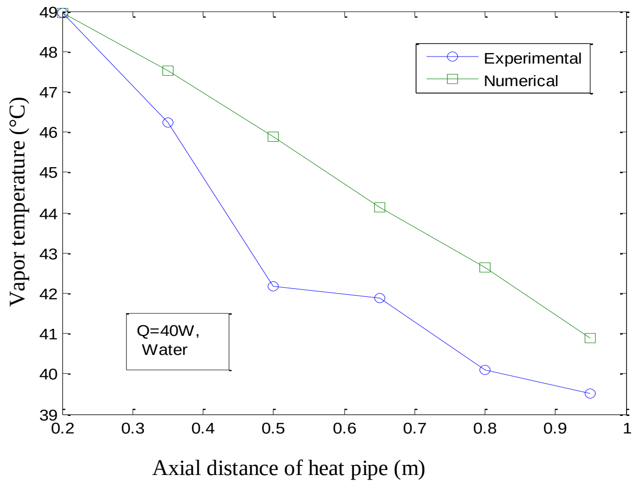

Figure 21. Comparison of experimental and numerical methods (Vapor temperature).

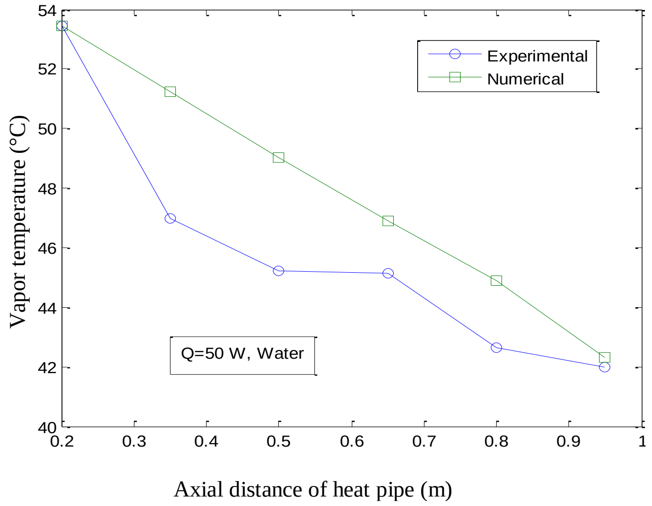

Figure 22. Comparison of experimental and numerical methods (Vapor temperature).

increase in temperature gradient. Figures 21 and 22 show the comparison of vapor temperature obtained by experimental and numerical methods for water for different heat inputs. It is found that both the results are matching. Figures 23 and 24 show the comparison of vapor temperature for acetone for different heat inputs; Figure 25 shows comparison of vapor velocity obtained by experimental and numerical methods for water. Figure 26 shows comparison of entropy generation rate obtained by experimental and numerical methods for water as working fluid. It is found that the results obtained by the numerical method are not much varying with those results obtained by the experimental method.

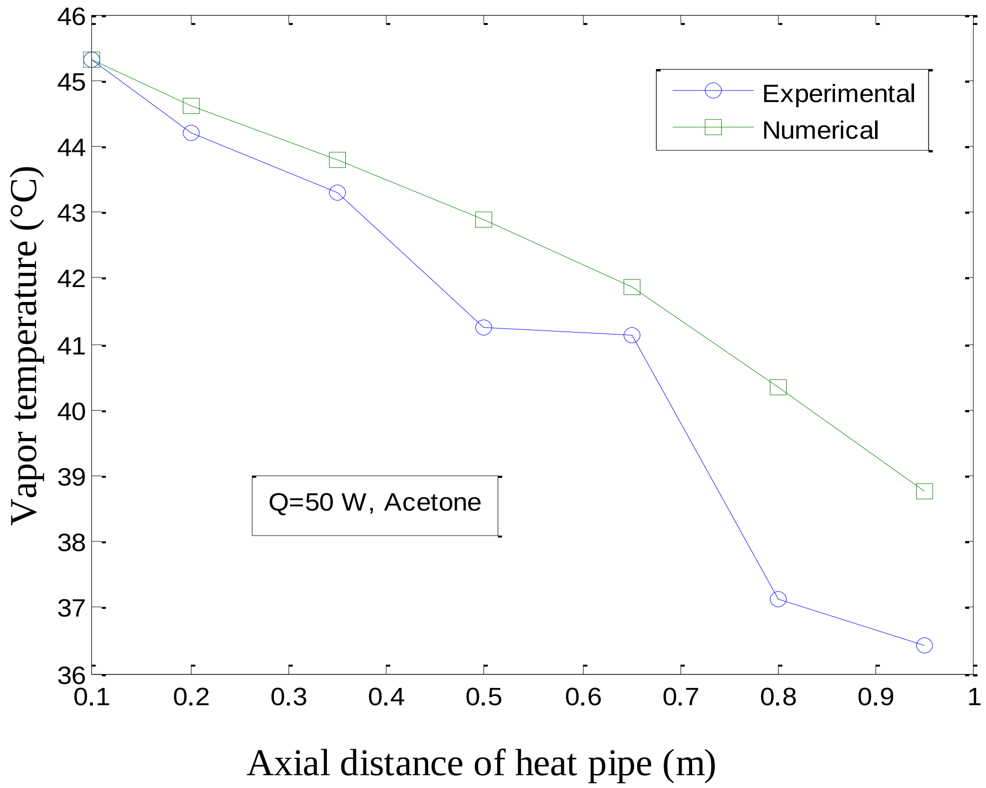

Figure 23. Comparison of experimental and numerical methods (Vapor temperature).

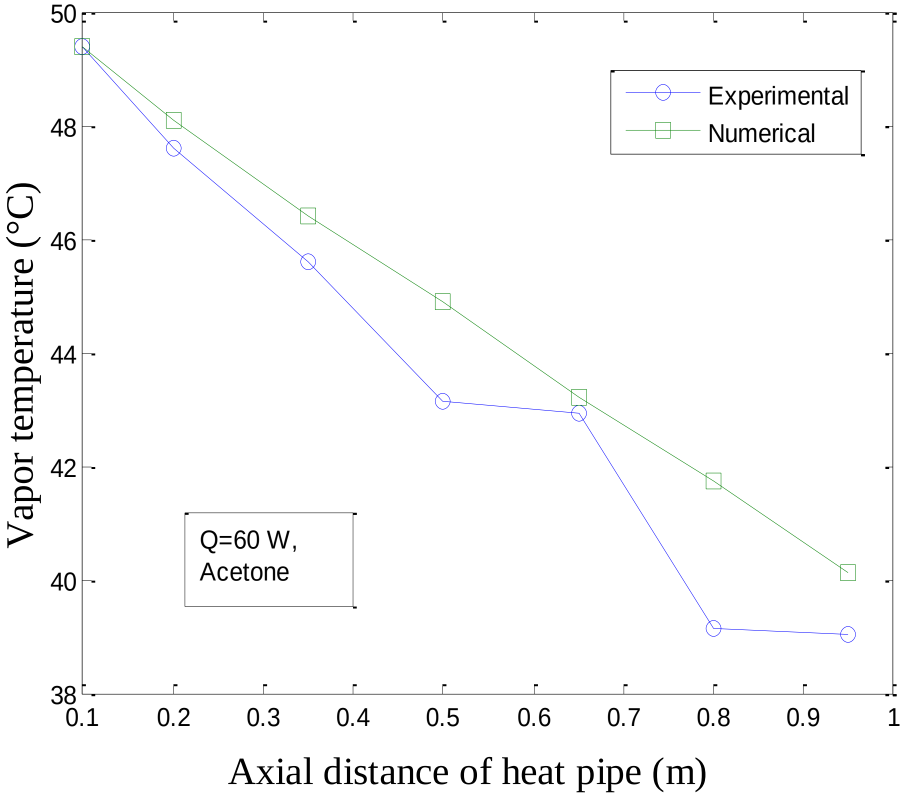

Figure 24. Comparison of experimental and numerical methods (Vapor temperature).

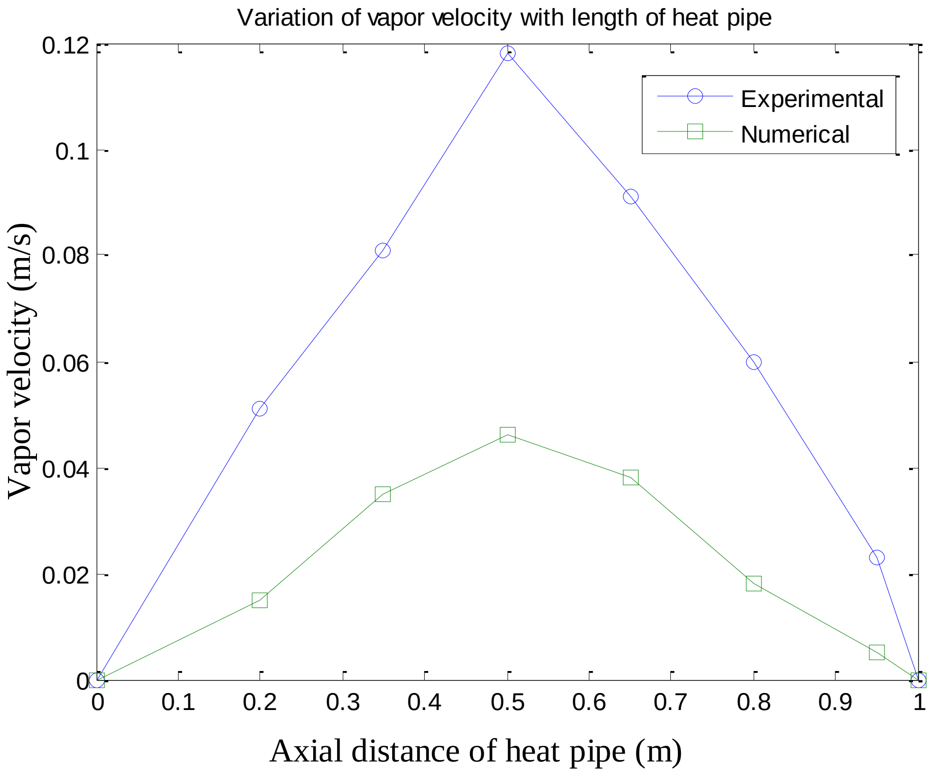

Figure 25. Comparison of experimental and numerical methods (Vapor temperature).

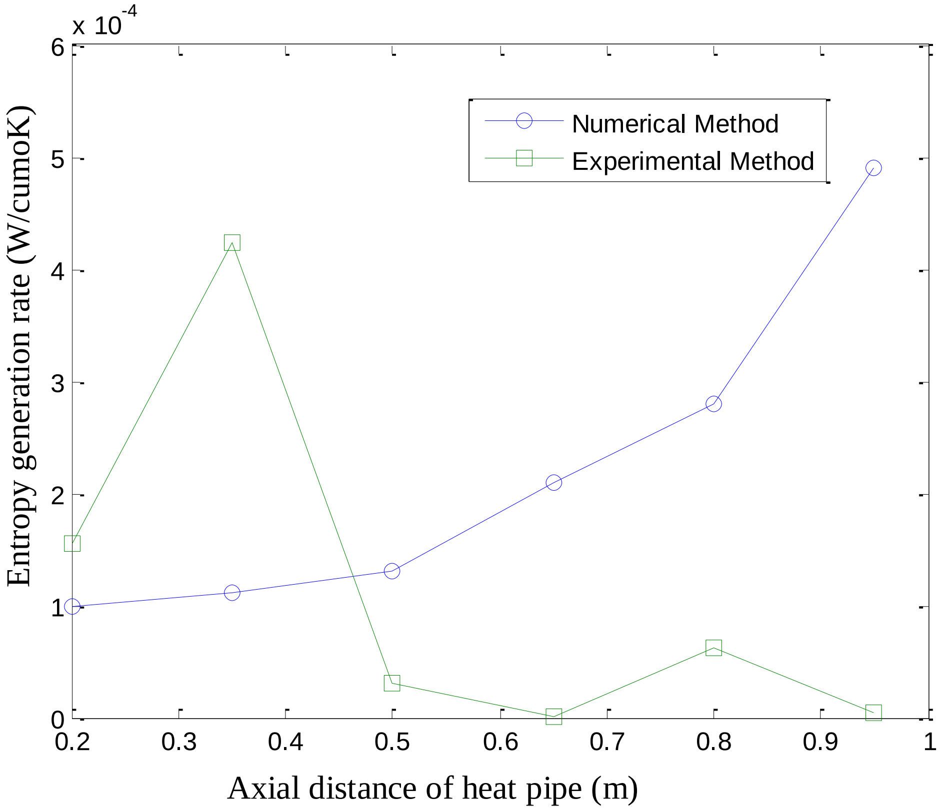

Figure 26. Comparison of experimental and numerical methods (Vapor temperature).

Nomenclature: K, Thermal conductivity, W/mK; **S,** entropy, J/kgK; $\mathbf{S}^{111}_{\mathbf{gen}}$**,** volumetric entropy generation, W/m^{3}K; **T,** temperature, K; **u,** longitudinal velocity, m/s; **v,** transverse velocity, m/s; **x,** axial distance, m; **y,** transverse distance, m.

Greek symbols: μ, Dynamic viscosity, Ns/m^2; ϕ**,** viscous dissipation.

REFERENCES

Bankston CA, Smith HJ (1973). Vapor Flow in Cylindrical Heat Pipes, J. Heat Transfer, 95: 371-376.

Bejan A (1982). ”Entropy Generation Through Heat and Fluid Flow”, Wiley, New York.

Chen MM, Faghri A (1990). ”An Analysis of Vapor Flow and Heat Conduction Through the Liquid Wick in a Heat Pipe with Single or Multiple Heat Sources”. Int. J. Heat Mass. Transfer, 33: 1945-1955.

Cotter TP (1965). Theory of Heat Pipes, Los Alamos Scientific Laboratory Report No. LA-3246-MS,

Faghri A (1986). Vapor Flow Analysis in a Double walled Concentric Heat Pipe, Numerical. Heat Transfer, 10: 583-593.

Khalkali, Faghri A, Zuo ZJ (1999). ”Entropy Generation in a Heat Pipe System”. Appl. Thermal. Eng., 19: 1027-1043.

Rajesh VG, Raveendran KP (1994). ”Optimum Heat Pipe design: a non linear programming”, M. Tech thesis, NIT Calicut.

Unnikrishnan VV, Sobhan CB (1997). ”Finite Difference Analysis of the Transient Performance of a Flat Heat Pipe” Int. Conference on Numerical Methods in Thermal Problems”, Swansea, UK, pp. 391-400.

Van Ooijen H, Hoogendoon CJ (1981). Experimental Pressure Profiles Along the Vapor Channel of a Flat Heat Pipe, Procs. International Heat Pipe Conference, London, pp. 415-426.

Van Ooijen H, Hoogendoon CJ (1981). Vapor Flow Calculation in a Flat Heat Pipe, AIAA J, 17: 1251-1259.

Vasilev LL, Konev SV (1990). ”Thermodynamic Analysis of Heat Pipe”, Proceedings of seventh International Heat Pipe Conference, Minsk,