A NUMERICAL APPROACH FOR ESTIMATING THE ENTROPY GENERATION IN FLAT HEAT PIPES

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ABSTRACT

Heat Pipe is a thermodynamic device which transports heat from one location to another 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 objective of the present work is to estimate the entropy generation in a flat heat pipe. A computational model is developed for the analysis of steady state operation of a flat heat pipe. The analysis involves the solution of one dimensional continuity, momentum and energy equations in the vapor core with the transport equations for a porous medium in the wick. The entropy generation depends on both temperature and velocity variations of vapor and liquid. Alternating Direction Implicit (ADI) scheme is used to convert the partial differential equations into finite difference equations. A code is developed in C language to solve the system of linear and non linear equations. Variation in temperature, pressure and velocity fields are obtained by solving the system of equations using the developed code. The temperature and velocity distributions in the heat pipe are employed for estimating the entropy generation rate in the system.

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 [12]. The design of heat pipe is simple and it is easy to manufacture and maintain. 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 the past few decades. Cotter [1] analyzed the laminar, steady, incompressible one-dimensional vapor flow in a cylindrical heat pipe. Bankston and Smith [2] 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 [3]. They also conducted experimental studies to obtain pressure profiles along the vapor channel of a flat heat pipe [4]. Numerical analysis of the vapor flow in a double walled concentric heat pipe was presented by Faghri [5]. Chen and Faghri [6] 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 [7].

Vasilev and Konev [8] presented a thermodynamic analysis based on the assumption of constant vapor pressure along the heat pipe. Rajesh and Ravindran [9] developed an optimum design of heat pipe using nonlinear programming technique. Khalkali et al. [10] presented the entropy generation in a heat pipe system. They developed a thermodynamic model of conventional 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. A computational model for the analysis of the transient operation of a flat heat pipe was presented by Shobhan [11].

This paper aims for finding the entropy generation developed by thermodynamic irreversibility for a one 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 flows.

The major three 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.

A computational model for analyzing steady state performance of a copper-water flat heat pipe system is presented here. The wick and vapor region are analyzed by solving the appropriate governing equations to obtain temperature, velocity and pressure distributions in the heat pipe. ADI method is used for the discretization of governing equations into finite difference equations. SIMPLE algorithm is used for solving the equations. Using the obtained velocity and temperature distributions, entropy generation rate due to vapor and liquid flows are estimated.

NOMENCLATURE

C	[J/kgK]	Specific Heat Capacity at Constant Pressure,
C_E	[-]	Ergun's Constant
Da	[-]	Darcy's Number
D	[m]	Wick Thickness
h_{fg}	[J/kgK]	Latent Heat of Vaporization
h	[m]	Vapor Core Thickness
k	[W/mK]	Thermal Conductivity
K	[m^2]	Wick Permeability
L	[m]	Length of Heat Pipe
P	[Pa]	Pressure
S	[J/kgK]	Entropy
$S^{III}gen$	[W/m^3K]	Volumetric Entropy Generation
T	[K]	Temperature
u	[m/s]	Axial Velocity
x	[m]	Axial Distance

Greek Symbols

μ	[Ns/m^2]	Dynamic Viscosity
ρ	[kg/m^3]	Density
ε	[-]	Porosity
θ	[-]	Non dimensional Temperature
φ	[-]	Viscous dissipation factor

Subscripts

a	Adiabatic section
amb	Ambient
c	Condenser section
e	Evaporator section
f	Liquid
v	Vapor
sat	Saturated

ANALYSIS OF HEAT PIPE

The heat pipe consists of an evacuated chamber, the interior of which is lined by a wick 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 the heat transfer and fluid flow between the reservoirs, entropy is generated. The entropy generation is formulated as follows.

ENTROPY GENERATION

The volumetric rate of entropy generation in a convective heat transfer problem is given as (13),

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

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

For a heat pipe the parameters in the above equation are:
k = thermal conductivity of the working fluid (vapor or liquid form)
T = operating temperature, μ = absolute viscosity of the working fluid,
∇T = temperature gradient, ϕ = viscous dissipation factor.

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

$$S^{III}gen = (k/T^2)(dT/dx)^2 + (2\mu/T)(du/dx)^2 \qquad (2)$$

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

The Physical model

The present analysis involves a flat heat pipe of 10 cm length (evaporator length = 4 cm, condenser length = 3 cm and adiabatic length = 3 cm). Water is chosen as the working fluid. The wick and wall are made of copper. A wick porosity of 0.65 is used in the present analysis with the voids being saturated with water. The adiabatic section is externally insulated such that there is no heat exchange between this section and the exterior.

The assumptions taken are:

1. Body forces are negligible.
2. One dimensional steady, laminar flow of vapor and liquid
3. Thermo physical properties of the working fluid remain constant
4. Vapor is assumed to be saturated ideal gas.

MATHEMATICAL FORMULATION

Governing Equations for liquid and vapor flow

. ***Continuity Equation***

For vapor flow:

$du/dx - \eta = 0$ for evaporator section

$du/dx = 0$ for adiabatic section and

$du/dx + \eta = 0$ for condenser section

For liquid flow

$du/dx + \eta = 0$ for evaporator section

$du/dx = 0$ for adiabatic section and

$du/dx - \eta = 0$ for condenser section

where η is the mass source term and can be expressed in terms of u_0, velocity at the wick-vapour core interface, hv, thickness of vapour core etc

Momentum Equations

For vapor core

$$\rho((u\,(du/dx)) = -dp/dx + \mu\,(d^2u/dx^2) \qquad (3)$$

For liquid wick,

$$(\rho/\varepsilon)((u\,(du/dx)) = -dp/dx + (\mu/\varepsilon)\,(d^2u/dx^2) - (\mu/K)\,u - C_E/K^{0.5}\,u\,|u| \qquad (4)$$

Energy Equation

For vapor core:

$$\rho C\,((u\,(dT/dx)) = u(dp/dx) + k\,(d^2T/dx^2) + 2\mu\,(du/dx)^2 \qquad (5)$$

For liquid wick:

$$\rho C_f\,((u\,(dT/dx)) = k\,(d^2T/dx^2) \qquad (6)$$

Boundary Conditions

For vapor core:

At x=0 and L, u=0

At x=0, , $T=T_h$

At x=L, $T=T_{amb}$

For liquid wick:

At x=0 and L, u=0

Initial Condition

At time t = 0, $T = T_{amb}$, and in the liquid and vapour $p=p_{sat}$

Non Dimensionalisation:

$X= x/L$, $U= u/uo$, $\theta = (T-T_\infty)/(T_h-T_\infty)$

Then the governing equations becomes

Momentum Equations

For vapor core momentum equation is

$$U\,(dU/dX) = -dP/dX + (1/Re)\,(d^2U/dX^2) \qquad (7)$$

For liquid wick, momentum equation is

$$U/\varepsilon\,(dU/dX) = -dP/dX + (1/\varepsilon Re)\,(d^2U/dX^2) - (U/Re\,Da) - (C_E/Da^{0.5})\,U|U| \qquad (8)$$

Energy Equation

For vapor core:

$$U(d\theta/dX) = Ec\,U\,(dP/dX) + (1/RePr)\,(d^2\theta/dX^2) - 2Ec/Re\,(dU/dX)^2 \qquad (9)$$

For liquid wick

$$U(d\theta/dX) = (1/RePr)\,(d^2\theta/dX^2) \qquad (10)$$

SOLUTION PROCEDURE

The finite difference equations formed are a set of linear and nonlinear equations. A code was developed in C++ to solve the above set of equations using the appropriate boundary conditions. The important characteristics of working fluid flows like vapour velocity, liquid velocity and temperature variation are predicted. Utilizing these results, variation of entropy generation in the heat pipe is estimated.

Results and Discussion

Steady state results obtained for the flat heat pipe from the computations are discussed here. A flat heat pipe with an overall length 100mm is considered for the analysis. The length of evaporator zone is 40mm and that of adiabatic and condenser sections are of 30mm each. The important results of analysis are the distributions of the axial velocity component, pressure, and temperature along with entropy generation rate in the heat pipe.

Axial Variation of Non dimensional Vapour Velocity

Figure 1 represents the axial distribution of nondimensional velocity component along the vapour core at different Reynolds numbers. The steep increase in velocity along the evaporator section observed is due to the mass addition into the vapour core. By receiving heat from the source the liquid in the wick of the evaporator zone continuously evaporates. At the adiabatic and condenser sections the velocity is found to be decreasing. The rate of decrease is very less at the adiabatic section. The steep decrease in velocity at the condenser section is due to high rate of mass transfer from the vapour core into the wick by constant condensation.

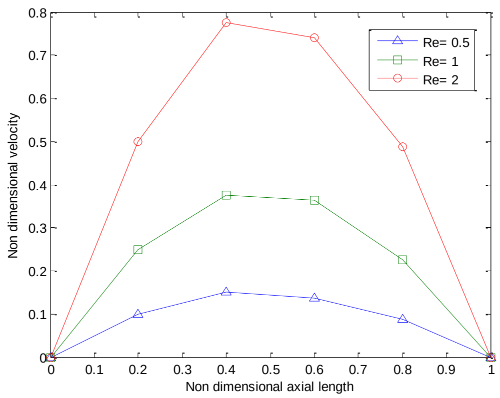

Figure 1 Variation of Non-dimensional Vapour Velocity along the Axial Length

Axial Variation of Vapour Velocity

Figure 2 represents the axial distribution of velocity component along the vapour core at different Reynolds numbers. The nature of the curves is same as that of the non-dimensional velocity because of the reasons explained in the previous section.

Axial Distribution of Vapour Temperature

Figure 3 represents the axial distribution of vapour temperature at steady state along the vapour core for different values of Reynolds number. It is found that as Reynolds number increases the vapour temperature also increases. This is because when Reynolds number increases the mass flow rate of vapour increases. The increase in mass flow rate results from increase in heat flux causing increase of temperature. The temperature is found as decreasing along the axial direction.

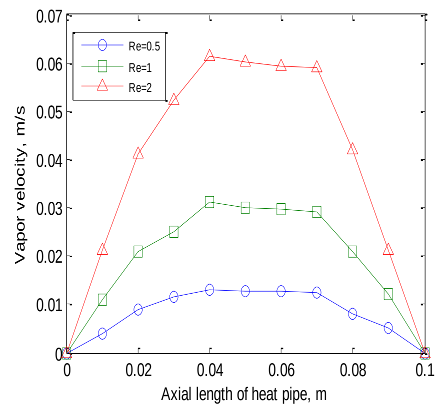

Figure 2 Variation of Vapour Velocity against Length of Heat Pipe

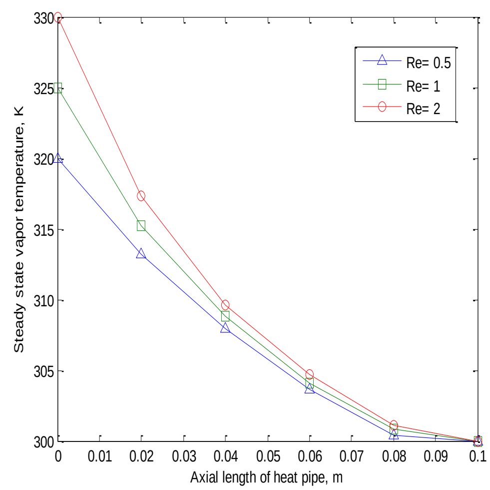

Figure 3 Variation of Vapour Temperature against Length of Heat Pipe

Axial Distribution of Vapour Pressure

Figure 4 gives the axial distribution of vapour pressure at steady state along the vapour core. The pressure distribution matches with the temperature distribution since the ideal gas equation is used to compute the pressure of vapour.

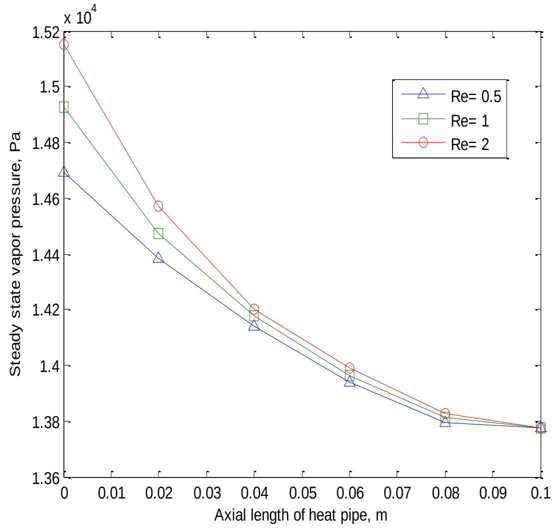

Figure 4 Axial Variation of Vapour Pressure in the Heat Pipe

Entropy Generation due to Vapour Flow

The variation of entropy generation rate due to vapour flow along the axial direction of the heat pipe for different values of Reynolds number is depicted in Figure 5. It is observed that the entropy generation rate due to friction in the vapour flow is negligible comparing with the entropy generation due to heat transfer. This is due to very low value of vapour viscosity. The entropy generation rate due to the heat transfer depends on the temperature gradient in the heat pipe. It is found that the temperature gradient decreases from evaporator to condenser section. Due to this decrease in temperature, the entropy generation rate also decreases along the axial direction.

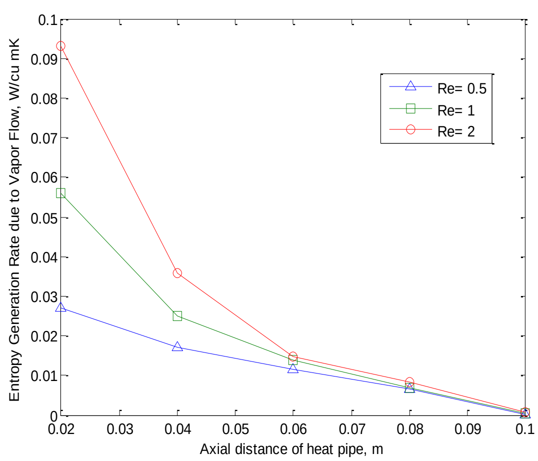

Figure 5 Entropy Generation Rate against Length of Heat Pipe

Axial Liquid Velocity Variation

Figure 6 shows the distribution of the axial liquid velocity component along the capillary wick. The axial component of velocity shown is in the negative x-direction. The nature of the liquid velocity distribution is similar to the vapour velocity distribution at each time instant. The liquid velocity increases steeply at the section where mass addition takes place (here condenser section) and decreases at very slow rate at the adiabatic section and decreases at a faster rate where mass depletion takes place (evaporator section). As expected, the magnitude of vapour velocity is very much higher than that of liquid due to vapour-liquid density difference.

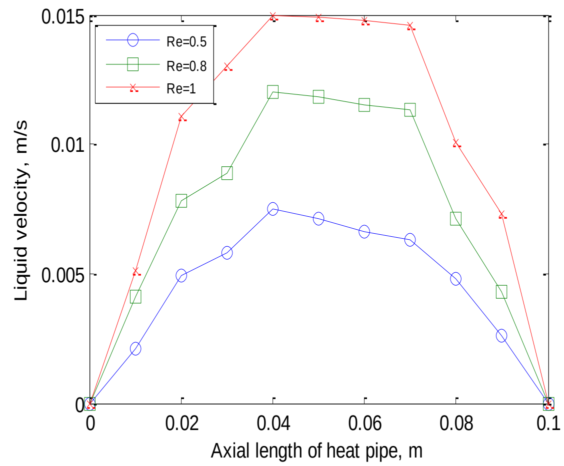

Figure 6 Variation of Liquid Velocity against Length of Heat Pipe

Entropy Generation due to Liquid Flow

Figure 7 describes the variation of entropy generation rate due to liquid flow through wick along the axial direction for different Reynolds number values. It can be observed that in the case of entropy generation rate due to liquid flow, the effect of heat transfer is negligible since the temperature drop for the liquid flow is very low. So the entropy generation rate is only due to the flow effect, ie. due to the velocity gradient. It is also observed that the velocity gradient decreases with axial direction of the heat pipe; similar nature is observed for entropy generation rate due to liquid flow. It can also be observed that the magnitude of entropy generation rate due to liquid flow is negligible in comparison with the entropy generation rate due to vapour flow.

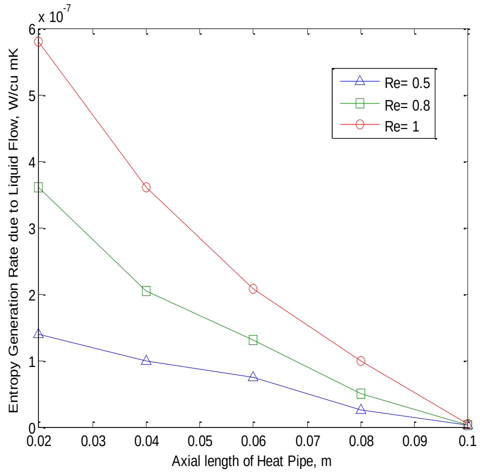

Figure 7 Variation of Entropy Generation due to Liquid Flow against Axial Length of Heat Pipe

CONCLUSION

The entropy generation rate in the heat pipe is considered as a function of temperature and velocity of working fluid. The total rate of entropy generated due to heat transfer, and liquid and vapour pressure drops was estimated using numerical method for a flat heat pipe considering one dimensional laminar flow. The important characteristic curves like variation of liquid and vapour temperatures, liquid and vapour velocities with the length of heat pipe and entropy generation rate due to vapour and liquid flows were obtained. It is found that the entropy generation rate due to liquid flow is negligibly small compared to the entropy generation rate due to vapour flow. Also the entropy generation rate due to heat transfer is much higher compared to the entropy generation rate due to fluid friction.

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