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Entropy generation analysis of cylindrical heat pipe using nanofluid

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ABSTRACT

Thermal performance of cylindrical heat pipe with nanofluid is studied based on the laws of thermodynamics. The objective of the present work is to investigate nanofluids effect on different sources of entropy generation in heat pipe caused by heat transfer between hot and cold reservoirs and also frictional losses and pressure drop in the liquid and vapor flow along heat pipe. An analytical study was performed to formulate all sources of entropy generation and the predicted results are compared with experimental ones. Cylindrical miniature grooved heat pipes of 250 mm length and 6.35 mm outer diameter were fabricated and tested with distilled water and water based TiO_2 and Al_2O_3 nanofluids at different concentrations as working fluids. Analytical and experimental results revealed that the entropy generation in heat pipes decreases when nanofluids are used as working fluids instead of basefluid which results in improved thermal performance of the heat pipes with nanofluids.

1. Introduction

Heat pipe is a two phase heat transfer/thermodynamic device which is widely used especially in cooling system to transfer heat from one point to another. Due to the two phase heat transfer with one or two order of magnitude higher heat transfer coefficient compared with single phase heat transfer which occurs in heat pipe thermodynamic cycle, the temperature drop is extremely small. Heat pipes are proven devices for heat transport and compete effectively with other available cooling systems. Each heat pipe consists of three different parts, evaporator where heat is added to the system from an external source, condenser where heat is rejected from the system to an external heat sink and adiabatic section which connects these two parts. Heat absorption in evaporator causes the working fluid to evaporate, then, the vapor travel through the core of the container to another end which is condenser. The vapor then condenses and releases the heat. Returning the condensed liquid through the wick by means of capillary force driven from condenser to evaporator forms a close loop. As the working fluid operates in a thermodynamic cycle, based on the second law of thermodynamic, proper design of heat pipe container and wick structure and also suitable selection of working fluid are essential to the successful operation of a heat pipe with highest efficiency. Based on the definition of the second law of thermodynamic, frictional losses in the working fluid flow and heat transfer across a finite temperature difference generates entropy. As in most thermodynamic systems [1–3], the entropy generation quantifies the irreversibility of the heat pipe and consequently the amount of lost work during the process.

Although, a large number of experimental, numerical and theoretical studies have been reported on performance analysis of different types of heat pipes, there are a few numbers of studies with the focus on minimization of entropy generation [4–6]. Khalkhali et al. [5] explained and developed a thermodynamic model based on the second law of thermodynamics to examine the effects of various parameters on entropy generation in heat pipe. Maheshkumar and Muraleedharan [6] studied the effect of adiabatic length and heat load on the optimum design variables and corresponding entropy generation in flat heat pipe. Other studies on optimization of heat pipe design based on the second law of thermodynamics were done by Rajesh and Ravindran [7] and Bejan and Lorente [8].

According to the reasons of entropy generation in heat pipe, the minimization of entropy generation can be accomplished by proper design of heat pipe dimensions and operating conditions as well as proper selection of working fluid. One solution for minimizing the entropy generation may be using nanofluid which is nanotechnology-based colloidal suspensions fabricated by suspending nanoparticles in a base liquid. Over past decade, experimental studies have shown and confirmed nanofluids potential to be used in heat transfer systems instead of conventional fluid like water and ethylene glycol because of enhanced heat transfer properties [9–13]. Various types of

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Nomenclature

a	Constant
b	Constant
d	Diameter, m
f	Friction factor
h	Heat transfer coefficient, W/m^2/K
h_{fg}	Latent heat of vaporization, J/kg
k	Thermal conductivity, W/m/K
r	Radius, m
A	Area, m
C_p	Specific heat, J/kg/K
L	Length, m
P	Pressure, Pa
Q	Heat input, W
R	Thermal resistance, K/W
R_g	Gas constant, J/kg/K
T	Temperature, K

Subscripts

c	Condenser
e	Evaporator
l	Liquid
nf	Nanofluid
p	Particle
s	Solid
sat	Saturation
v	Vapor

Greek symbols

ε	Porosity
μ	Viscosity, Pa.s
ρ	Density, kg/m^3
δ	Film thickness, m
δ_o	Nonevaporating film thickness, m

nanofluids with different concentrations, particle sizes and shapes have been used in heat pipes as working fluids and interesting results on thermal performance enhancement are achieved [14–20].

The scope of this experimental/analytical study is on investigation of nanofluids effect on minimization of entropy generation in heat pipe. Different factors contribute to entropy generation in heat pipe are studied one by one to show nanofluids effect on each of them and consequently the irreversibility of the whole system.

2. Heat pipe performance analysis

The heat transfer process of a heat pipe is primarily influenced by the container material and dimensions, wick structure and working fluid properties. Nanofluid as a heat pipe working fluid has influence on thermal behavior of heat pipe by altering the wick characteristic and fluids properties. Effective thermal conductivity of the wick increases using nanofluid. In addition, evaporation rate is influenced by nanoparticles deposition at liquid/vapor interface on the wick surface. Above description indicates that using either basefluids or nanofluids lead to different thermal performance due to different fluid flow and heat transfer behavior of those fluids as working fluid in heat pipe. It means that the entropy generated in the system may be different between nanofluids and the basefluids.

3. Entropy generation

When a working fluid undergoes between different states in a thermodynamic cycle, the entropy is generated in the process due to irreversibilities occurring inside the system such as friction and transfer of energy over a finite temperature difference. In a heat pipe system, the entropy generation can be caused by temperature differences between the vapor and external reservoirs as well as vapor and liquid pressure drop during the process. Nanofluids with different thermodynamic properties than basefluids may have significant influence on the friction and heat transfer rate in heat pipe. So, the entropy generation in heat pipe with nanofluid is different from that of the same heat pipe with basefluid. The entropy generated in a cylindrical heat pipe using nanofluid as a working fluid is as follow:

3.1. Entropy generation due to temperature differences between the vapor and external reservoirs

The heat exchange between a heat source and heat sink in a thermodynamic cycle across finite temperature differences generates entropy. In heat pipe system the relation between temperature difference and heat load is as follow,

$$Q = \frac{T_h - T_l}{R_{total}} \tag{1}$$

where T_h and T_l are heat source and heat sink temperatures and R_{total} is overall thermal resistance of the heat pipe. From Eq. (1), the heat sink temperature is as below:

$$T_l = T_h - Q \times R_{total} \tag{2}$$

According to second law of thermodynamics the entropy generated due to heat transfer is given by [21]

$$S_{HT} = \oint \frac{\delta Q}{T} = \frac{-Q}{T_h} + \frac{Q}{T_l} = Q \times \left(\frac{T_h - T_l}{T_h T_l} \right) \tag{3}$$

Substituting Eq. (2) into Eq. (3), the entropy generation due to temperature differences between the vapor and external reservoirs is as below,

$$S_{HT} = \frac{Q^2 \times R_{total}}{T_h (T_h - Q \times R_{total})} \tag{4}$$

Eq. (4) shows that the entropy generation due to heat transfer is a function of heat load, the overall thermal resistance and heat source temperature.

3.2. Entropy generation due to vapor and liquid pressure drop

The working fluid flow at both phases of liquid and vapor generates entropy which is due to frictional losses and also heat transfer between the flow and the heat pipe wall. Many parameters have influence on these losses and an increasing fluid flow friction contributes to a larger entropy generation in the system. According to the first and second laws of thermodynamics, the entropy generated due to the vapor pressure drop is given by [21],

$$S_{vapor} = \frac{m \times \Delta P_v}{\rho_v \times T} \tag{5}$$

where the pressure drop and mass are given by,

$$\Delta P_{vapor} = \frac{8 \mu_v \times V \times L_{eff}}{R_v^2} \tag{6}$$