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Numerical study of the heat transfer and flow characteristics of heat pipes

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Abstract. In this work, a three-dimensional (CFD) analysis is used to investigate the heat transfer and fluid flow of a heat pipe using water and nanofluids as working fluids. The study focused mainly on the effects of volume concentrations of nanoparticles and the operating temperature on the heat transfer performance of the heat pipe using the nanofluids, but there is revealed also aspects concerning flow characteristics of fluids. The analysis was performed for water and two types of nanofluids, two volume concentrations of nanoparticles (1.0% and 4 vol.%) and three operating temperatures (70 °C, 80 °C and 90 °C). Nanofluids were composed of water and SiC and TiC nanoparticles with the diameter of 10nm. The numerical results indicate that the volume concentration of nanoparticles has an important effect in reducing of the temperature difference between evaporator and condenser. The present study shows also that the thermal performance of a heat pipe can be significantly improved by using of both wick structure and nanofluids.

1. Introduction

The use of heat pipes is becoming widespread in a large number of applications, from the space programs to electronic cooling, as these devices are generally passive in their operation and provide effective heat transport with minimal losses. A heat pipe operates on a closed two-phase cycle and utilizes the latent heat of vaporization to transfer heat with very small temperature gradients. Circulation of a working fluid inside the heat pipe is accompanied by phase changes at both the evaporator and the condenser [1], as shown in figure 1.

As a new research frontier, the nanofluid two-phase flows have the potential to improve heat transfer and energy efficiency in thermal management systems. It has been demonstrated that nanofluids can have remarkably higher thermal conductivities than those of conventional pure fluids and significantly better heat transfer characteristics than the base fluids. Up to now, studies concerning application of nanofluids in heat pipes are experimental and only a few reports the modelling of the heat pipe characteristics in the presence of a nanofluid [2-8].

Because, numerical works concerning the fluid flow and heat transfer processes in heat pipes using nanofluids are limited, the goals of the present study are the analysis of these processes coupled with liquid flow in the wick structure and finding of that nanofluid which could enhance significantly thermal performance of the heat pipes.

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2. Thermo-physical properties of nanofluids

Thermo-physical properties of nanofluids are very important in the study of nanofluid two-phase flow. Temperature dependency of different physical properties (k, c_p , ρ , μ) of the working fluids has been considered to improve the accuracy of the calculations and results are tabulated in Table 1.

Fluid/ Nanoparticles	Density, ρ (kg/m ³)	Specific heat, c_p (J/kg·K)	Thermal conductivity, k (W/m K)	Dynamic viscosity, µ (kg/ms)
Water	997.0	4181.7	0.6069	0.0008899
SiC	3370	1340	350	-
TiC	4930	711	330	-

Table 1. Thermo-physical properties of the fluid and nanoparticles [9].

3. Simulation methodology

The CFD code used for this study was ANSYS CFX, which is fully integrated fluid dynamics analysis software of ANSYS Workbench platform [10].

3.1 Geometry and grid resolution

The geometry of the heat pipe studied in the present work, with a grooves shaped wick, is shown in Figure 1. The dimensions of the heat pipe are similar with those of Li et al. [11], as given in Table 2.



Figure 1. Sketch of heat pipes working principle (a) and cross section of current wick (b).

A multi-block structured grid has been used to generate the computational domain. It consists of two main regions with rectangular prism elements, in order to get a higher quality mesh. Transition between these two regions was made with some layers of triangular prism elements. This approach provides the possibility to concatenate the grid points nearest to surfaces of the walls, necessary to capture the flow of the liquid phase along the heat pipe, and also to use a reasonable grid in terms of number of elements. Several grid distributions have been tested to ensure the results are grid independent. Therefore, a mesh consisting of 4.896.000 elements has been selected for the present computations of the heat pipe.

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Dimensions of the heat pipe [mm]	Present study	Li et al. [11]
Length	300	300
Diameter (outer)	8	8
Evaporator	45	50
Adiabatic section	210	200
Condenser	45	50
Groove width	0.20	0.20
Groove height	0.20	0.25
Number of grooves	60	74

Table 2. Dimensions of the heat pipe.



Figure 2. Multi-block structured grid used for the heat pipe in cross section.

3.2. Governing equations and conditions of simulations

The governing equations of flow and heat transfer inside of the heat pipes were solved in the Cartesian coordinate system for steady state conditions, assuming that both liquid and vapour phases are in equilibrium. Gravitational effect was considered, too. The set of equations solved were continuity equation, RANS (Reynolds Averaged Navier-Stokes) equations and thermal energy equation. For modelling of heat pipes, the phase change model [10] has been used. Vapour phase was modelled as continuous fluid and liquid phase as a dispersed fluid. As boundary conditions, constant wall temperatures on evaporator, T_e , and condenser, $T_c = 293 K$, were imposed. An initial liquid water volume fraction of 15% (initial liquid filling ratio) was considered.

4. Results and discussion

The analysis was carried out by incorporating the effect of nanofluids in the geometrical model given by Li et al. [11]. Two different types of water based nanofluids, SiC and TiC, were used to perform the numerical simulations. A reasonable range of concentration was chosen for solid particles, 1.0%, and 4.0%, each of them studied for three different values of operating temperature of evaporator $T_e =$ 343.353 and 363 K.

4.1. Comparison between heat pipe and wickless heat pipe

In order to reveal the influence of the wick on thermal performances of the heat pipe, a study was performed for both cases of heat pipe with and without grooves, for all three temperatures considered, using water as working fluid. The results, shown in Figure 3, reveal that in the case of the heat pipe (with groove) the temperature difference between evaporator and condenser sections is more higher compared to of the wickless heat pipe. In this figure, an increase with 70% of the temperature difference between evaporator and condenser is obtained for an operating temperature of 70°C, meaning that heat pipe works efficiently at low operating temperatures. It is also clearly shown that

the wick structure of the heat pipe has a great effect on the reduction of the temperature along of the heat pipes.



Figure 3. Comparison of the temperature difference between evaporator and condenser sections for heat pipe with groove and wickless heat pipe.

4.2. Heat transfer

In order to quantitatively evaluate the thermal performance of the heat pipes, the temperature profiles of the heat pipes using both water and the nanofluids are compared.

Figures 4 and 5 depict the effect of volume concentrations of nanoparticles on thermal performances of heat pipe under various the operating temperatures. As can be seen from these figures, increases the particle concentration decrease the temperature difference between the evaporator and condenser. For 4.0% SiC and TiC particles and an operating temperature of 80°C, the temperature difference is reduced up to 8.71% and 10.33% respectively. It is clearly shown that the volume fraction of nanoparticles has a great effect on the reduction of the temperature difference along of the heat pipes.



Figure 4. Effect of the SiC particle concentration on thermal performance of a heat pipe under various operating temperature.



Figure 5. Effect of the TiC particle concentration on thermal performance of a heat pipe under various operating temperature.

4.3. Fluid flow

In order to characterize the flow inside the heat pipe were checked velocity fields and liquid volume fraction in the cross sections. Figures 6 and 7 depict averaged variations of the maximum velocity of vapours and liquids along the heat pipe under the operating temperatures.

Concerning the vapours velocity for cases studied, it decreases with decreasing of $T_e - T_c$, following a curve as in Figure 6. Thus, after a fast growing in the evaporator, followed by a maximum constant value until the middle of the heat pipe, the velocity of vapours decreases in the second part. The decreasing rate becomes smaller to the end of condenser.

In the opposite direction, the maximum velocity of liquid phase increases from condenser to last third of the adiabatic section then becomes constant until near the bottom wall of the evaporator. There are no significant variations in the liquid phase velocity with operating temperature range, but an increase of speed occurs for cases with nanofluids, higher for TiC, as in figure 7, showing that the mass forces dominate for the liquid phase.



Figure 6. Variations of water velocity (r = 3.2 mm) and vapours velocity (r = 0.0 mm) along of the heat pipe.



Figure 7. Variations of maximum liquid velocity for Te = 363 K.

To find values of the maximum liquid speed, the velocity profile was checked along the heat pipe, as shown in figure 8 for water. The velocity is constant inside grooves, where the adhesion forces dominate. Outside grooves, the influence of the mass forces increase from condenser to adiabatic section where are dominant, and therefore the velocity profile changes, revealing also the mechanism of flow due to phase change process.



Figure 8. Water velocity profile along of the heat pipe, Te = 363 K.

Contours of water volume fraction and to an operating temperature of 90 °C are shown in Figure 9. Based on the volume fraction profile, the liquid phase returns on condenser walls due to capillary force in the wick. The vector plots show that the vapours flow upward and the liquid phase flows downward through the condenser walls.



Figure 9. Contours of water volume fraction in cross section.

5. Conclusions

In this paper the thermal and hydrodynamic behaviors of water and nanofluids flowing inside a heat pipe were numerically investigated in stationary conditions and for laminar flow. Two types of nanofluids (i.e SiC/water and TiC/water) were analyzed. The heat pipe temperature and velocity are obtained for different volume concentrations of nanoparticles and different operating temperatures of the heat pipe. The results have showed that the heat transfer behaviours of the nanofluids were highly depended on the volume concentration of nanoparticles. Also, the numerical results confirm experimental results obtained of many researches so far as well as the thermal performances of the heat pipes are improved and the temperature difference between the evaporator and condenser is reduced when nanofluids are used as the working fluid.

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