CFD Study of the Heat Pipes with Water-Nanoparticles Mixture

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Abstract:
The steady incompressible flow has been solved in both vapour and liquid regions and wall. The governing equations in vapour and liquid regions are continuity, momentum and energy equations. In the present study, the enhancement of heat pipe efficiency with water–nanoparticles mixtures, using professional CFD (Computational Fluid Dynamics) software is presented. The heat pipe is made from copper tube with the outer diameter 8.9 [mm] and the length 200 [mm]. The water is used as a base working fluid while the nanoparticles used in the present study are the copper oxide nanoparticles. Three cases with volume fraction 0, 1% and 4% for CuO are considered.

Keywords: Heat pipe, heat transfer, multiphase flow

1. INTRODUCTION

Due to the heat transport by evaporation and condensation of the working fluid, a heat pipe is an effective by simple device, which has a very high thermal conductance. Since 1960's, these devices have been developed tested and put into operation in various types. With these developments, heat pipe are used in many engineering field nowadays [1], [2]

The heat pipe can be divided into three sections: the evaporator which is located near the heat source, the condenser which is located near the heat sink and the middle portion called the adiabatic section.

Thermal input at the evaporator region vaporizes the working fluid and this vapor travels to the condenser section through the inner core of heat pipe. At the condenser region, the vapor of the working fluid condenses and the latent heat is rejected via condensation. The condensate returns to the evaporator by means of capillary action in the wick. As previously mentioned there is liquid vapor equilibrium inside the heat pipe. When thermal energy is supplied to the evaporator, this equilibrium breaks down as the working fluid evaporates. The generated vapor is at a higher pressure than the section through the vapor space provided. Vapor condenses giving away its latent heat of vaporization to the heat sink.

The idea of dispersing solid particles into liquids initially came from James Clerk Maxwell [3]. In previous years, the lack of industrial interest for enhanced thermal properties by those suspensions containing millimeter– or micron-sized particles was mainly due to their poor stability and rheological problems. Particle sedimentation from the suspensions resulted in clogged channels. It has recently been demonstrated that solid nanoparticles with dimensions of ~10-40 nm are extremely stable and exhibit no significant settling under static conditions, even after weeks or months [3]. Conventional heat transfer fluids such as water, ethylene glycol or oil, containing ultra-fine metallic particles have been of special interest.
amongst many researchers in recent years [4,5,6,7]. This is because the prepared nanofluid gave rise to a heat transfer enhancement compared to the conventional heat transfer fluids.

The heat transfer rate of a nanofluid involves three main parameters. These are viscosity, thermal conductivity and heat capacity, where one or more of these parameters may be quite different from the base fluid [8].

Recent works have shown that the presence of the nanoparticles in heat pipe causes an important enhancement of his thermal characteristics.

Das et al. [9] go detailed into investigating the increase of thermal conductivity with temperature for nanofluid with water as base fluid and particles of $\text{Al}_2\text{O}_3$ or $\text{CuO}$ as suspension material, and the results indicated an increase of enhancement characteristics with temperature, which makes the nanofluid even more attractive for applications with high energy density than usual room temperature measurements reported earlier.

Also, some researcher [10] investigated gold nanofluid on meshed heat pipe thermal performance. The circular meshed heat pipe has a length $170$ [mm] and an outer diameter of $6$ [mm]. The thermal resistance of heat pipe ranges form $0.17$ to $0.215$ [K/W]. The measured results show that the thermal resistance of the heat pipes with nanofluids is lower than with DI - water.

2. CFD METHODOLOGY

The flow fluid and heat transfer into heat pipe is a process very complex. In consequence, the efficiency of a thermal CFD simulation depends on many factors. Creation of the model geometry and its integration in a physical domain, grid generation and choice of a suitable numerical computing scheme are significant factors that can determine the level of success of the simulation process. The main steps of the performed studies are briefly described in the following paragraphs.

2.1. CAD Model

The geometry creation, which consists of annular concentric heat pipe, through which circulates water and water vapour, were drawn as a CAD data, with the aid of a professional software – package, ACAD 2002, and imported in ANSYS Workbench environment as SAT file.

The characteristic geometry and dimensions of the heat pipe are present in Figure 1 and Table 1.

![Figure 1: The heat pipe geometry](image)

Table 1: The dimensions characteristic of the heat pipe
2.2. Computational grid and boundary conditions

The computational grid was generated using multi-blocks scheme with wedges and hexahedral elements nearest to surface of the heat pipe, in order to solve accurately the flow and heat transfer in the proximity of the later. In this sense, the side length of the elements on the surface of the heat pipe was 0.05 [m] (Fig. 3). Thus, the dimensions of the computational grid were:
- global number of grid points: 33089;
- global number of elements: 26800.

According with previously mentioned, the boundary conditions of the processes were are following:

- at the outer wall of the evaporator section, a positive and constant heat flux was assigned: \( q_E \);
- at the outer wall of the condenser section, a negative and constant heat flux was assigned: \( q_C \);
- for the interference surfaces of the domains, the conservative interface flux was applied;
- an uniform and constant velocity were imposed at the inlet boundary for vapour region:
  \( v_v = v_{vapour} \)
an uniform and constant velocity were imposed at the inlet boundary liquid region
\( v_w = v_{\text{water}} \);
both end of the heat pipe, the adiabatic conditions were applied;

### 2.3 Conditions of simulations

The coupled heat transfer/fluid flow problem was modeled using ANSYS CFX. This finite volume software solves simultaneously the continuity, momentum and energy governing equations. The analyses were performed in steady state, adiabatic, laminar conditions, multiphase flow, for a saturation pressure and temperature of the fluid \( p_{\text{sat}} = 0.12335 \text{ [bar]} \), \( T_{\text{sat}} = 325.15 \text{ K} \). The study was performed for heat input: \( Q = 30 \text{ [W]} \) and volume fraction of \( \text{CuO} \) particles of 0, 2% and 4%.

The radial and axial velocities at vapour – liquid interface are given by [11]:

\[
v = \frac{\dot{m}}{\rho} = \frac{q}{\rho h_{fg}} \tag{1}
\]

where mass flow rate \( \dot{m}_v = \dot{m}_w \), \( q \) is heat flux, \( \rho \) is density and \( h_{fg} \) is latent heat of vaporization. According to the coordinate system (Fig. 1), interface velocity \( v \) is negative in the evaporator section and positive in the condenser section to balance the mass flow. In consequence, result an average velocity in liquid region of \( v_{w,\text{ave}} = -9.407 \cdot 10^{-4} \text{ [m/s]} \) and in vapour liquid of \( v_{v,\text{ave}} = 3.832 \text{ [m/s]} \).

### 3. RESULTS AND DISCUSSIONS

The solution was considerate finished, when the variations of normalised rate of change for the variables of processes were insignificant for the final steps of iterations. These variables include the components of momentum and mass and heat transfer. The main convergence criteria, checked very carefully, were the followings:

- decreasing of the residuals below \( 1e^{-004} \);
- variations of the temperatures which are acting on heat pipe smaller than 0.5% for the final steps of the iterations:

\[
\Delta T_i = 100 \cdot \frac{T_i - T_{i-1}}{T_i} \%
\tag{2}
\]

Figure 4 shows the distribution of wall temperature of heat pipe with DI - water and nanofluid prepared by different concentration. The results show that, in the case of the DI - water, the variation temperature between the evaporator section and the condenser section is more significant. These results have been verified with available experimental data [12] and have shown good agreement. Also, the results show that distribution of wall temperature of heat pipe containing DI - water varied from \( 323.842 \text{ [K]} \) to \( 321.808 \text{ [K]} \). After adding small amount of copper oxide nanoparticles in the DI - water illustrated the increasing wall temperature of heat pipe than filled with DI- water, from \( 325.8 \text{ [K]} \) to \( 324.8 \text{ [K]} \) (2%). As the more the nanoparticles were dispersed in working fluid, the variation of wall temperature of heat pipe was smaller than DI - water filled in heat pipe.

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Figure 4: Wall temperature of heat pipe with DI - water and nanofluid with different concentration

Figure 5 illustrates the thermal resistance of heat pipe containing copper oxide nanoparticles and DI - water as working fluid. It can be seen that by increasing concentration of nanoparticles the thermal performance of heat pipe is decreased.

Figure 5: Thermal resistance of heat pipe with DI - water and nanofluid with different concentration
The effect of adding copper oxide nanoparticles on the thermal performance of the heat pipe is more evident if the data are expressed as a plot of $R_{\text{water}} - R_{\text{nanofluid}} / R_{\text{water}}$ versus volume fraction, as shown in Figure 6. This graph shows the reducing rate of thermal resistance under different concentration, respectively.

![Figure 6: Reducing rate of thermal resistance at different concentrations](image)

4. CONCLUSIONS

It has been shown that steady state heat transfer and flow equations in both vapour and liquid regions and wall can be simulated using this numerical model with accuracy. This paper deals with the thermal enhancement of the heat pipe performance, using copper oxide-water as the working fluid. A nanofluid is an innovative heat pipe working fluid with metal nanoparticles dispersed on it. In present case, the DI - water with copper oxide particles was numerical modeled, showing that the thermal performance of the heat pipe was considerably increased.

Increasing the thermal performance of heat pipe by using water – nanoparticles mixture can be explained as follows: The critical heat flux and convective heat coefficient of nanofluid is higher than DI - water. Therefore, it is expected that the thermal performance of heat pipe will be enhanced. As a result, the higher thermal performances of the nanofluid have proved its potential as substitute for conventional DI - water in the heat pipe.

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