COMPUTATIONAL ANALYSIS OF THE PERFORMANCE OF A HEAT PIPE USING NANOFLUIDS IN ITS INTERIOR

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Abstract. *Application of nanofluids in heat pipes usually results in satisfactory experimental results regarding heat transfer enhancement. However, the available computational studies connecting heat pipes and nanofluids lack a deeper discussion regarding the models used for the evaluation of the properties. Thus, the present study seeks to evaluate the precision of the existing correlations used for the evaluation of these properties of those nanofluids. Thereunto, the study uses a computational code previously developed and based in the finite volume method, adapted and applied to a heat pipe previously studied experimentally, to obtain the temperature, pressure and velocity fields. These results seek to allow the evaluation of the precision of these models, and determine a suitable model to predict the thermal and the flow behavior of a nanofluid into a heat pipe.*

Keywords: *Heat Pipes. Nanofluids. Computational Analysis.*

1. INTRODUCTION

Recent experimental studies reveal that the introduction of nanofluids into heat pipes usually presents desirable results regarding the heat transfer enhancement, and lead to the belief that this application has excellent perspectives. The properties obtained by introducing those nanofluids enable a very significant enhancement in the heat transfer that occurs at the phase change phenomenon existing inside those heat pipes.

A heat pipe is a tube made of thermal conductor material, containing a porous material of annular format and a working fluid confined in its interior. This porous material (entitled wick) covers the inner surface of the tube through all its length, while the working fluid fills the empty space inside the porous material as a saturated liquid, and the rest of the heat pipe interior as a saturated gas. This pipe is constructed to operate as a passive heat pump, extracting heat from a hot part, conducting this heat by its structure (without using energy) and rejecting this heat to a cold part. This heat is responsible for the phase change process of the working fluid inside the heat pipe, enabling the obtainment of high heat transfer coefficients and very high heat transmission efficiency.

Nanofluids are obtained by mixing a base fluid, like water, oil or ethylene glycol, and nanoparticles of a solid material, dispersed in suspension along the base fluid. A large amount of solid materials can be used at the composition of a nanofluid, like metals, oxides or even carbonic structures like diamonds or carbon nanotubes. These particles have medium sizes under 100 nm and are uniformly dispersed, remaining suspended in the fluid. Some typical nanofluids are ethylene glycol with copper nanoparticles and water with copper oxide nanoparticles, among others.

The review published by Liu and Li (2012) presents the experimental results obtained for the heat pipe and nanofluid combination applied to several kinds and formats of heat pipes, and different nanofluids composed with different mass fractions and multiple combinations of materials used for the base fluid and for the nanoparticles. In this study, forty different combinations were analyzed, and only four of them presented a lower performance than using the base fluid alone in the heat pipe. In some of the positive cases, the thermal resistance of the heat pipe was reduced to less than the half of the original thermal resistance. It means that, with a fixed temperature difference, more than twice of the original heat can be transferred by this heat pipe. Newer reviews were published by Buschmann (2013) and Sureshkumar *et al.* (2013), and also obtained similar results regarding the heat transfer performance.

The existing analytical studies associating nanofluids and heat pipes are still considerably rare and focused in limited practical applications. Moreover, the predictive models used for the prediction of the physical properties of nanofluids still present many unconformities each, regarding the physical mechanisms that influence this heat transfer enhancement using nanofluids, specially using non-conventional materials like ethylene glycol or carbon nanotubes. This point a necessity of a deeper analysis of the equations used for the evaluation of properties like the thermal conductivity and the dynamic viscosity of a specific nanofluid used inside a heat pipe.

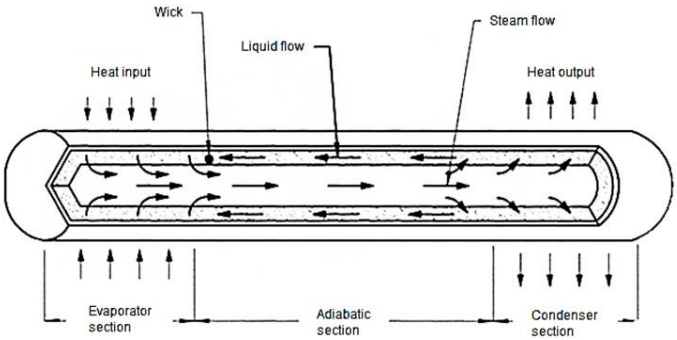

Figure 1. A heat pipe's operation scheme (Chi, 1976)

The main contribution done by this work consists in listing a set of equations more suitable for the evaluation of the selected nanofluids properties. This relation is going to be made by a computational simulation of one heat pipe existing in the literature, using an existing and adapted model based in the finite volume model. This computational simulation must enable the obtainment of the thermal and hydrodynamic characteristics of the operation of a heat pipe using nanofluids, like temperature, pressure and velocity fields. So, the objective of the current work consists in obtaining a set of equations capable to represent the physical properties of the selected nanofluids into a heat pipe. As a final result, it is expected that is possible to select a most suitable set of equations for the determination of each physical property of a nanofluid in a heat pipe.

2. ANALYSIS

The modeling of the thermal behavior of a heat pipe containing conventional working fluids already has a significant amount of works involving analytical and experimental solutions. In the experimental field, the work of Zerbini (1984) analyzed heat pipes in moderate temperatures, evaluating values for the effective thermal conductivity of a heat pipe. The thermal characteristics of an experimental model were evaluated, so that the thermal profiles through the heat pipe could be determined. The results showed enhancements for the effective thermal conductivity even 27 times higher than the thermal conductivity obtained from a pure copper bar.

Among the analytical solutions, the work of Mahjoub and Matabroshan (2008) proposed a numerical solution for the working fluid flow along the entire heat pipe. In this work's model, the mass, energy and motion conservation equations were used together with the finite volume method applied with cylindrical coordinates, using the software FLUENT to obtain the solution of the resulting system of equations. The mathematical model used by the authors, based on such model of Mahjoub and Matabroshan (2008), divides the heat pipe in three sections: evaporator section, adiabatic section and condenser section. They considered that the flow is steady, incompressible and laminar, and that there is angular symmetry. Also, it was assumed that the steam region fluid does not have contact with the porous region fluid of the heat pipe. So, the equations that describe the mass conservation, the motion conservation in directions z and r and the energy conservation inside the heat pipe, respectively, are:

$$\frac{\partial u_v}{\partial z} + \frac{\partial v_v}{\partial r} + \frac{v_v}{r} = 0 \tag{1}$$

$$\rho_v \left(u_v \frac{\partial u_v}{\partial z} + v_v \frac{\partial v_v}{\partial r} \right) = -\frac{\partial P_v}{\partial z} + \mu_v \left(\frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial u_v}{\partial r} \right] + \frac{\partial^2 u_v}{\partial z^2} \right) \tag{2}$$

$$\rho_v \left(u_v \frac{\partial v_v}{\partial z} + v_v \frac{\partial v_v}{\partial r} \right) = -\frac{\partial P_v}{\partial r} + \mu_v \left(\frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial v_v}{\partial r} \right] + \frac{\partial^2 v_v}{\partial z^2} \right) \tag{3}$$

$$\rho_v c_{p,v} \left(u_v \frac{\partial T_v}{\partial z} + v_v \frac{\partial T_v}{\partial r} \right) = k_v \left(\frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial T_v}{\partial z} \right] + \frac{\partial^2 T_v}{\partial z^2} \right) + S \tag{4}$$

At the wick region of the heat pipe, the motion conservation and the energy conservation equations for the fluid in the liquid state are based in the Darcy's Law:

$$\rho_l \left(u_l \frac{\partial u_l}{\partial z} + v_l \frac{\partial v_l}{\partial r} \right) = -\frac{\partial P_l}{\partial z} + \mu_l \left(\frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial u_l}{\partial r} \right] + \frac{\partial^2 u_l}{\partial z^2} \right) - \frac{\mu_l . u_l}{K_z} \tag{5}$$

$$\rho_l \left(u_l \frac{\partial v_l}{\partial z} + v_l \frac{\partial v_l}{\partial r} \right) = -\frac{\partial P_l}{\partial r} + \mu_l \left(\frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial v_l}{\partial r} \right] + \frac{\partial^2 v_l}{\partial z^2} \right) - \frac{\mu_l . v_l}{K_r} \tag{6}$$

$$\rho_l c_{p,l} \left(u_l \frac{\partial T_l}{\partial z} + v_l \frac{\partial T_l}{\partial r} \right) = \frac{k_{ef}}{\varepsilon} \left(\frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial T_l}{\partial z} \right] + \frac{\partial^2 T_l}{\partial z^2} \right) + S \tag{7}$$

where k_{ef} represents the effective thermal conductivity of the wick filled with liquid. In this work, this conductivity was obtained by associating the liquid conductivity k_l, the wick conductivity k_{mp} and the porosity of the wick ε:

$$k_{ef} = \frac{k_l[(k_l + k_{mp}) - (1-\varepsilon)(k_l - k_{mp})]}{(k_l + k_{mp}) + (1-\varepsilon)(k_l - k_{mp})} \tag{8}$$

Also it is necessary to introduce the thermal effect caused by the phase change of the working fluid. So, a source and a sink of heat are introduced in the evaporator and the condenser section, whose values are:

$$S_e = -\frac{\dot{Q}_e}{\pi((R_i + t)^2 - R_i^2) L_e} \tag{9}$$

$$S_a = 0 \tag{10}$$

$$S_c = \frac{\dot{Q}_c}{\pi((R_i + t)^2 - R_i^2) L_c} \tag{11}$$

At the interface between the heat pipe wall and the wick, the condition adopted corresponds to the heat conduction between the two regions, represented by:

$$k_{ef} \frac{\partial T_l}{\partial r} = k_w \frac{\partial T_w}{\partial r} \tag{12}$$

Finally, at the heat pipe's walls, the heat conduction equation in cylindrical coordinates is:

$$k_w \left(\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial T_w}{\partial z}\right] + \frac{\partial^2 T_w}{\partial z^2}\right) = 0 \quad (13)$$

Afterwards, the boundary conditions adopted for the solution of the heat pipe problem were:

- At the liquid-steam interface, the phase change of the fluid is responsible for the formation of motion, suctioning the fluid from one of the interfaces and expelling the fluid to the other region that forms the interface. The representing this phenomenon requires the introduction of suction and expelling velocities at the liquid-steam interface containing the following values at the steam region:

$$V_{e,v} = \frac{\dot{Q}_e}{2\pi R_i L_e \rho_v h_{lv}} \quad (14)$$
$$V_a = 0 \quad (15)$$
$$V_{c,v} = -\frac{\dot{Q}_c}{2\pi R_i L_c \rho_v h_{lv}} \quad (16)$$

  and the following values at the wick/liquid region:

$$V_{e,l} = -\frac{\dot{Q}_e}{2\pi R_i L_e \rho_l h_{lv}} \quad (17)$$
$$V_a = 0 \quad (18)$$
$$V_{c,l} = \frac{\dot{Q}_c}{2\pi R_i L_c \rho_l h_{lv}} \quad (19)$$

- At the external surface of the heat pipe walls, the boundary conditions applied are correspondent to the heat introduction performed at the evaporator section and to the heat extraction performed at the condenser section:

$$Evaporator: \frac{\partial T_w}{\partial r} = \frac{\dot{Q}_e}{2\pi R_o L_e} \quad (20)$$
$$Adiabatic: \frac{\partial T_w}{\partial r} = 0 \quad (21)$$
$$Condenser: \frac{\partial T_w}{\partial r} = -\frac{\dot{Q}_e}{2\pi R_o L_c} \quad (22)$$

- Finally, at all the presented regions, the longitudinal border of the heat pipe presents a boundary condition equivalent to an adiabatic wall:

$$u = v = 0 \quad (23)$$
$$\frac{\partial T}{\partial z} = 0 \quad (24)$$

Regarding the thermal study of nanofluids, the correct determination of the nanofluids properties are a key aspect at the simulation of the physical behavior of these materials, once the equations that describes the flow and the heat transfer in a fluid contain those properties as parameters. So, there are specific works that seek to elaborate mathematical models that enable the correct representation of the main physical properties behavior of a nanofluid.

The main properties of those fluids consists in the density (or specific mass), the dynamic viscosity, the specific heat and the thermal conductivity, wherein the last one is the most important property regarding heat transfer.

For determining the density of a standard nanofluid, the literature adopts the same models used for microscopic particles mixtures, and assumes that a nanofluid density is equivalent to the density of a simple mixture between a fluid and solid particles. The corresponding equation is presented in Pak and Cho (1998) for any liquid containing solid particles dispersed along this fluid. The same equation is referenced in Shafahi *et al.* (2010), Gavtash *et al.* (2012) and Rashidi and Mosavari Nezamabad (2011), and correspond to:

$$\rho_{nf} = \rho_{np}\varphi + \rho_{fb}(1-\varphi) \quad (25)$$

Where φ is the volume fraction of the nanoparticles along the nanofluid. The subscripts nf, np and fb are, respectively, "nanofluid", "nanoparticle" and "base fluid".

Regarding the specific heat of the nanofluids, O'Hanley *et al.* (2012) presents two models capable of predicting this property of a nanofluid. The second and most important model is based in the hypothesis that there is thermal balance between the nanoparticles and the base fluid in a nanofluid. So, this model uses the formerly presented definition of density and the formal definition of specific heat in order to obtain the following expression:

$$c_{p,nf} = \frac{\varphi(\rho c_p)_{np} + (1-\varphi)(\rho c_p)_{fb}}{\varphi\rho_{np} + (1-\varphi)\rho_{fb}} \quad (26)$$

Xuan and Roetzel (2000) also used an adapted form of the Eq. (26) in order to determine the specific heat of a generic nanofluid in their study, thus enabling the calculation of the heat transfer rate along this nanofluid.

For the calculation of the dynamic viscosity of different nanofluids, the review studies of Mishra *et al. (*2014) and Halelfadl *et al.* (2013) sought to gather several existing models. The models presented in these studies consist in approaches to different situations in which one or more characteristics have direct influence at the determination of the nanofluid viscosity. Those characteristics can be defined by properties of the nanofluid components, like the base fluid viscosity, properties of the nanofluid composition, like the volume fraction of nanoparticles, or even characteristics obtained at the nanofluid synthesis, like the agglomeration radius of nanoparticles. The most relevant models for the present work are the models of Einstein, Nielsen, Batchelor, Brinkman, Pak & Cho, Chow, and Krieger & Dougherty.

Regarding the thermal conductivity, a great number of studies and models were proposed in order to determine this property in nanofluids. These models have direct relation with the physical characteristics of the nanofluids components, like the thermal conductivity of the base fluid and of the nanoparticles. From studies of Sundar *et al.* (2014), Pastoriza-Gallego *et al* (2014), Kwak and Kim (2005), Liu *et al* (2005) and Yu *et al.* (2009), it were gathered the most relevant models for the present work: Hamilton & Crosser, Wasp, Chen et al., Jeffrey, Yu & Choi, Turian, and Murshed.

The studies involving heat pipes and nanofluids together still are few and involve a limited amount of nanoparticles applied to these nanofluids. Concerning ethylene glycol, the study of Putra *et al.* (2012) seeks to relate the enhancement obtained in the thermal performance of a heat pipe containing wicks made of screen meshes and nanofluids containing water or ethylene glycol as a base fluid and nanoparticles of Al_2O_3, TiO_2 and ZnO in different volume fractions.

The use of those nanoparticles enabled the obtainment of significant enhancements in the thermal conductivity of the base fluid. Figure 2, extracted and adapted of Putra *et al.* (2012), shows the behavior of the ratio between the thermal conductivity of the resulting nanofluids and the thermal conductivity of the liquid ethylene glycol, measured experimentally, in function of the volume fraction of the nanofluid.

For the construction of the heat pipe of this study, straight tubes of copper with external diameter of 8 mm, internal diameter of 7,44 mm and length of 200 mm were used, wherein the evaporator and the condenser section contain 60 mm each. The wick used in this heat pipe comprehends a single-plaited screen mesh made of stainless steel, and containing wires with 56,5 μm of diameter and 6,7416 plaits per mm, with four layers of screen mesh.

It is possible to notice the thermal behavior obtained in the heat pipe using 30W of power at the evaporator section for different working fluids with the temperature profiles associated to base fluids and nanofluids, present in Fig. 3.

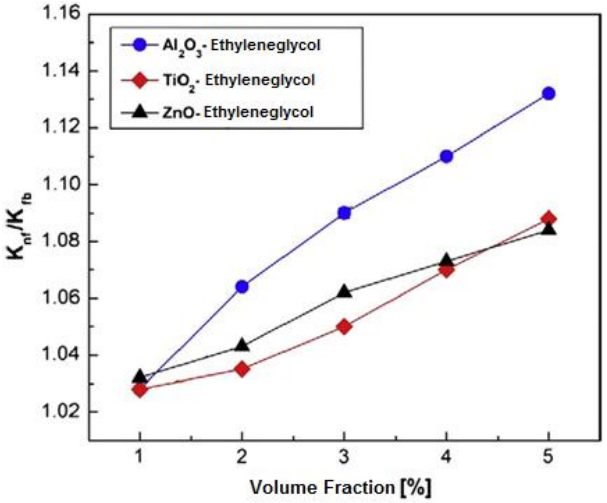

Figure 2. Thermal conductivity enhancement of nanofluids containing ethylene glycol (Putra et al., 2012)

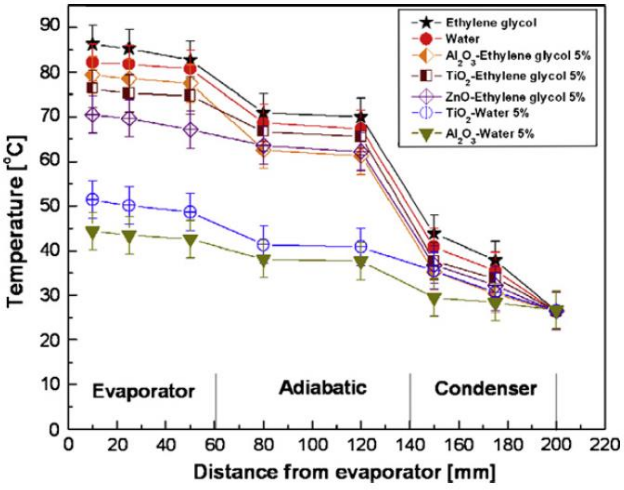

Figure 3. Temperature profiles of heat pipes containing different nanofluids (Putra et al., 2012)

From Fig. 3, one can notice that the use of any composition of nanofluids enable the obtainment of a noticeable reduction of the maximum temperature obtained at the evaporator section. It means that, for a fixed heat rate introduced in the heat pipe, the addition of nanofluids allow the heat pipe to operate in lower temperature ranges, reducing the thermal resistance of the whole heat pipe.

The temperatures profile also show that, at the condenser end of the heat pipe, all temperatures remain constant for all situations and equal to nearly 25ºC. It is assumed that the experimental conditions of this study are defined that this temperature remains constant because of the experimental set.

It was also concluded at the end of this study that the use of nanofluids was responsible for the formation of a thin layer at the surface of the wick, and this layer enabled the enhancement of the capillary transport along the heat pipe, so that the heat transfer could be higher than the expected by the simple enhancement of the thermal conductivity.

3. METHODOLOGY

The construction of a computational model can be divided in three main phases. The first phase corresponds to the creation of the computational grid, which is a geometric domain discretized in many small dimension volumes, so that the union of all these volumes compose the full domain in which are applied the boundary conditions and the

conservation equations. The second phase consists in the right determination of the physical properties of each section of the constructed domain, in order to represent correctly the corresponding materials used in each studied heat pipe. Finally, the third phase corresponds to the application of the representative initial and boundary conditions of the problem at the calculation domain, so to represent the physical phenomena that define the problem.

For the construction of the computational grid, the software ICEM CFD® was selected. This software permits the creation of two-dimensional meshes and three-dimensional grids, and has many tools that help in the construction and the evaluation of the quality of a computational mesh or grid. Two-dimensional mesh was constructed in the present work, once every studied heat pipe presents angular symmetry all along its length.

The dimensions presented in Tab. 1 correspond to the dimensions used on the creation of a representative geometric model for the heat pipe studied in Putra *et al.* (2012).

Table 1. Representative dimensions used in generation of the computational mesh of heat pipe used in Putra et al. (2012)

Length (mm)	200
Evaporator (mm)	60
Condenser (mm)	60
External diameter (mm)	8
Wall thickness (mm)	0,3
Steam chamber diameter (mm)	7

This mesh was created using the automatic routine for mesh construction based in the problem geometry, contained in the ICEM CFD. It was assumed that there is rotational symmetry along the heat pipe, enabling the construction of a mesh containing just half the size of the full heat pipe.

The smaller dimension used in this computational mesh was defined as 5 hundredths of a millimeter (corresponding to 25% of the minor order of magnitude of this heat pipe) to obtain the desired precision. So, the corresponding regions to the copper tube wall were radially divided in 4 equal parts, the corresponding regions to the wick were radially divided in 6 equal parts and the corresponding region to the steam chamber was dividing in 70 equal parts. The evaporator and the condenser sections were longitudinally divided in 300 equal parts and the adiabatic section was longitudinally divided in 400 equal parts. All the created elements received 100% in the quality rating of the ICEM CFD. The resulting mesh of this heat pipe contained 80000 elements.

The conversion of the mesh to the analysis software CFX® required the mesh to be three-dimensionalized. So, to avoid spatial effects, the angular dimension must assume a small dimension and must have symmetry applied to both transversal faces of the three-dimensional model. A dimension of 1 mm took place at the present study, so that this behavior could be achieved.

For the determination of the physical properties of each section of the created domain, it is possible to divide the materials used in the construction of the heat pipe in three categories, according to application. These categories are: heat pipe wall, wick and working fluid.

At the heat pipe wall, it is necessary that the material is able to contain the working fluid under pressure inside the heat pipe. Simultaneously, this material must have a thermal conductivity high enough that the heat received by the heat pipe is transmitted to the working fluid efficiently. So, a material that matches these specifications is the copper, and will be used in this application.

Copper is a widely used material in engineering applications by its attractive physical properties, such as thermal conductivity and electrical conductivity. At 300 K, the copper has a specific heat of 0,385 kJ/kg.K, specific mass of 8930 kg/m³ and thermal conductivity of 401 W/m.K.

The wick used in the heat pipe present in the work of Putra *et al.* (2012) consists in a wrapped screen mesh, made of a single-plaited stainless steel. Stainless steel is a steel alloy composed by iron and different proportions of chromium, so that this chromium is responsible for turning the steel stainless in proportions above 12%. The corrosion resistance obtained from this composition permits the use of this material in applications involving direct contact with oxidant fluids, like in a heat pipe. The physical properties can vary according to the chromium proportion. As a reference, we can take as the average properties a density of 7955 kg/m³, a specific heat of 0,510 kJ/kg.K and a thermal conductivity of 15,5 W/m.K.

The study of Putra *et al.* (2012) provides as parameters of the wrapped screen wick the wire diameter of the screen with the value of 56,5 μm, and the mesh number (N), correspondent to the number of plaits by unit of length, with the value of 6,742 plaits of wires per mm.

On the determination of the porosity of wicks made of wrapped screens, Eq. (28), presented in Chi (1976), associate the porosity with the wire diameter and the mesh number:

$$\varepsilon = 1 - \left(1{,}05 N \pi d_f / 4\right) \tag{28}$$

So, the value of the porosity of the wick used in the heat pipe of the study of Putra *et al.* (2012) is 0,686.

With this value, it is possible to determine the value of the permeability using the modified equation of Blake-Kozeny, defined for wrapped screen meshes and provided by Chi (1976):

$$K = {d_f}^2 \varepsilon^3 / 122(1-\varepsilon)^2 \tag{29}$$

Applying the obtained properties of this wick, the value obtained for the permeability is $8{,}558.10^{-11}$ m².

Still in the work of Putra *et al.* (2012), the working fluid consists in ethylene glycol and nanofluids containing ethylene glycol used as a base fluid.

The ethylene glycol is a fluid used in applications that is desirable that the fluid does not solidify along the flow. The melting point of ethylene glycol is lower than the melting point of water, guaranteeing this behavior.

The ethylene glycol properties in liquid state are widely known and correspond to the following values, for the fluid at 20ºC and 1 atm : $\rho_{EG,l}$ = 1076,1 kg/m³; $c_{p,EG,l}$ = 2343,9 J/kg.K; $\mu_{EG,l}$ = 0,00368 kg/m.s; $k_{EG,l}$ = 0,26 W/m.K. At the vapor state at 100 kPa and 471 K, ethylene glycol properties are: $\rho_{EG,v}$ = 2,573 kg/m³; $c_{p,EG,v}$ = 1410 J/kg.K.

An estimate of the transport properties can be performed using the Reichenberg method and the Misic and Thodos equations, applied to pure gases containing non-linear molecules, non-hydrocarbons and polar, at any temperatures. These methods and equations were extracted from Green and Perry (2007). From Reichenberg method dynamic viscosity of saturated ethylene glycol vapor is estimated to be $\mu_{EG,v} = 1{,}304.10^{-5}$ Pa.s, and from the equations of Misic e Thodos it is obtained $c_{v,EG,v}$ = 79205 J/kmol.K and $k_{EG,v}$ = 0,0227 W/m.K. Finally, the vaporization enthalpy of the ethylene glycol at boiling point and atmospheric pressure is about 800 kJ/kg.

The nanoparticles used on the study of Putra *et. al.* (2012) are aluminum oxide (Al_2O_3), titanium dioxide (TiO_2) and zinc oxide (ZnO). At the present paper, the evaluated nanofluid is the ZnO. It is necessary to set three properties of the ZnO nanoparticles in order to use the defined models: density, specific heat and thermal conductivity. Morkoç and Özgür (2009) and Pastoriza-Gallego *et al* (2014) provide such properties, so that the properties used at the present work for the ZnO nanoparticles are: ρ_{ZnO} = 5607 kg/m³; $c_{p,ZnO}$ = 495,2 J/kg.K; k_{ZnO} = 49 W/m.K.

Finally, in order to apply the representative initial and boundary conditions of the problem, the calculation domain was subdivided in five subdomains by using the CFX, so that the regions corresponding to the heat pipe wall, the wick (subdivided into three parts) and the steam chamber of the heat pipe could be defined. The configuration of these domains corresponds to:

- COPPER region (heat pipe wall): solid domain, continuous, stationary; material defined as Copper; heat transfer calculated by the thermal energy method (neglects compressibility effects); initial temperature defined as the temperature at the steady state; cylindrical coordinates; temperature fixed at the condenser end as 25ºC (due to Putra *et al.* (2012) results used for comparison);
- STEAM region (steam chamber): fluid domain, continuous, stationary; material defined as ethylene glycol (gas), pre-defined using the presented properties of ethylene glycol in vapor state; initial temperature defined as the temperature at the steady state; reference pressure defined as the saturation pressure of the working fluid at the initial temperature; heat transfer calculated by the thermal energy method (neglects compressibility effects); flow defined as laminar; cylindrical coordinates.
- WICK region: subdivided into WICKAD (wick contained in the adiabatic section), WICKCOND (wick contained in the condenser section) and WICKEVAP (wick contained in the evaporator section); fluid domain, stationary; fluid material defined as ethylene glycol (liquid), pre-defined using the presented properties of ethylene glycol in liquid state; solid material defined as stainless steel, pre-defined using the presented properties of the stainless steel; thermal conductivity of this full region defined using equation (19) and porosity fixed as 0,686; porous permeability defined as a volumetric negative source term [according to Eqs. (5) and (6)]; permeability defined as $8{,}558.10^{-11}$ m². initial temperature defined as the temperature at the steady state; reference pressure defined as the saturation pressure of the working fluid at the initial temperature; fluid flow defined as laminar; heat transfer calculated by the thermal energy method (neglects compressibility effects); cylindrical coordinates.

Regarding the boundary conditions, the heat input and output conditions, represented by equations (20) to (22) must be applied to the evaporator and condenser sections in order to represent the main heat transfer conditions of the problem.

At the interface between the STEAM region and the WICK region, occurs the phase change. To represent the conversion of thermal energy in internal energy consequent of this phase change, heat source terms were inserted in the interface. These heat sources are analogue to the volumetric conditions represented in equations (9), (10) and (11), in proportion to the volume of the studied model. Similarly, for the flow representation of the motion insertion due to the phase change process, the equations (14) to (19) are used in order to insert this motion in the form of an equivalent mass flow per unit of area. This was achieved by eliminating the density term in all these equations.

Also, an energy conservation analysis was conducted at the heat pipe wall in the condenser section in order to evaluate the effect of the heat pipe wall temperature set at 25ºC at the end of the condenser section. A energy conservation analysis was realized at the condenser section and the results showed that about 98% of the heat generated from of the condensation process at the condenser section of the heat pipe is transmitted to the exterior of the heat pipe by the lateral condenser walls, while 2% are transmitted to the ambient because of the fixed temperature at the heat pipe's condenser end, so the source terms of the present model were adapted to consider this change as well. All the remaining internal boundaries correspond to wall-type boundaries. That means that these boundaries respect the energy conservation along them, but do not allow the flow of motion through them.

The external remaining boundaries correspond to wall/adiabatic-type boundaries. That means that the flows of energy and motion that go through them have value zero.

It is also important to define the solution controls of the problem, so that the numeric solution of the conservation equations can lead to a converged solution. Thereunto, it is necessary to define four main configurations: Advection scheme, residual convergence control, maximum number of iterations and numeric timescale.

From the CFX options , the advection scheme that seemed more suitable for the solution of this problem consists in the second order scheme represented by the introduction of a blending factor with value 1 (Specified Blend Factor). The residual convergence control was set according with the orders of magnitude of the problem, and was set as 10^{-6}. The maximum number of iterations was set as 2000, although this value was not reached in any simulation. The numeric timescale was set as automatic.

4. RESULTS AND DISCUSSION

The developed model was validated using experimental data of Putra *et al.* (2012). The thermal results obtained at the heat pipe wall using ethylene glycol as heat pipe working fluid (k_{ef} = 0,7098) are presented in Fig. 4, and Fig. 5 shows the evaporator and adiabatic sections temperatures with higher detail.

It is easy to notice that there is a high difference obtained between the experimental data and the numerical solution at the condenser section. A possible explanation for such behavior may be the type of boundary conditions applied at the condenser section. So, in a future study, this condition has to be improved in order to the represent better this region. Besides that, in the remaining regions the maximum deviation obtained corresponds to 1,23ºC or 1,71%.

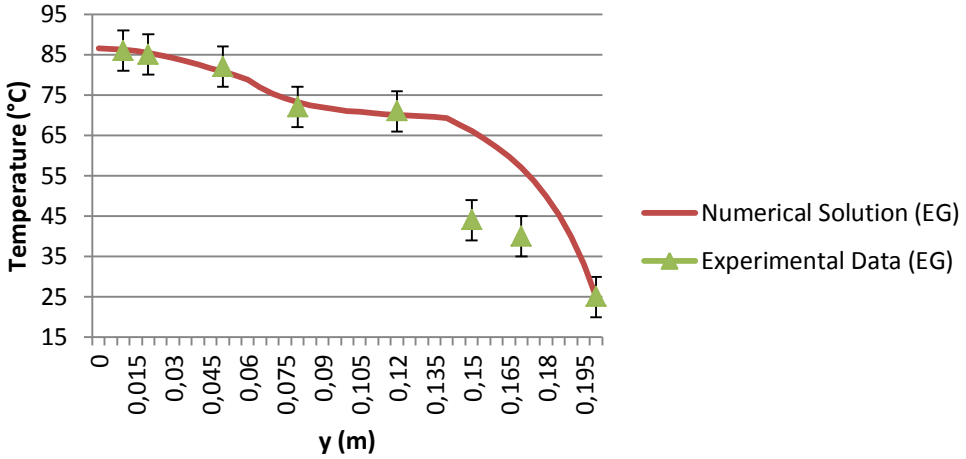

Figure 4. Temperature profile at the heat pipe wall.

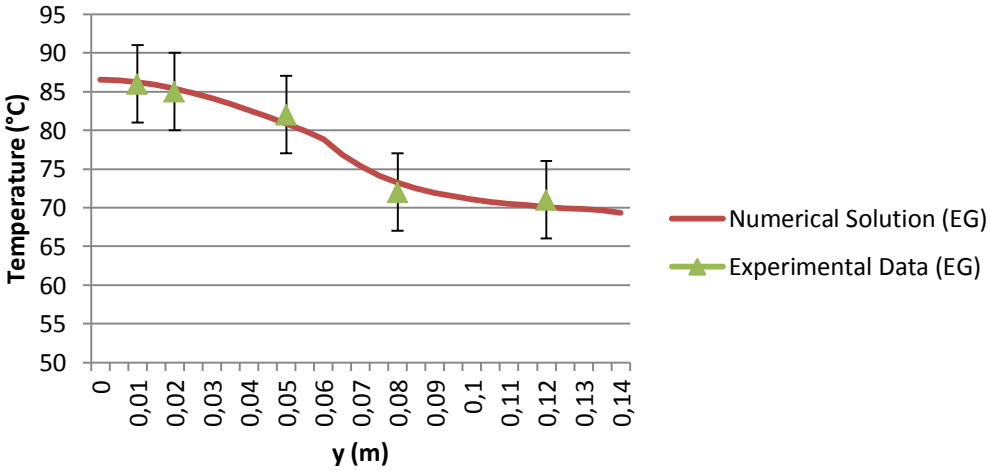

Figure 5. Temperature profile at evaporator and adiabatic sections of the heat pipe.

For the evaluation of the nanofluids properties effect in the present model, nanofluids composed by ethylene glycol and zinc oxide with a volumetric fraction of 5% are simulated using the same previously constructed computational model. Using Eqs. (25) and (26), it is possible to define the values for the specific mass and the specific heat of this nanofluid: ρ_{nf} = 1302,65 kg/m³ and $c_{p,nf}$ = 2355,72 J/kg.K.

Furthermore, using the Eq. (19) together with the models for dynamic viscosity and effective thermal conductivity, it is defined the following set of properties for μ_{nf} of the nanofluid and the k_{ef} of the wick. So, the most critical results obtained, corresponding to the simultaneous maximum effective thermal conductivity and minimum dynamic viscosity and to the simultaneous minimum effective thermal conductivity and maximum dynamic viscosity, were defined as "Einstein – Chen" and "Yu and Choi - Pak and Cho". These results should define a range of values in which the nanofluids properties must be located.

Table 2. Dynamic viscosity of the ZnO nanofluid from different models

Model	Dynamic Viscosity
Einstein	4,14E-03 Pa.s
Nielsen	4,39E-03 Pa.s
Batchelor	4,20E-03 Pa.s
Brinkman	4,16E-03 Pa.s
Pak and Cho	1,58E-02 Pa.s
Chow	6,20E-03 Pa.s
Krieger & Dougherty	7,43E-03 Pa.s

Table 3. Values defined for the effective thermal conductivity of the heat pipe's wick

Model	Effective Conductivity
Hamilton & Crosser	0,9087
Wasp	0,8215
Chen et al.	1,3042
Jeffrey	0,8268
Yu & Choi	0,7578
Turian	0,9219
Murshed	0,8427

The thermal and pressure effects obtained by these pairs of models can be observed in figures 6 and 7 in comparison to the experimental data of Putra *et al.* (2012).

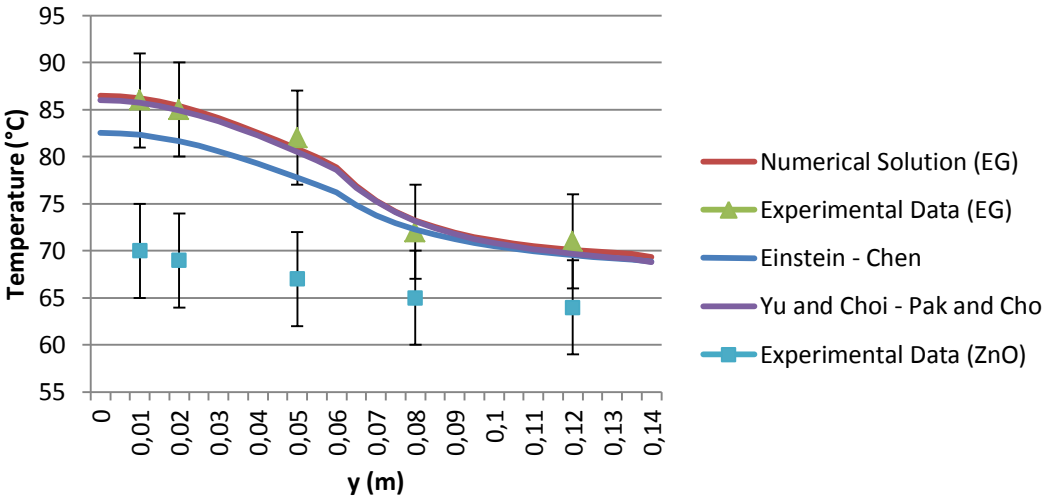

Figure 6. Temperature profile at the evaporator and the adiabatic section of a heat pipe containing ethylene glycol and ZnO nanofluids

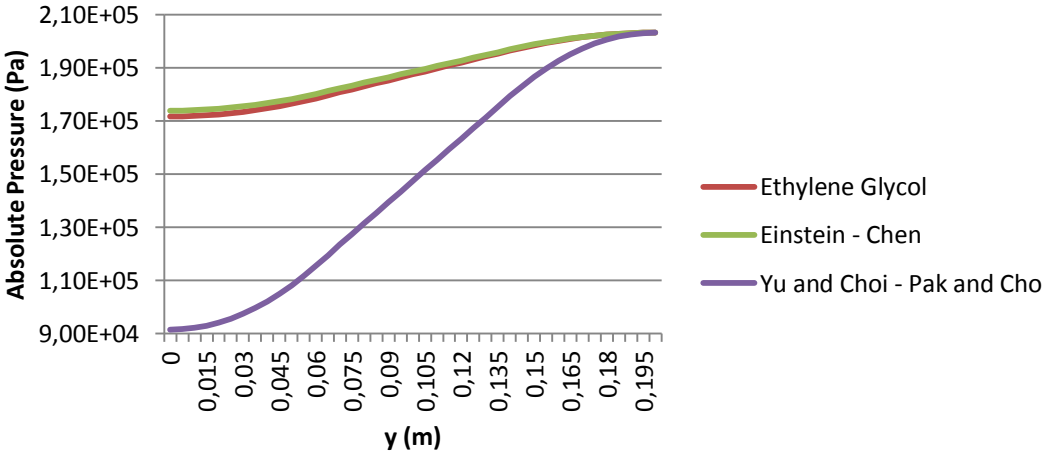

Figure 7. Pressure profile of a heat pipe containing ethylene glycol and ZnO nanofluids

It is important to notice that the study of Putra *et al.* (2012) does not obtain the pressure field along the wick structure. However, studies like Gavtash et al. (2012) and Zhu and Vafai (1999) obtain qualitative similar results to the presented pressure fields.

From Fig. 6, it is clear that the simple introduction of the nanofluids properties wasn't able to reproduce the effect obtained in the experimental study of Putra *et al.* (2012). However, the behavior of the properties alteration is qualitatively similar to the expected effect, once the linear correlation obtained between experimental data and the Einstein-Chen solution is 0,99 at the condenser and adiabatic sections. So, there is a possibility that the introduction of

nanofluids in heat pipes have a direct effect in the steady state temperature, so that the average temperature could be reduced to the desired levels.

From Fig. 7, it is important to notice that, although the enhancement of the dynamic viscosity is much more identifiable than the change of the other parameters, the change of the specific mass can result in a nanofluid with less pressure drop than the original base fluid.

In order to compare the effect of a different working fluid along the nanofluids studied, an evaluation of the thermal behavior of the heat pipe using water (k_{ef} = 1,6092) was also verified and the results can be observed at Fig. 8.

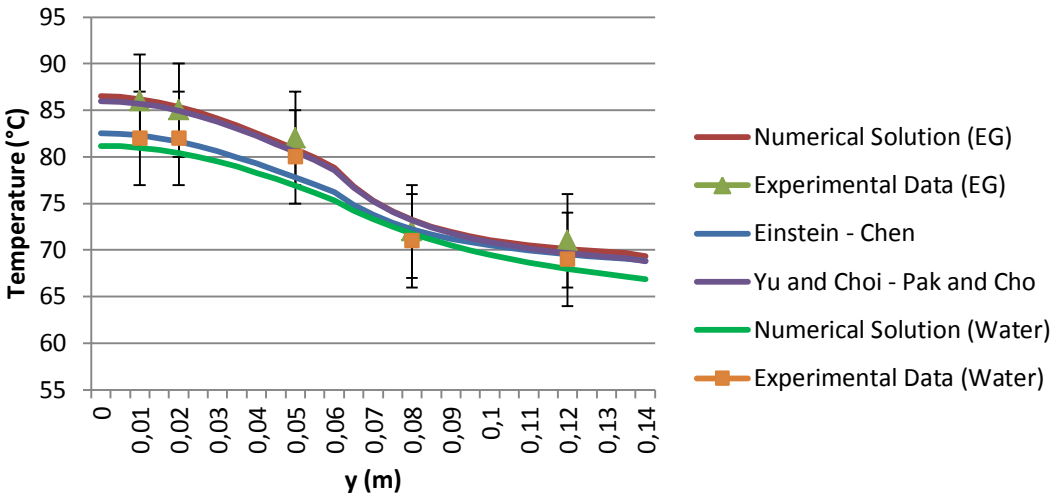

Figure 8. Temperature profile at the evaporator and the adiabatic section of a heat pipe containing ethylene glycol, ZnO nanofluids and water

It is important to notice that the effective thermal conductivity of the Einstein-Chen solution (1,3042) stands between the effective conductivity of the ethylene glycol (0,7098) and the effective conductivity of the water (1,6092), and this behavior is quite well reproduced in Fig. 8. Also, the behavior of the fluids that does not contain any nanoparticle is reproduced quite well in the evaporator and the adiabatic section, with a maximum deviation of 3,09 ºC, or 3,87%, obtained with water.

5. CONCLUSIONS

It has been well defined that the simple change of the properties of the working fluid on the presented computational model used for numerical simulation of a heat pipe cannot represent exactly the behavior of a heat pipe containing nanofluids. So, the main objective of defining a set of equations to represent the behavior of these nanofluids into a heat pipe could not be achieved by the present work.

However, once the linear correlation obtained between the experimental data using ZnO nanofluids and the Einstein-Chen model at the evaporator and adiabatic sections reached 0,99, it is sufficiently safe to say that the obtained numerical solution is a precise qualitative solution, and that there must exist some kind of adjustment independent of the thermal conductivity that drop the temperature of the heat pipe to the experimentally obtained levels. This idea is reinforced by the behavior of the thermal conductivity presented at the Putra *et al.*(2012) study, once the thermal enhancement ratio obtained in this study was lower than the thermal conductivity obtained by all the studied correlations. And once the specific mass, the dynamic viscosity and the specific heat were also changed in this study with the introduction of nanofluids, this adjustment should have direct relation with other parameters, like the vaporization enthalpy or the steady state temperature.

It must be also said that the behavior obtained by the change of the fluids properties reproduce correctly the behavior expected by the simple change of the effective thermal conductivity, once the higher effective thermal conductivity obtains the lower evaporator temperature, the lower effective thermal conductivity obtains the higher evaporator temperature and all the intermediate cases are located between these two cases.

Also, the simple addition of a fixed temperature at the end of the condenser section of the heat pipe could not reproduce correctly the thermal behavior obtained in the study of Putra *et al* (2012). However, the remaining sections were reproduced by the numerical model with a high precision level while using only base fluids (minimum of 96,13% using water). This leads to believe that the boundary condition applied to the evaporator section should be modified to get closer to the corresponding experimental condition used in the study of Putra *et al.*(2012).

Finally, it is important to acknowledge that the simple enhancement of the thermal conductivity was responsible for a reduction on the temperature of the evaporator in all studied cases, which proves the correct sensibility of constructed model to the fluid properties. This can be also observed by the obtained pressure fields, where both dynamic viscosity and specific mass had their influence in the obtained results.

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