Modelling of a screen mesh wick heat pipe using Al$_2$O$_3$ nanofluids

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Abstract. In this work, a phenomenological model that considers the interaction of nanoparticles of a Al$_2$O$_3$/water nanofluid within a cylindrical mesh wick heat pipe has been developed. The model is based on Navier-Stokes equations and it uses population balance as a method to account for the interaction of nanoparticles. The model predicted values of capillary limit with nanofluids up to 32% higher than that of the heat pipe using DI water. Those values were in agreement with the values found experimentally. Although the better performance of the capillary limit in the model was a consequence of the reduction of the pore radius which increases the capillary pressure, that was not the main cause for better capillary limit in experimental conditions at lower nanofluid concentrations. On the other hand, it was found that exists an optimum concentration of nanoparticles which decreases the effective thermal resistance of the heat pipes. In this work, that concentration was 0.5% w/w.

1. Introduction

Heat pipes are an alternative technology for making compact and high effectiveness heat exchangers. However, heat pipes are subject to operating limits, which are a series of physical phenomena that stop heat transfer. Therefore, a modification of the physical properties of the working fluid or the wick structure can help to counteract the effects of the operating limits, particularly the capillary limit.

In the mid-90s, the concept of suspensions of nanoparticles in common fluids denominated as “nano fluids” was first proposed [1]. It has been shown that nanofluids modify some properties of the base fluid, such as thermal conductivity, viscosity, wetting angle and the amount of heat that can be transferred by boiling [2–7]. On the other hand, since nanoparticles can be transported together with the base fluid within the wick in a heat pipe, it is possible that nanoparticle deposition on the surface of the wick occurs. The nanoparticle layer so formed can modify the capillarity of the wick [8].

Several theoretical studies have considered the nanoparticle layer existence on the surface of the wick of heat pipes [7,9–11]. Those works found an optimum concentration of nanoparticles to achieve a low thermal resistance of the heat pipe. The optimum concentration of nanoparticles is generally

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associated to the competition between two effects: on one hand, there is an extension of the evaporation surface because of the formation of the nanoparticle layer; on the other hand, there is an increase in the pressure drop along the wick due to the increased thickness of the nanoparticle layer [10]. However, those results were obtained only considering the effect of variation in the nanofluid physical properties such as viscosity and density as a function of the concentration of nanoparticles. No interactions of the nanoparticles in nanofluid to form a porous layer was considered. In other cases, the authors increased arbitrarily the diameter of the threads in the screen mesh of the wick to account nanoparticles deposited layer [11], assuming an uniform deposition.

On the other hand, population balance has been widely used to analyze how particles can be born or destroyed inside a control volume. This is particularly interesting in systems where phenomena like aggregation occur, such as the aggregation of nanoparticles in nanofluids. Therefore, accounting for the change of the nanoparticle size and concentration is useful to model changes in thermal properties of nanofluids within a heat pipe. The problem of modeling of nanofluids agglomeration and thermal conductivity using population balance has been addressed in previous researches [12,13] and it has been concluded that population balance is useful to model the stability, aggregation and growth of nanoclusters when there are interactions between the nanoparticles.

In this work, a phenomenological model that considers the interaction of nanoparticles of Al₂O₃ in a nanofluid to form a layer of nanoparticles in the wick of a cylindrical heat pipe has been developed. The model is based on Navier-Stokes equations for mass and energy, including energy balance to account for the vaporization and condensation mass flow. The Darcy – Forchheimer equation was used to model velocity and pressure profiles in the porous wick. A coupling between the population balance equations and the hydrodynamic of the liquid in the wick was used as a method to account for the interaction of nanoparticles and how this interaction influences the formation of a layer of nanoparticles over the porous wick. Validation of the model results have been performed by comparison with experimental data obtained in a heat pipe using a Al₂O₃/water nanofluid.

2. Materials and methods

2.1. Model description
The computational domain consists of the wick and wall of a cylindrical heat pipe as shown in Figure 1, since the heat pipe has been supposed to be axisymmetric. Transient, laminar and incompressible one dimensional continuity equation was solved for the liquid in the wick:

$$\frac{\partial}{\partial t} (\varepsilon \rho_l) + \frac{\partial}{\partial z} (\rho_l v_{lz}) = \dot{m}_{L-V}$$  (1)

![Figure 1. Outline of the control volume for the numerical model.](image)

The Darcy – Forchheimer equation was used to calculate velocity and pressure profiles of the nanofluid
within the wick:

\[
\frac{dP_l}{dz} = -\frac{\mu}{K} v_{l,z} - \rho_l g \frac{dh}{dz} - \frac{C_E}{\sqrt{K}} \rho_l v_{l,z}^2
\]  

(2)

\(C_E\) is the Ergun coefficient, which is calculated as follows:

\[
C_E = \frac{1.75}{\sqrt{150} \varepsilon^{3/2}}
\]  

(3)

A 2D transient energy equation was applied to the wall around the wick:

\[
\frac{\partial}{\partial t} (\rho_w C_{pw} T_w) = \frac{\partial}{\partial z} (k_w \frac{\partial T_w}{\partial z})
\]  

(4)

In order to simplify the calculations in the central region of the heat pipe, it has been assumed that vapor is saturated at constant pressure [14]. On the other hand, an energy balance in the wick-vapor interface was performed to calculate the temperature:

\[
\dot{m}_{L-v} h_{fg} + \dot{m}_{L-v} C_{pv} T_i = \frac{T_w - T_i}{R_{eff}} + \dot{m}_{L-v} C_{pl} T_i
\]  

(5)

In the wick-vapor interface, there is a constant mass flow of vapor and liquid due to the phase change of the working fluid. This flow was calculated according to the Knudsen, Hertz and Scharage equation [15]:

\[
\dot{m}_{L-v} = \frac{2 \eta_{ev}}{2 - \eta_{ev}} \sqrt{\frac{M}{2 \pi \overline{R}}} \left[ \frac{P_i}{\sqrt{T_i}} - \frac{P_v}{\sqrt{T_v}} \right]
\]  

(6)

The experimental accommodation coefficient \(\eta_{ev}\) was supposed to be 0.03 because of the evaporation inside the heat pipe occurs at low temperature [16]. Due to the phase change, it is necessary to calculate the pressure in the interface, which could be done by applying the Clausius – Clapeyron equation:

\[
\frac{\overline{R}}{h_{fg}} \ln \left( \frac{P_i}{P_0} \right) = \frac{1}{T_0} - \frac{1}{T_i}
\]  

(7)

As the liquid flows through the wick, an effective thermal conductivity of this section of the heat pipe can be calculated as follows:

\[
k_{eff} = \frac{k_l (k_l + k_m - (1 - \varepsilon)(k_l - k_m))}{k_l + k_m + (1 - \varepsilon)(k_l - k_m)}
\]  

(8)

The porosity and absolute permeability of the screened mesh wick were calculated according to equations (9) and (10):

\[
\varepsilon = 1 - \frac{S_c \pi N_m d_m}{4}
\]  

(9)
\[ K = \frac{d_n^2 \varepsilon^3}{122(1 - \varepsilon)^2} \]  \hspace{1cm} (10)

The boundary conditions were defined as shown in Table 1:

**Table 1. Boundary conditions of the model**

| Boundary                  | Description                  |
|---------------------------|------------------------------|
| Evaporator wall           | Constant heat flux           |
| Adiabatic section wall    | Constant heat flux = 0       |
| Condenser wall            | Convective heat transfer     |
| Upper and lower caps wall | Constant heat flux = 0       |
|                           | Velocity of the liquid = 0   |

\[ Q_{in} = h_c A_c (T_w - T_\infty) \] \hspace{1cm} (11)

Thermal conductivity of the nanofluid was calculated according to heat conduction on the nanolayer [17]:

\[ k_{nf} = \frac{k_{pe} + 2k_l + 2(k_{pe} - k_l)(1 + \beta)^3 \phi}{k_{pe} + 2k_l - (k_{pe} - k_l)(1 + \beta)^3 \phi - k_l} \] \hspace{1cm} (12)

\[ k_{pe} = \frac{[2(1 - \alpha) + (1 + \beta)^2(1 + 2\alpha)]\alpha}{-(1 - \alpha) + (1 + \beta)^3(1 + 2\alpha)} k_p \] \hspace{1cm} (13)

\[ \alpha = \frac{k_{layer}}{k_p} \] \hspace{1cm} (14)

\[ \beta = \frac{w}{r_p} \] \hspace{1cm} (15)

The thickness of the nanolayer \( w \) was supposed to be 2 nm [17], but a further analysis is required to find a more exact value. To complete the calculation of the thermal properties, the following equations were used to calculate viscosity [18], surface tension [19], density and specific heat [20] of the nanofluid, respectively:

\[ \mu_{nf} = \mu_l (1 + 39.11\phi + 533.9\phi^2) \] \hspace{1cm} (16)

\[ \sigma_{nf} = \sigma_l (1 - \phi) \] \hspace{1cm} (17)

\[ \rho_{nf} = (1 - \phi)\rho_l + \phi\rho_p \] \hspace{1cm} (18)

\[ C_{p,nf} = \frac{(1 - \phi)\rho_l C_{p,l} + \phi\rho_p C_{p,p}}{(1 - \phi)\rho_l + \phi\rho_p} \] \hspace{1cm} (19)

The population balance of nanoparticles was discretized according as follows:
Retention of nanoparticles in the wick in every time step was calculated with the following Ordinary Differential Equations system:

$$\frac{\partial N_{i,r}(t)}{\partial t} = \kappa_a \left( 1 - \frac{\varepsilon}{\rho_m \rho_p} \right) N_i(t) - \kappa_d N_{i,r}(t)$$

(23)

The values for $\kappa_a$ and $\kappa_d$ were $2.3 \times 10^{-3}$ and $2.0 \times 10^{-3}$ s$^{-1}$, respectively [23]. Coupling of the hydrodynamic model with the population balance was as follows: the velocity and the temperature fields were calculated with equations (1) - (7) in every time step. Once those fields are known, population balance equations (20) and (23) were solved and the new distribution of nanoparticles size was calculated in every cell of the grid. As retention of nanoparticles on the wick reduces the bulk suspended nanoparticles, the porosity and pore radius of the wick were reduced in proportion to the volume of the retained nanoparticles. After modification of the later properties of the wick, capillary pressure was calculated in every cell of the domain. With the new number of suspended nanoparticles, the physical and thermal properties were calculated, and a new time step was initiated. This procedure continued until the steady state of vapor pressure in the heat pipe was reached.

2.2. Experimental setup

To validate the numerical results, four copper heat pipes 0.6 m long and 3/4 inches diameter were used. The length of the evaporator, adiabatic zone and condenser was 0.2 m, respectively. Inside the tubes, a copper 100 mesh/inch screen was rolled three times to form the porous wick. Heat input was provided by two electrical resistances attached to two aluminum pieces in contact with the evaporator walls. The intensity of the heating was controlled with a variable current and voltage power supply. A jacket filled with cool water at 20°C coming from a thermostatic bath was attached to condenser wall. The following number of type K thermocouples were attached in the heat pipe wall: 3 in the condenser, 3 in the adiabatic zone and 7 in the evaporator. Data of temperature profile was obtained with a data acquisition system. The inclination of heat pipe was 0°. The experimental setup can be seen in Figure 2.

CuO nanoparticles (Sigma Aldrich, < 50 nm) were suspended in DI water using an ultrasonic probe at 20 kHz for 20 minutes. The four heat pipes were filled separately with DI water and nanofluids containing 0.1%, 0.5% and 1.0% w/w of CuO nanoparticles.

After preparation of the nanofluids, a Dynamic Ligh Scatering – DLS (NanoPlus HD – Particulate Systems) analysis was conducted to each nanofluid to determine the distribution of number and size of the nanoparticles on the surface of the wick was supposed to follow a Langmuir isothermal according to equation (21):

$$\rho_m (1-\varepsilon) \frac{\partial S}{\partial t} = \kappa_a \left( 1 - \frac{S}{S_{\text{max}}} \right) \varepsilon - \rho_m (1-\varepsilon) \kappa_d S$$

(21)

In this work, $S_{\text{max}}$ was calculated according to geometrical considerations as:

$$S_{\text{max}} = \frac{\pi}{3\sqrt{3}} d_p \rho_p \rho_s$$

(22)
particles and aggregates. These distributions are shown in Figure 3 after data processing using MATLAB®. This information was used later to set the initial conditions for population balance in the model.

Figure 2. Test rig. 1) Condenser 2) Evaporator 3) Adiabatic 4) Thermocouple signal (T1 – T13) 5) Thermostatic bath 6) Acquisition system 7) Power supply 8) Computer

Figure 3. DLS number distributions of nanoparticles in the nanofluids. a) 0.1% w/w b) 0.5% w/w c) 1.0% w/w
3. Results and discussion

There are several complications when nanofluids are used as working fluid due to the instability of the suspension of the nanoparticles. Figure 3 shows how the amount of nanoparticles suspended has a strong dependence on concentration. When the concentration of nanoparticles is low, there are more nanoparticles suspended and they form aggregates in a wide range of particle size. As concentration is higher, the number of nanoparticles suspended is consequently higher but the distribution of particle size falls in a narrow range, which is an indication of a precipitation of aggregates of higher size. Indeed, when the maximum concentration was analyzed, a secondary distribution of higher size was detected before it precipitated totally. These instabilities have incidence in the filling of the heat pipe since bigger aggregates go straight to the lower end of the tube and therefore, the concentration of nanoparticles within the wick is lower than the initial concentration which the nanofluid was prepared. In Figure 4, a SEM image of a part of the wick close to the bottom cap when the nanofluid 1.0% w/w was used. The presence of a big mass of aggregated nanoparticles which blocks the pores of the wick is mainly associated to the sedimentation of nanoparticles during the filling of the heat pipe.

![SEM image of the wick near the lower cap with nanofluid at 1.0% w/w](image)

Figure 4. SEM picture of the wick near the lower cap with nanofluid at 1.0% w/w

A comparison between the pressure drop and the capillary pressure in the wick is shown in Figure 5. This comparison is achieved after 2000 time steps, which are equivalent to 2000 seconds as the time step was fixed at 1 second. Every figure shows the approximate input power where capillary pressure is very close to total pressure drop in the mesh for every nanofluid concentration. If the pressure drop in the vapor is assumed as negligible, Figure 5a-d actually show the capillary limit in every case.
Figure 5. Pressure drop and capillary pressure in wick a) Water at 62 W b) Nanofluid 0.1% w/w at 73 W c) Nanofluid 0.5% w/w at 79 W d) Nanofluid 1.0% w/w at 82 W

Capillary limit for DI water was 62W, corresponding to a capillary pressure around 102.7 Pa. Furthermore, the capillary limit and the pressure drop increased as the concentration of nanoparticles was augmented. The numerical capillary limit was 73, 79 and 82 W for nanofluids 0.1%, 0.5% and 1.0% w/w, respectively, and the capillary pressures were 223.4, 619.5 and 799.5 Pa, respectively. This result is explained considering that the numerical model account for the attaching of nanoparticles in the mesh, which diminishes the porosity and the effective pore radius. This reduction causes an increasing of the capillary pressure as it has been established by the Young-Laplace equation:

\[ P_c = \frac{2\sigma_{nf}}{r_{eff}} \]  \hspace{1cm} (24)

Therefore, it is expected that the more nanoparticles are suspended in the nanofluid, the more of them are susceptible to deposit in the wick wires and so, the capillary limit could be increased significantly at high nanofluid concentrations. However, comparison with the experimental results shown in Figure 6 evidences that higher nanofluid concentrations actually can affect negatively the performance of the heat pipe. In order to determine the capillary limit experimentally, the effective thermal resistance of the heat pipe was calculated with the equation (25) and it was plotted against the input power in the evaporator, as shown in Figure 6:

\[ R_{hp} = \frac{T_{ev} - T_{cd}}{Q_{in}} \]  \hspace{1cm} (25)
Detection of capillary limit has been addressed to identify the heat input rate where effective thermal resistance show an increasing after a constant decrease [24]. The average thermal resistance for each working fluid is shown in Figure 6. It can be seen that experimental capillary limit with water is between 60 and 70 W, which agrees with the numerical capillary limit around 62 W. For the nanofluid 0.1% w/w, the experimental capillary limit was found between 70 and 80 W, while the numerical prediction was around 73 W. Similarly, experimental capillary limit for nanofluids 0.5% w/w and 1.0% w/w were found in the ranges 70 - 80 W and 70 – 90 W, respectively. The numerical predictions for these capillary limits were 79 W and 82 W, respectively.

As can be seen from the results, capillary limit prediction of the numerical model taking into account the deposition and agglomeration of nanoparticles was in acceptable agreement with the experimental evaluation, although exact values could not be found in the experimental conditions. Therefore, inclusion of nanoparticles proved to be effective to increase the capillary limit of the studied heat pipes. However, the relative improvement of the heat pipe performance with nanoparticles should not be attributed only to the deposition of them on the wick. The condition of the wick after the experimental tests is shown in Figure 7. These images correspond to a magnification of 1000x. It can be seen that deposition of nanoparticles was only significant for the nanofluid with concentration 1.0% w/w. With the other two nanofluids (0.1% and 0.5% w/w), few aggregates were observed in the wick, which means that the deposition in these cases is not suitable to reduce the effective pore radius significantly. However, since some nanoparticles are present in the base fluid, there are modification of physical properties as the surface tension, which affects the capillary pressure. This effect was considered in the numerical model with the simple relation in equation (17), but it is possible to think the real behavior to be more complex due to the effect of the temperature and the modification of the wick surface.
Figure 6 also shows how the concentration of the nanoparticles influences the thermal performance of the heat pipes. The thermal resistance of the DI water and the nanofluid at 0.1% w/w were statistically the same in the point where the capillary limit was reached. However, the nanofluid at 0.5% showed a meaningful reduction of the effective thermal resistance in all the heat inputs. This means that addition of nanoparticles increases the heat transfer through the wick and this is likely due to the increasing of the effective thermal conductivity of the working fluid. However, further increasing in the concentration of nanoparticles leads to massive agglomeration and deposition of aggregates in the wick as shown in Figure 4 and Figure 7c. Such deposition creates and additional thermal resistance in the wick and it is expected that the effective thermal resistance of the heat pipe increase. This could be the reason which...
the nanofluid at 1.0% had the worst performance according to the results shown in Figure 6. Therefore, there is likely an optimum amount of nanoparticles to improve the performance of the heat pipes. In the present case, that concentration was 0.5% w/w.

4. Conclusions
A numerical model was developed to account for the effect of nanoparticle interactions when nanofluids are used as working fluid in a heat pipe. The model consisted in a coupling of a hydrodynamic model based on the Navier-Stokes equations and population balance. The numerical calculations were compared with experimental results.

Experimental results showed that stability of the nanoparticles suspensions affect the performance of the heat pipe because during the filling of the heat pipe, the early formation of aggregates in the nanofluid creates big deposition on the porous wick, blocking the circulation of the working fluid.

The numerical model predicted values of capillary limits with nanofluids up to 32% higher than that using DI water. Those predicted values were within the intervals where the capillary limit was found experimentally. According to the numerical results, the improvement in the capillary limit can be explained in the reduction of the effective pore radius which increase the capillary pressure. However, inspection of the wick after the operation of the heat pipes showed that deposition of nanoparticles was not significant at low concentrations (0.1% and 0.5% w/w), which means that the apparent decrease of the pore radius is not the main cause for improvement of the capillary pressure and other effects should be analyzed in future research such as the modification of the surface and the effect of coupled interaction of nanoparticles and temperature on properties such as the surface tension.

Finally, there was an optimum amount of nanoparticles which decreases effective thermal resistance of the heat pipes, which was 0.5% w/w in this work. Concentrations higher than that optimum concentration are suspected to increase the thermal resistance in the wick due to massive deposition of nanoparticles.

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Nomenclature

\[
\begin{align*}
A_c & : \text{area of the condenser (} m^2) \\
c & : \text{volumetric concentration of nanoparticles (} kg/m^3) \\
C_{pl} & : \text{specific heat of the liquid (} J/kg.K) \\
C_{p, nf} & : \text{specific heat of the nanofluid (} J/kg.K) \\
C_{p, p} & : \text{specific heat of the nanoparticle (} J/kg.K) \\
C_{pv} & : \text{specific heat of the vapor (} J/kg.K) \\
C_{pw} & : \text{specific heat of the wall (} J/kg.K) \\
d_m & : \text{diameter of the mesh wire (} m) \\
d_p & : \text{diameter of the nanoparticles (} m) \\
g & : \text{acceleration of gravity (} m/s^2) \\
h & : \text{height respect of a reference level (} m) \\
h_c & : \text{convective coefficient (} W/m^2.K) \\
h_{fg} & : \text{latent heat of vaporization (} J/kg) \\
K & : \text{absolute permeability (} m^2) \\
k_{eff} & : \text{effective thermal conductivity (} W/m.K) \\
k_l & : \text{thermal conductivity of the liquid (} W/m.K) \\
k_{layer} & : \text{thermal conductivity of the nanolayer (} W/m.K) \\
k_m & : \text{thermal conductivity of the wick (} W/m.K) \\
k_p & : \text{thermal conductivity of the nanoparticles (} W/m.K) \\
k_w & : \text{thermal conductivity of the wall (} W/m.K)
\end{align*}
\]
\(M\) : molar mass (kg/kmol)
\(n_{\text{flow}}\) : mass flow in the interface (kg/m³.s)
\(m_i\) : mass of a nanoparticle (kg)
\(N_i\) : nanoparticles per volume of nanofluid (m⁻³)
\(N_{i,r}\) : nanoparticles retained (m⁻³)
\(N_{p}\) : pores per lineal meter (m⁻¹)
\(P_{ref}\) : reference pressure (Pa)
\(P_e\) : capillary pressure (Pa)
\(P_l\) : pressure of the liquid in the wick (Pa)
\(P_i\) : pressure in the interface (Pa)
\(P_v\) : vapor pressure in the vapor core (Pa)
\(Q_{in}\) : volumetric flow of heat in the wall (W/m³)
\(Q_{out}\) : volumetric flow of heat out of the wall (W/m³)
\(R\) : universal constant of gas (8.314 kJ/kmol.K)
\(\bar{R}\) : particular constant of gas (kJ/kg.K)
\(R_{eff}\) : effective conductive thermal resistance (W/m.K)
\(R_{np}\) : effective thermal resistance of the heat pipe (°C/W)
\(r_{eff}\) : effective pore radius (m)
\(r_p\) : radius of the nanoparticle (m)
\(S_d\) : mass of nanoparticles retained per mass unit of the wick (kg/kg)
\(S_{max}\) : max. mass of nanoparticles which can be retained per mass unit of the wick (kg/kg)
\(T_{w_o}\) : reference temperature (K)
\(T_{w,c}\) : average wall temperature across the condenser (K)
\(T_{w,e}\) : average wall temperature across the evaporator (K)
\(T_i\) : temperature in the interface (K)
\(T_v\) : temperature in the vapor core (K)
\(T_w\) : temperature of the wall (K)
\(T_{c}\) : temperature of the cool stream (K)
\(v_{ax}\) : axial velocity (m/s)
\(v_{in}\) : inlet velocity (m/s)
\(v_{out}\) : outlet velocity (m/s)
\(x_i\) : volume of nanoparticle (m³)
\(w\) : thickness of the nanolayer (m)
\(\Delta Z\) : size of the grid (m)
\(\varepsilon\) : porosity
\(\phi\) : volumetric fraction of nanoparticles
\(\kappa_a\) : adsorption rate (s⁻¹)
\(\kappa_d\) : desorption rate (s⁻¹)
\(\mu\) : viscosity of the liquid (N.s/m²)
\(\mu_b\) : viscosity of the base fluid (kg/m³)
\(\mu_{nf}\) : viscosity of the nanofluid (N.s/m²)
\(\rho_l\) : density of the liquid (kg/m³)
\(\rho_{nf}\) : density of the nanofluid
\(\rho_p\) : density of the nanoparticle (kg/m³)
\(\rho_s\) : surface area per unit mass of the wick (m²/kg)
\(\rho_w\) : density of the wall (kg/m³)
\(\sigma_l\) : surface tension of the liquid (N/m)
\(\sigma_{nf}\) : surface tension of the nanofluid (N/m)

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