THE EFFECTS OF NANOFLUIDS ON THERMAL PERFORMANCE OF HEAT PIPES

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Abstract

A new technique in determining the thermal efficiency in heat pipes is to use nanofluids as working fluids in the heat pipes. Heat pipes are effective heat transfer contraptions which nanofluid operates in two phases: evaporation and condensation. The heat pipe transfers the heat supplied in e.g. an oven, from the evaporator to condenser. Nanofluids are mixtures of nanoparticles (e.g. nano-sized silver particles) and a base fluid (e.g. water). The aim of this research has been to examine the effect of nanofluids on heat pipes on the subject of temperature parameters and thermal resistance in the heat pies, through findings in literature and an applied model. The study, based on literature and an applied model, found that higher particle conductivity and higher concentration of nanoparticles reduce the thermal resistance in the heat pipes, resulting in an enhanced thermal efficiency of the heat pipes with nanofluids as working fluids. It is however concluded that difficulties in finding the optimal synthesis of nanofluids, the concentration level of nanoparticles and the filling ratio of nanofluids in heat pipes, set bounds to the commercial use of nanofluids in heat pipes. It is suggested that, in order to increase the heat transfer capacity of nanofluids in heat pipes, to conduct further research concerning e.g. synthesis of nanofluids and concentration aggregate of nanoparticles in nanofluids.

Introduction

Heat pipes are used to transfer heat in vehicles and hard ware applications as for instance computers. With continued development of technological equipment it is important to find effective ways to manage heat transfer in heat pipes. By using nanofluids as working fluids in heat pipes the thermal efficiency of heat pipes is enhanced (Shafahi et al., 2010a). Consequently, the key questions in this research to be answered, in order to increase the comprehension of the topic, are the following:

1. What is a nanofluid?
    - How are nanoparticles produced
    - What are the empirical affecting a nanofluid?
2. **2.** How does a heat pipe function?
3. **3.** What is the effect of nanofluids on heat pipes v13 av13 thermal resistance?
    - What about the effect of concentration and thermal conductivity in nanofluids?

Report

The core of the report is divided into three layers. In part one a literature study of nanofluids concerning their definition, synthesis and thermal conductivity will be provided.

Part two will describe the basic function of a heat pipe and the effect of nanofluids in heat pipes by investigating the effects of nanofluids from eight different studies.

Part three will discuss the methodology of the report as well as defining the model limitations and calculations steps of the model. Furthermore the thermal resistance network in heat pipe and the applied model will be presented the results from the applied model on i.e. thermal resistance in the heat pipe will be x-rayed in relation theoretical background. A sensitivity analysis is then presented by identifying key parameters in the model and the nanofluid related parameters are synthesized.

Furthermore, essential findings from part one, two and three will be discussed compared and concluded in the final chapters. In Appendix A, the program code of the model is attached.

Problem and objective statement

In order to grasp the relevance and functionality of nanofluids and the effect of nanofluids in heat pipes, an adequate research on the subject is needed. It is proposed to complete a study in the interface between nanofluids and heat pipe with focus on heat transfer principles e.g. thermal resistance and thermal conductivity, through a literature study and model analysis on the subject.

The objective of this research has been to analyze nanofluids and their effect on heat pipes based on thermophysical parameters. This is the intermediate objective has been to produce a model for analysis of the effect of nanofluids on heat pipes regarding temperature and thermal resistance. The results from the model are then to be discussed in relation to the literature studies in order to draw conclusions from both model and literature studies.

Definition of Nanofluids

Fluids have been utilized as a working material for cooling purposes such as engine oil, water and ethylene glycol. These fluids have lower thermal conductivity than metals and ionic components such as: copper, silver, and copper oxide. The properties of these metals and ionic components gave rise to a fluid that consist of a mixture of a base fluid and metals, initiated by Maxwell. This idea of a suspension, resulted to the improvement in one of the most important parameters in a working fluid: thermal conductivity (Behi and Mirmohammadi, 2012). A suspension is a heterogeneous mixture in which solute-like particles settle out of a solvent-like phase sometime after their introduction (Chemicool, 2014).

Choi et al. defined the nanofluids as “an innovative new class of heat transfer fluids that can be engineered by suspending nanoparticles in conventional heat transfer fluids” (Iborra Rubio, 2012) where nano-sized particles of 1-100 nm were added to base fluids in order to improve performance of heat transfer by significantly enhancing the thermal conductivity of the fluid. The benefits of nanofluids in comparison to microfluids (of micro-sized particles) have been researched and it is found that nanofluids possess longer suspension time, higher thermal conductivity and are more energy efficient. Improving thermal transport properties of nanofluids has been claimed to be vital for obtaining a higher heat exchanging efficiency, cost reduction and reducing the system size (Iborra Rubio, 2012).

Nanoparticles exist in form of e.g. metals, metal oxides and carbon materials. They are of various morphological characteristics and appear as spheres, cylinders, disks etc. (Nagarajan, 2008). The thermal conductivity of nanoparticles is usually up to hundred times larger than base fluids. For instance, non-metallic solids such as diamond have a thermal conductivity if 3300 W/mK while non-metallic liquids such as water have a thermal conductivity of 0,613 W/mK (Das et al., 2007b). In addition to thermal conductivity, there are three other parameters impacting nanofluids: specific heat capacity, dynamic viscosity and density (Das et al., 2007a, b, d). However, they are not included in the scope of this report and therefore not deeply discussed.

Synthesis of nanoparticles

The preparation process and synthesis of nanofluids is an important to obtain increased performance of nanofluids and improved thermal transport properties. It is important to achieve homogenous suspensions in order to optimize thermophysical properties of nanofluids. Current scientific experiments and researches are focusing on improving the thermal conductivity by considering the effective parameters of thermal conductivity and predicting the behavior of nanofluids (Behi and Mirmohammadi, 2012). Substances, also known as additives, are used to prepare nanofluids by utilizing base fluids and nanoparticles in order to increase the stability and enhance the performance of the dispersion of nanofluids.

The production process of nanoparticles is divided into two approaches: top- and bottom-down synthesis of nanomaterial and fabrication of nanostructures (Iborra Rubio, 2012). The top down approach involves the process of breaking down bulk material into nano-sized particles and structures. The approach is an extension of methods that have been used for producing microsized particles, considered more suitable for creating cohesive structures. Mechanical size reduction such as grinding and milling are examples of top down approaches. The more economical alternative, the bottom up approach, refers to a controlled assembly process in the build-up of a material, using atom-by-atom, or molecule-by-molecule procedures. This method is preferable for creating identical structures with atomic precision (Das et al., 2007a, b, c, d, e).

Thermal conductivity of nanoparticles and base fluids

The heat transfer efficiency of a heat pipe is related to the thermophysical restrictions of the working fluid. Thermophysical restrictions on the other hand depend mainly on the thermal conductivity of the working fluid. Thermal

conductivity illustrates the ability of a substance to conduct heat. The higher the thermal conductivity of the fluid the more effective is the heat transfer capability of heat pipe (Iborra Rubio, 2012).
In order to enhance the thermal conductivity, highly conductive solid nanoparticles can be added to a base fluid (Shafahi et al., 2010a) e.g. water, ethylene glycol or pump oil (Behi and Mirmohammadi, 2012). The result is a nanofluid i.e. a colloidal suspension of solid particles with the size lower 100 nanometers (Behi and Mirmohammadi, 2012).

The increased effect of nanofluids in heat pipes
Nanofluids are used in heat pipes in order enhance the thermal efficiency of the heat pipe and they are evaluated by their effect on the thermal efficiency. The thermal efficiency represents the ratio of heat rejected at the condenser section and the heat input at evaporator section (Senthilkumar et al., 2011). The considered parameters of thermal efficiency are the following (Naphon et al., 2008):

- Charge amount of working fluid
- Tilt angle of heat pipe
- Volumetric concentration of nanoparticles
- Thermal resistance
- Temperature gradient

Moraveji et al. studied the effects of aluminum oxide ($Al2O3$) and water-based nanofluids in heat pipes. The experiment was based on a straight copper tube with an outer length of 8 and 190 mm and a 1mm wick-thickness sintered circular heat pipe. Three working fluids were used: pure water and water-based aluminum oxide with volumetric concentration of 1 and 3 %. Furthermore the heat load varied from 5 to 60 W. The essential findings are referred to two effects (Keshavarz Moraveji and Razvarz, 2012): a) the temperature difference between evaporator and condenser in relation to heat load and b) the thermal resistance of the heat pipe in relation to heat load. Concerning effect a) Moraeveji et al. concluded that higher volumetric concentrations of aluminum oxide resulted in smaller temperature differences up to heat loads of 52 W. With higher heat load than 52 W, the temperature difference of 1% aluminum oxide turned out to have the smallest temperature difference, while pure water constantly had the highest temperature difference. All working fluids also present the same sequential behavior with increased heat load: increasing temperature difference, sudden decrease in temperature difference and another cycle of increased temperature difference. This behavior depends on the improved rate speed between condenser and evaporator and the fraction of vapor in the process (Keshavarz Moraveji and Razvarz, 2012).

The incremental decrease of thermal resistance was negligible for heat loads higher than 40 Watt for all three working fluids: pure water, 1 % and 3% aluminum oxide based water. In fact, there was also a notable anomaly in regard to the 3% concentration of Aluminum oxide. A decrease in temperature difference between evaporator and condenser with increasing heat input to critical point was observed in the findings of Moraveji et. al. The temperature decrease of aluminum oxide was identified as smaller than that of the base fluid. Moraveji et al. also concluded that increased nanoparticle concentration resulted in reduced thermal resistance ensuing an improved thermal performance (Keshavarz Moraveji and Razvarz, 2012).

Research conducted by Senthilkumar et al. on a copper heat pipe is based on three distinct parameters: inclination of heat pipe to the horizontal axis, heat inputs and concentration of nanoparticles. The maximum thermal efficiency, approximately 60 %, is obtained at 45 ℃ angle of inclination, at maximum heat input of 70 W and with the 100 mg/lit concentration of copper nanoparticles. The highest concentration of 125 ml/lit did not outperform due to the fact of resistance to the fluid flow caused by the nanoparticles Notably, the thermal efficiency of 50 mg/lit nanofluid is higher or equal to the thermal efficiency of 125 mg/lit nanofluid at all heat inputs and angle of inclinations. Consequentially, this has positive economic and environmental outcome, with less nanoparticles performing overall better than more. The most effective nanofluid of 100 mg/ it has an incremental effect in thermal efficiency of less than 5 % at 70 W input and 45 ℃ angle of inclination. This increase does not vary at other heat inputs and inclinations (Senthilkumar et al., 2013).

Naphon et al. evaluated the thermal efficiency of various volumetric concentrations at the optimum of 45 ℃ angle of inclination. Due to the suspension of nanoparticles the overall thermal efficiency increased with the nanoparticle concentration. The volumetric concentration of 0.1 % titanium nanoparticles in pure alcohol (base fluid) resulted in the highest thermal efficiency of approximately 80% at heat flux of 7.27 $kW/m2$. Compared with pure alcohol the incremental thermal efficiency enhancement is 10.5 % (Naphon et al., 2008).

Teng et al. conducted comparable research to Moraveji et al. and came to the conclusion that nanofluid of aluminum oxide weight fraction 1% at inclination 60 ℃ and charge amount 20% had the highest thermal efficiency with 79.3%. Analogous to experiments by Naphon et al., the higher concentration of aluminum oxide nanoparticles with 3% wt. (weight percent) resulted in fact in a lower thermal efficiency reaching 75.6%, due to reduced convection performance at the evaporator section (Teng et al., 2010).

Research by Asirvatham et al. showed the that thermal conductivity of silver based nanofluid increased with 42.4%, 56.8% and 73.5% respectively for 0.003%, 0.006% and 0.009% volumetric concentration. Additionally a 76 % decrease in thermal resistance is observed for the 0.009% volumetric concentration. The authors declared three reasons for the heat transfer enhancement. First, an increased thermal conductivity due to the silver nanoparticles. Second, the coating layer formed on the wick and heating surface by the nanoparticles that improved the heat transfer effect. Third, the occurrence of Brownian motion due to silver and distilled water particles collision (Asirvatham et al., 2013).

Research conducted by Kang et al. focused on heat pipe temperature distribution and thermal resistance as parameters of thermal efficiency. Experiments on heat loads 30 W, 40 W, 50 W and 60 W with 10 nm nanoparticles reveal that the highest temperature gradient decrease from the base fluid (water) occurred when nanofluids with 50 ppm concentration were applied. However the highest incremental decrease of temperature gradient occurred when going from base fluid to the 1ppm nanofluid concentration, shifting from 41.06 ℃ to 40. 56 ℃ at the same position with 30 W heat-load (Kang et al. 2006). The application of 35 nm nanoparticles revealed analogous results in temperature gradient variations for the same concentrations and heat loads, implying that there is no significant difference in using 10 nm to 35 nm nanoparticles at given heat loads concerning temperature gradients (Kang et al., 2006).

Tsai et al. applied gold nanoparticles of diameters 2-75 nm by reducing adjusted amounts of the materials: aqueous hydrogen tetrachloroaurate with trisodium citrate and tannic acid. The nanoparticles were then added to distilled water (base fluid) at four different synthesis conditions of the materials mentioned. The thermal resistance of the base fluid and nanofluid during various heat inputs were evaluated on thermal performance. Distilled water obtained an average thermal resistance of 0.27 $℃/W$ compared to nanofluid of condition A (0.2 ml trisodium citrate, 2.5 ml tannic acid and 3 ml tetrachloroaurate) with an average thermal resistance of 0.17 $℃/W$. That corresponds to a 37 % decrease in thermal resistance (Tsai et al., 2004).

Shafahi et al., performed experiments on a cylindrical heat pipe using three different nanofluids at various concentrations consisting of water and aluminum oxide ($Al2O3$), copper oxide (CuO) and titanium oxide ($TiO2$) nanoparticles The heat pipe was exposed to different heat inputs for exploration of thermal resistance; temperature gradient and maximum heat transfer limits (Shafahi et al., 2010b). The thermal resistance was studied under heat load varying from 200 W to 800 W for all three nanofluids at four different concentrations. The study reveals that increasing concentrations of nanoparticles result in decreasing thermal resistance, implying a better thermal performance. Copper oxide particles had throughout the biggest effect on thermal resistance reduction, accounting for 75 % reduction with a 4% concentration. At the same concentration level aluminum oxide and titanium oxide particles accounted for a 77% and 86 % reduction respectively. The temperature gradient changes were studied with up to 4% particle concentration. The results reveal an incremental decrease of end to end temperature gradient (evaporator to condenser) with 5 % for nanoparticles aluminum oxide and titanium oxide, while copper oxide account for a 3% decrease (Shafahi et al., 2010b). It is notable that the temperature difference between evaporator and condenser increases with bigger nanoparticle diameter implying that smaller sized nanoparticle are more effective. That corresponds to the findings of Li et al. (see chapter 4.1.1.).

The experimental results of Shafahi et al. also reveal that there for every nanofluid exist a maximum heat transfer capacity at a given concentration level. A continues increase of concentration after reaching given levels in fact decreases the heat transfer. The optimum concentration level were found to be approximately 5 %, 15 % and 7 % for aluminum oxide, copper oxide and titanium oxide respectively (Shafahi et al., 2010b).

The model applied in this report is based on the mathematical model of Shafahi et al. for investigating the thermal performance of cylindrical heat pipes using nanofluids (Shafahi et al., 2010b). However, the model applied in this report is an overall simplification of realistic heat pipe functions with focus on nanofluids impact for solely temperature parameters (,, Tc and $Tdifference$) and thermal resistance. For more information on the model, see chapter 7.

Methodology

The methodology applied in this report is derived from the definition of a paradigm. Science is a collection of facts, theories and methodologies. Homogenous rules in methodologies are vital in order to classify a science as legitimate (Kuhn, 1996). Consequential to this logic the following operations framework is applied in this report, where the operations 1 and 3 as well as 2 and 3 are conducted concurrently:

1. **Definition:** literature study in order to gain fundamental knowledge of nanofluids and their effect on thermal performance of heat pipes
2. **Implementation:** Modeling with experimental data from KTH Lab research by Ghanbarpour and analytical data from the web
3. **Reporting:** analysis, comparison and evaluation of findings in literature and results from the model

Definition, the first operation, embeds an extensive literature study, divided in to two parts. Part one is concentrated on nanofluids in respect to inter alia: the concept, definition and thermal conductivity of nanofluids. Part two emphasizes the effect of nanofluids on the thermal performance of heat pipes.

Implementation, the second operation, consists of modeling the effect of nanofluids on heat pipes. The framework for the model is derived as mentioned from (Shafahi et al., 2010b) . The model will be based on analytical and experimental data. Laboratory research results of nanofluids in heat pipes performed by PhD student Morteza Ghanbarpour, at the Energy and Technology Department at KTH, accounts for the experimental data (see Appendix B). The analytical data is derived from the web (see Appendix C). The program language used for the modeling of formulas is the computer algebra system Maple. The code is attached to this report (see Appendix A).

Reporting, the third operation, deans as tool for keeping track of the alignment of the study

Model inputs and limitations

The model used in this study focuses on the effect of nanofluids based temperature parameters and thermal resistance of the heat pipe. The temperature parameters include specific temperature at evaporator, adiabatic and condenser section. Additionally the temperature difference between evaporator and condenser can be derived, which indicates the overall thermal efficiency of the heat pipe. Furthermore the thermal resistance of the heat pipe can be studied by using the data of temperature difference between evaporator and condenser as well as the heat transfer rate in the heat pipe. The results based on analytical data for alumina oxide ($Al2O3$) are then compared to experimental results of Ghanbarpour on the effect of alumina oxide in a heat pipe.

The model nanoparticle variables (Eq.1-3) and heat transfer rate in the heat pipe (Eq.20) inconstant data. Data for the heat pipe (Eq.11, 13-19) and inputs (Eq.21-22) are derived from Ghanbarpour and considered as constant data. Ghanbarpour used in his experiment a copper tube with a screen mesh wick with 70% porosity, with length of evaporator, adiabatic and condenser section of 3 cm, 14 cm and 3 cm respectively. The heat pipe was thin-walled with outer and inner radius of 3.175mm and 2.93mm (see Appendix B). The experimental study conducted by Ghanbarpour, consists of a two-phase (vapor and fluid) heat pipe with water as a base fluid at 323 K.

Model calculation steps

The programming code of the model is presented in Appendix A, where the equations are numbered 1-27. The equations presented in chapter 7 and 8 are labeled with letters a-h

Since the study of nanofluids refers to the amount of solute (nanoparticles) that dissolves in solvent (base fluid), the volume concentration is used when preparing solutions of liquid. The volumetric concentration $\emptyset i$ also called volume fraction in the study is defined as the solute volume Vi divided by the sum of all the volume constituent V of the solution according to equation a:

Vi $\quad$ Vi

$\emptyset i$ =-------- =---------- (a)

$\sum Vi \quad V$

Nanoparticle density (Eq.2) and thermal conductivity of the nanoparticle (Eq.3) are solid factors and are not temperature dependent in the small temperature range applied in the study. These solid factors are therefore assumed to be constant.

Viscosity is an important property that has an immense effect on heat transfer and pressure drop. Einstein's well known correlation derives the effective viscosity of nanofluids according to equation b (Shafahi et al., 2010b):

μnf = 1 + 2.5∅ (b)

μf

An experimental study carried out by Ghanbarpour et al., where the dynamic viscosity was compared with different correlations at temperatures of 293 K and 313 K, showed that the viscosity strongly depends on solid particles concentration (Ghanbarpour et al., 2014). A large deviation from the results was observed using Einstein's correlation in comparison to Corcione's and Krieger's correlations on viscocity. Ghanbarpour et al. showed that Corcione's and Krieger's correlations predicted the viscosity of Al2O3 with highest accuracy and lowest deviation of ±10 % error in all concentrations (Ghanbarpour et al., 2014). Since Krieger's correlation strongly depends on the nanoparticle morphology, the shape and structure of the nanoparticle is needed to use this correlation (Ghanbarpour et al., 2014). Anoop et al., concluded that Einstein's correlation, which involves viscosity value of 2.5, significantly underestimates the effective viscosity of nanofluids in comparison to experimental data. Anoop et al., proposed therefore a viscosity value of 10 (see Eq. c), which matched better with their experimental data, and is also applied in the model in this study (Anoop et al., 2009)

μnf = 1 + 10∅ (c)

μf

Thermal conductivity of the nanofluid in the wick structure can be determined using two approaches: an engineering approach involving e.g. Maxwell's correlation of thermal conductivity or a material approach, in which data for Brownian motion is necessary and not available in this study.

In this report the engineering approach is applied using Maxwell's classical analysis of heat conduction correlation is based on effective heat theory and defined in equation d (Xue, 2003):

$$knf = 1 + .. \frac{3\ (\ (j-1)\emptyset}{(j+2)-(j-1)\emptyset}\ ) \quad \text{(d)}$$

where knf, $and\ kl$ are the thermal conductivity of the nanofluid and water. The nondimensional variable j is equivalent to nanoparticle conductivity divided by water conductivity (see Eq. 9). Maxwell's correlation is based on analyzing the heat flow in the material surrounding and the particle behavior in where the analysis is carried out in an infinite region (This approach leads to problems since the result and application of Maxwell's model only can be applied to a highly disperse fluids where the particles are so far apart that energy change and reactions between each particles are negligible (Macdevette et al., 2013). Thus, increasing particle concentration will limit the accuracy of this model and lead to source of errors. Maxwells's model of thermal conductivity is based on a steady-state solution, which also leads to issues since one would wish to study the nanofluid behavior in a time-dependent region (Chi and S.W. 1976). Furthermore, problems of applying Maxwell model become apparent when particle size decreases to nano-scale (MacDevette et al., 2013).
In order to identify the effective thermal conductivity in the wick, the porosity of the wick needs to be considered according to equation e (Shafahi et al., 2010b):

Conclusions
Based on the findings in literature studies (Chapter 3-6), results of the model (Chapter 9) and the discussion (Chapter 11) the following conclusion can be drawn:

- A higher particle conductivity of nanoparticles increases the thermal conductivity of the nanofluid, which in turn increases the effective thermal conductivity of the heat pipe, ultimately decreasing the thermal resistance in the heat pipe (see Figure 5) and enhancing the thermal performance.

- A higher concentration of nanoparticles increase the thermal conductivity of the nanofluid, which in turn increases the effective thermal conductivity of the heat pipe, ultimately decreasing the thermal resistance in the heat pipe (see Figure 6) and enhancing the thermal performance.
- The difficulties with the production process, e.g. high production cost, of nanofluids stall the commercialization of nanofluids in heat pipes
- More effort must be put on research in the .field of nanofluids concerning synthesis, thermophysical properties, filling ratio and concentration level of nanoparticles.

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