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EXPERIMENTAL AND NUMERICAL INVESTIGATION ON THE IMPACT OF NANOPARTICLES IN THE DEVELOPMENT OF THERMOSYPHON

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ABSTRACT

Addition of nanoparticles is a known way to modify the behavior of a fluid in terms of heat transfer. This fact reaches its limits when it comes to natural convection. The aim of this paper is to show that the conventional characteristics to look at to choose a particle are no more the same for a phenomenon such as thermosyphon. Thus, the famous Alumina, compared thanks to tests and modeling, finds itself inferior to the low conductive Lithium Hydroxide in this configuration. Another aim of this article is to discuss the possibility to model nanofluids using single fluid approach and to show the limitations for long terms uses.

INTRODUCTION

Heat transfer improvements or developments are gaining importance day after day. The Kyoto protocol (regarding climate change and environmental contamination) and other measures highlight the importance of a correct use of energy consumption and put the attention on the concept of "energetic efficiency". Improving Thermal Heat Transfer is therefore one of the main interests of researches and studies. Low thermal conductivity of a fluid is one of the primary limitations existing in the Heat transfer problematic. Efficient heat transfer fluids need good thermal conductivity in order to be effective and useable. The use of suspension of nanoparticles in conventional fluids, called "Nanofluids", respond to this need and provide potentially efficient fluids with very high thermo-physical properties, and represent one of the best hope for heat transfer enhancement nowadays. Thus, since its first use as nanofluid in 1995 [1], more than 4000 articles have been published on this topic. Nevertheless, even if most of them show an enhancement of the heat transfer thanks to the particles [2], some describe the phenomena as counterproductive [3], when used for natural convection.

This work reports a numerical / experimental investigation on the thermal behavior of nanofluids flowing in narrow channels, and their impacts on the development of a thermosyphon.

NOMENCLATURE

C_P	[J.kg^{-1}.K]	Specific heat
d	[m]	Hydraulic diameter
k	[W/mK]	Thermal conductivity
Pr	[-]	Prandtl Number
PTFE		Polytetrafluoroethylene
Re	[-]	Reynolds Number
T	[K]	Temperature
V	[m.s^{-1}]	Mean velocity of the fluid
vol %	[%]	Percentage in volume
wt %	[m]	Percentage in weight

Special characters

α	[-]	Volume fraction ratio
μ	[N.s.m^{-2}]	Dynamic viscosity
ν	[m^2.s^{-1}]	Kinematic viscosity
τ	[min]	Rise time

SELECTION OF THE NANOFLUIDS

Due to the limitations of water (evaporation, cavitation close to heating elements …), the experiments were conducted with mixtures based on oil. Thanks to its low cost and its use in many researches [4], γ-Al_2O_3 was first tested and then compared to Lithium hydroxides (LiOH). Although this specie is rarely used for nanofluids due to its low thermal conductivity, it owes a density of about half of the one of the Alumina. As the thermosyphon is mainly density dependent, this parameter was to be watched closely.

Order of magnitude at 20°C	ρ (kg.m^{-3})	Cp (J.kg^{-1}.K^{-1})
Oil	820	1900
γ-Al_2O_3 (solid)	3000	800
LiOH (solid)	1500	2700

Figure 1: Order of magnitude of the properties of the particles

For both particles, an average size of 100nm ±10nm was measured (see figure 2).

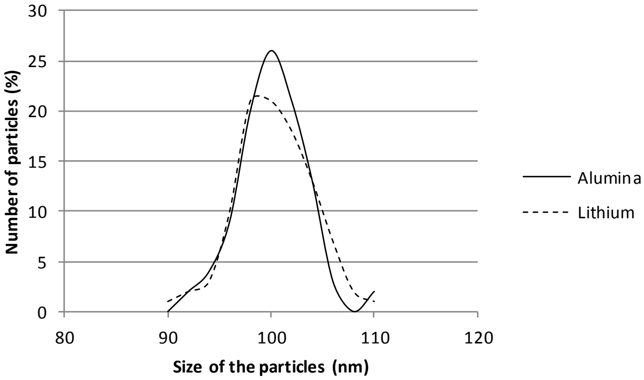

Figure 2: Sizes of the particles

Nanofluids were prepared with a concentration of 30 wt. % and then diluted in order to obtain α of 4 vol. %. As the study was on thermosyphon, low speeds were to be considered. Based on it, each mixture had to be really stable to prevent particles from falling down into the apparatus. Thus, each mixture had been prepared using surfactant.

EXPERIMENTAL PROCEDURES

To understand the development and the evolution of the thermosyphon, the experimental setup was reduced to its minimum. It was based on two vertical glass tubes linked together by six horizontal tubes of PTFE to prevent any reaction with oil. A last inclined tube was fixed between the two sides to power the setup and to help the flow to go in one defined direction. A previous test with a horizontal heating system (n°6 in figure 4) showed the non-formation of the thermosyphon for a symmetric system. The applied thermal flux was delivered thanks to a heating resistance rolled onto a copper tube and insulated thermally by silicon foams.

All tests were conducted on a single test bench with a given set of parameters and a defined geometry. It allowed us to have comparable results, whatever the specificities or the defaults of the whole test bench were.

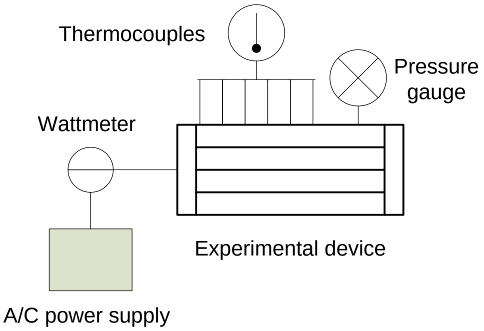

Figure 3: Schematic of experimental apparatus

The entire apparatus was instrumented with J-type thermocouples to measure fluid temperature, heating temperature and the room temperature, kept constant to 20°C. Each thermocouple was first calibrated and then controlled before and after each measurement. The first tests were powered with 80W.

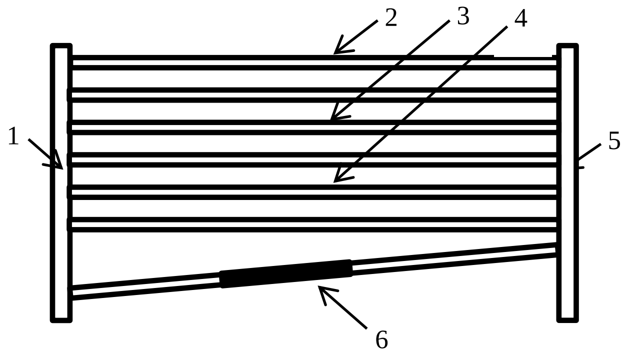

Figure 4: Location of the thermocouples

From the general point of view, thermosyphon can be characterized thanks to two main values: its time to stabilize and its thermal map. As predicted, nanoparticles helped the phenomena to speed-up (see figure 5). Alumina and lithium gave respectively 10.5% and about 15% of decrease for the time of stabilization.

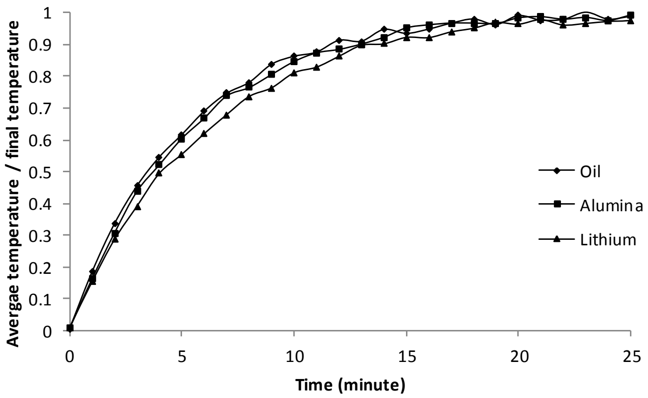

Figure 5: Rise time of the different fluids

Another interesting impact of the use of nanoparticles is the evolution of the thermal map. The average temperature has increased by 3.5°C for the alumina based fluid and by 5.8°C for the lithium one (See figure 6).

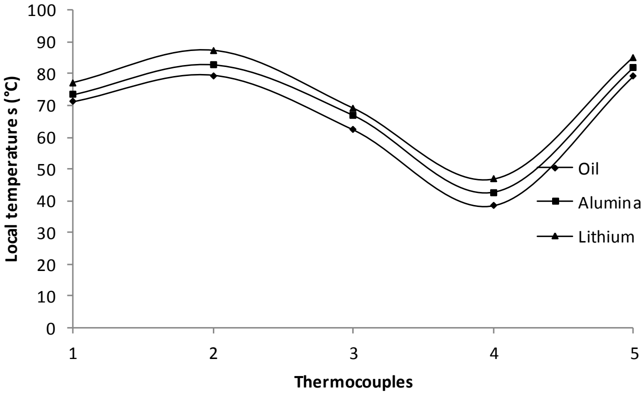

Figure 6: Local temperatures for the different fluids

In order to understand fully the phenomenon and to compare on the same basis the results, a second test was conducted. Its aim was to measure the speed of the flow in the hottest glass tube (tube with the thermocouple n°1 in figure 4). Thanks to its transparency and to the viscosity of the fluids, man could see with his own eyes the motion of the fluids. Nevertheless, it was not enough to quantify this displacement. Little glass spheres were added (see figure 7), as well as a ruler at the back of the apparatus.

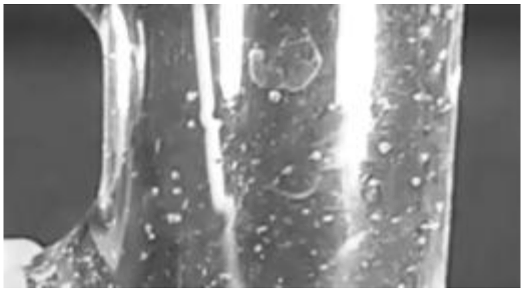

Figure 7: Glass beads and air bubbles

Measurements were realized ten times per fluid and for all of them, the standard deviations were below 3%. As expected from the previous results, the nanofluids presented a higher velocity compared to the base fluid (see figure 8).

	Oil	Al_2O_3-Oil	LiOH-Oil
Average velocity over oil velocity	1	1.07	1.12

Figure 8: Velocity of the fluids

THEORETICAL / NUMERICAL APPROACH

Additionally, computational fluid dynamics simulations were performed to represent these particular situations. As no agglomeration appeared during the tests, the fluid was modeled as homogeneous. A theoretical correlation of the thermal conductivity was given by Prasher at al. [5-6] on a Al_2O_3 based mixture.

As explained by Polidori [7] and Yu [8], the addition of particles has a direct impact on the dynamic viscosity, which has a key-role in modification of the heat exchange coefficient. Due to the numerous amounts of equations available in the literature, it was decided to take direct measurements of the viscosity. These were obtained thanks to a viscometer RM100 from LAMY.

From these, man could calculate an approximate Reynolds numbers ($Re = \frac{V*d}{\nu}$) in the hottest tube to check the hypothesis to be taken for CFD calculations (See figure 9).

	Oil	Al_2O_3-Oil	LiOH-Oil
Re	43.3	40.9	41.7

Figure 9: Reynolds number for each fluid

The computation was conducted on a commercially available code (ANSYS Fluent) with a Navier-Stokes model, considering the fluid as homogeneous (other properties were calculated thanks to the mixing law), the flow being modeled as laminar. The mesh, based on tetrahedrons, was refined on each change of directions as well as on the boundary layer (Figure 10).

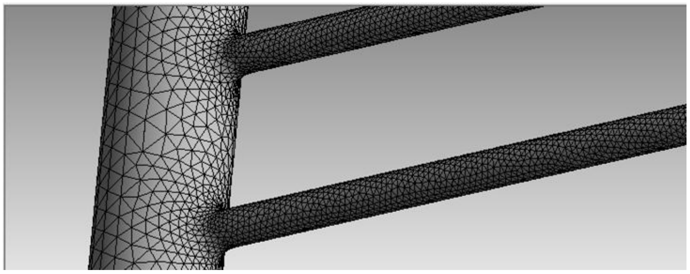

Figure 10: Meshing of a fraction of the fluid

VALIDATION OF THE CFD MODELS

Three main data were available to validate the models. The first one was the thermal map. As presented in figure 11, the temperatures of the simulations are close to the ones from the thermocouples. Although a difference of about 2°C can be noticed, most of the behavior is fully represented.

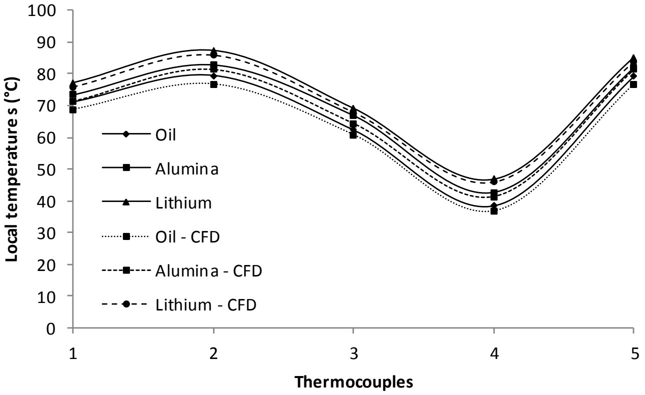

Figure 11: Comparison of the temperatures obtained from tests and CFD

This can be checked with the rise time (τ), defined as the time needed to obtain ${}^{2}/_{3}$ of the final temperature, this temperature being calculated as the average of the thermocouples. Depending on the fluid, the error is between 6 and 9%, which is a bit high but still acceptable.

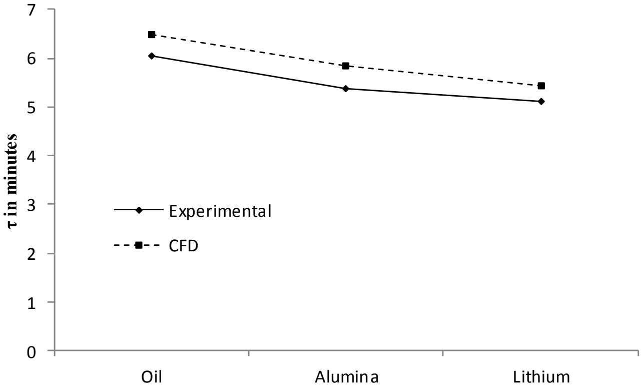

Figure 12: Comparison of τ between experimental and CFD results

The last aspect to analyze is the speed of the flow. Although measurements might have to be taken with care due to the means of measurements, they provided an excellent order of magnitude to compare with for the CFD results with values of about 2.10^{-2} $m.s^{-1}$. Thus, calculated velocities were higher than expected but they explained perfectly what could be seen during the experiments.

	Oil	Al_2O_3-Oil	LiOH-Oil
Average velocity (10^{-2} $m.s^{-1}$)	3.29	3.45	3.65

Figure 13: Computed velocities of the fluids

Indeed, repetitive motions were noticed during the measurements but they were only considered as vortex shedding after the results of the calculations, placing Reynolds Numbers in the range 48 to 180 described by Zdravkovich [9].

Nevertheless, despite the good results obtained here, CFD reaches its limits for long term behaviors. In order to test the models, experiments were reconducted during long periods (several months). Thus, the stable behaviors of the solutions were no more to be considered due to the apparition of sedimentations and aggregations. This phenomenon was partially treated by Prasher [10], as far as conductivity is concerned, or Palabiyik [11] but a huge work is still to be done on that topic.

RESULTS AND DISCUSSIONS

As it can be seen from the previous results, although the thermal conductivity is important, it is not the only property to pay attention to. Indeed, in this specific configuration, Lithium mixture is more efficient than the one with Alumina despite its low conductivity. This can be partially explained by the Prandtl Number ($Pr = \frac{C_P * \mu}{k}$) in this experiment. Indeed, with Pr above 100, convection takes precedence over conduction, which shows the importance of other properties of the fluid, linked to convection.

CONCLUSION

The preliminary results indicate that nanoparticles can enhance the heat transfer taking place into a thermosyphon and even modify its specific characteristics, in terms of rise time and heat dissipation.

Nevertheless, depending on the particles, man can obtain more or less unpredicted results. Indeed, it is important to remind that thermosyphon behaves in the way of natural convection where not only the thermal conductivity but also other thermal properties have to be considered.

Concerning CFD, although overall heat transfer values and behaviors can be found, homogeneous fluids do not allow to represent the entire fluid motion for a long period. Multiphase models should be worked on.

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