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Research paper

Enhanced effectiveness of nanofluid based natural circulation mini loop

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HIGHLIGHTS

- Thermal performance is enhanced by using nanofluids.
- A non-dimensionalized effectiveness factor was defined.
- The effectiveness factor provides more concrete results than temperature differences.
- Nanofluid provides elevated operation temperatures than the base fluid.
- Nanofluid based SPNCmL have a potential to be used for high heat dissipation devices.

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ABSTRACT

The goal of this study is to investigate experimentally the thermal performance of a single-phase natural circulation mini loop (SPNCmL). The experiments were carried out with de-ionized water (DIW) with different particle concentration (1–3 % vol.) and size (10 and 30 nm) of Al_2O_3–DIW nanofluids. During the study, the operating parameters such as applied power to the heater (10–50 W), heat sink temperature (10 °C and 20 °C) and inclination angle (0°, 30°, 60° and 75°) of the loop were varied. To interpret the thermal performance of SPNCmL, a non-dimensionalized effectiveness factor was used. It was found that the effectiveness of the system is enhanced by the increase of particle concentration and inclination angle for all samples at full power range. Moreover, the results indicate a remarkable thermal performance enhancement (effectiveness factor increased to 30%) with using Al_2O_3–DIW nanofluids as a working fluid at inclined conditions which was achieved for the first time in a nanofluid based SPNCmL.

1. Introduction

Natural circulation loops (NCL) are passive systems which do not have any moving or rotating mechanical parts. The density gradient between the hot and cold side drives the system, so that it can transfer heat from one side to the other side with natural convection. NCLs are single-phase NCL (SPNCL) or two-phase NCL (TPNCL) according to whether the density gradient is caused by a temperature gradient or phase change, respectively. In a recent study, Jiang et al. [1] built and presented a three-phase NCL (THPNCL) to improve the heat transfer performance of the TPNCL. Owing to its design complexity, requirement of precision control and exhibition of instabilities, the two-phase NCL has a restricted application range [2]. Some of the recent studies consist of TPNCL focused on cooling outdoor telecommunication equipments [3] and split-type solar water heaters [4]. In contrast, SPNCLs have a wide range of application because of its simplicity, enhanced safety and reliability [5]. They are very popular with their widespread engineering applications of turbine blade cooling [6], solar water heaters [7], nuclear reactor core cooling [8], electronic chip cooling [9], and refrigeration [10].

Nonhazardous operating conditions due to working without a pump system and widespread application range have encouraged researchers to study SPNCLs. The pioneering studies of Keller [11] and Welander [12] focused on a rectangular closed loop which had a heat sink and heat source at a point of top and bottom horizontal legs, respectively. Later, Creveling et al. [13] developed a toroidal loop with a distributed heat sink and heat source. This was the first study that indicated an observation of instability in a

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natural circulation system. The unstable flow in a SPNCL can be stabilized by pressure drops with small orifice diameters [14,15]. Furthermore, unstable fluctuations can be suppressed by altering the thermal boundary conditions and loop geometry. As concluded by Misale et al. [16], manipulating either heat sink temperature or working fluid can switch the unstable flow to stable without varying the heating power. The other ways to keep a SPNCL in the stable zone are decreasing the pipe inner diameter, vertical arm length and horizontal arm length [17].

For years, many experimental and numerical attempts have been made to explore the effects of parameters such as pipe material [18–22], heater and cooler orientations [23–25], and the inclination angle [26–29] on both the thermal stability and thermal performance of SPNCLs.

Among these studies, Misale et al. [18] used a two-dimensional model which takes into account the pipe thermal capacity and the axial conduction. They obtained smaller velocity results when compared with the one-dimensional simulations and attributed this result to the effect of the wall thermal capacity and the axial conduction on the general behavior of the system. Lin et al. [20] investigated the effects of the wall thermal conductivity and the wall thickness on the heat transfer behavior in a circulation loop. They concluded that varying the wall-to-fluid thermal conductivity ratio and/or wall thickness ratio can affect the contribution of the wall conduction to the total heat transfer extracted through the cooled section more than that removed from the heated section of the loop. Ambrosini et al. [21] studied the wall friction effect with a one-dimensional model. They concluded that the approach is not completely free of problems, but obtaining the greatest detail in flow description makes it worth being further pursued. Rao et al. [22] investigated the influence of wall core capacitance by using the transient one-dimensional conservation equations. They reported that the inclusion of the wall-core capacitance in the present study reveals the important fact that the stable state operating zone widens with the wall-core capacitance.

Vijayan et al. [23] conducted experiments on the stability behavior of SPNCL with different heater and cooler orientations and found that the vertical heater and cooler orientation provides the most stable operation. Swapnalee et al. [24] derived a generalized equation for the steady state flow in SPNCL, based on the one-dimensional theory by assuming the loop to be partly in laminar and partly in transition or turbulent flow. They tested the correlation with the experimental data in a rectangular loop for four different orientations and found that it is applicable for all orientations.

Petruzzi et al. [26] simulated the SPNCL in a micro-gravity condition by using a thermal-hydraulic system code and compared them with the experimental results. Their code results appeared consistent with the experimental data for all heating power levels and inclination angles of the loop at less than 60°. Acosta et al. [27] experimentally determined the natural convection flow of a tilted square loop a function of the heating flux and the tilt angle. They observed that for the large tilt angles, the flow velocities become very small and local temperature very high as a consequence. Misale et al. [28] investigated experimentally the influence of the inclination angle between 0° and 75° with distilled water on SPNCmL. They concluded that only the 75° inclination angle affects the temperature difference of the fluid, whereas the influence of 0° and 30° loop inclination angles are quite negligible.

Also another important parameter is the type of working fluid which not much information is available in literature for SPNCLs [14,16,29–32]. In few of these studies, a new generation heat transfer fluid called nanofluids were used as a working fluid.

Nanofluids are colloidal mixtures which consist of a base fluid and nanoparticles. The Nanofluid term was first used by Choi [33] in 1995. Since then, nanofluid related publications have shown an exponential increase [34]. Recent studies show that nanofluids have wide range of potential applications in electronics cooling [35], refrigerators [36,37], nuclear reactor cooling [38], automobile radiators [39,40], solar collectors [41], plate heat exchangers [42], micro-pin-fin heat exchangers [43] and minichannel heat sink [44].

Concerning the effect of nanofluids on the natural convective heat transfer systems, Haddad et al. [45], concluded that most of the numerical results indicate that the nanofluids significantly enhance the heat transfer capability, whereas experimental results show that the presence of nanofluids deteriorates the heat transfer. Moreover, in a recent publication, Taylor et al. [46] reviewed the studies on the diverse applications of nanofluids and mentioned that the results need to be completely non-dimensionalized for drawing a conclusion about enhancements in heat transfer. Another controversial topic is the effect of the nanoparticle size on the thermal performance of the nanofluid. Although it is a hotly discussed topic, there are only few systematic studies on the effect of nanoparticle size on the thermal performance of the systems. Anoop et al. [47] experimentally, and Davarnejad et al. [48] and Seyf et al. [49] numerically investigated the particle size effect on the heat transfer performance of the systems using nanofluids. They concluded that decreasing the nanoparticle size, increased the heat transfer performance. Contradictory to these studies, Ji et al. [50] and He et al. [51] reported experimental results revealing that the particle size does not have any systematic effect on the thermal performance of the nanofluid based systems.

So far, only water based nanofluids with CuO [31], TiO_2 [31], and Al_2O_3 [29,30,32] particles were studied in SPNCLs. Nayak et al. [30] experimented with the SPNCL behavior in a large scale rectangular loop with water and different concentrations of Al_2O_3 nanofluids (0.3–2% by wt. and particle size 40–80 nm). They concluded that using nanofluids provides an operation at elevated power ranges, more than usual. Moreover, they pointed out that the system efficiency is increasing with nanofluids, whereas instabilities are decreasing. With the same experimental setup, Nayak et al. [31] in a series of experiments used three different metallic oxide nanofluids (Al_2O_3, CuO, and TiO_2) with varying concentration and particle sizes. They concluded that the TiO_2 and Al_2O_3 seem to be more promising for all power ranges, since the flow rate increases consistently. As mentioned previously in Ref. [28], since the SPNCmLs are the potential devices for the thermal management of electronic systems, Misale et al. [29] investigated the effect of using nanofluids on the thermo-hydraulic performance of a SPNCmL. They used firstly distilled water and then Al_2O_3–distilled water nanofluid with different concentrations as a working fluid. They varied the input power between 10 W and 50 W; the loop inclination angle between 0° and 75°, and the heat sink temperature 10 °C and 20 °C. They concluded that the thermal performance of a mini loop is similar for distilled water and nanofluid; they only observed a slight enhancement at 75° with nanofluids. Contradictory to this result Turgut et al. [32] found that the thermal performance of SPNCmL is enhanced by the use of nanofluids, at 0° inclination angle and 20 °C heat sink temperature for the input power from 10 W to 50 W.

To the best of the authors' knowledge, there is no such study on the thermal performance of a nanofluid based SPNCL which investigates the influence of inclination angle by using a non-dimensionalized effectiveness factor. Therefore, this study aims to investigate the influence of the inclination angle, heating power and heat sink temperature on the thermal performance of a SPNCmL at different particle concentration and size of the Al_2O_3 nanofluids, for the first time, by using a non-dimensionalized effectiveness factor.