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A review on using nanofluids in heat pipes

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Abstract
The thermophysical specifications of working fluid play a key role in thermal performance of various types of heat pipes. Fluids with high thermal conductivity, low viscosity and surface tension are more favorable to be applied in heat pipes. In order to have fluids with higher thermal conductivity, adding nanoparticles can be an acceptable idea. In the present study, the effects of using nanofluids in several types of heat pipes are reviewed. The nanofluids are categorized based on the types of particles (as carbonic, metallic, etc.). Based on the results of the literature review, applying nanostructures in the base fluid can significantly reduce the thermal resistance of heat pipes compared with utilizing pure as operating fluid. For instance, it is observed that using graphene oxide/water nanofluid in pulsating heat pipe reduces the thermal resistance up to 42% in comparison with the water-filled heat pipe. In addition, reviewed studies revealed that the type of nanoparticle, concentration and their stability are among the most important parameters affecting thermal performance. The enhancement in thermal performance of heat pipes by using nanofluid is mainly attributed to higher thermal conductivity of the nanofluids and increase in nucleation sites.

Keywords Heat pipe · Nanofluid · Flow regime · Thermal conductivity

Introduction

Heat pipes are heat transfer mediums with significantly high effective thermal conductivity [1]. Various types of heat pipes including wick heat pipes, pulsating heat pipes and thermosyphons are applied in several energy systems and cooling devices [2–7]. The main parts of the heat pipes are evaporator and condenser. In addition to these two sections, adiabatic part can be applied in case there is a gap between them [8, 9]. These thermal devices are broadly employed in renewable energy systems, heat exchangers and electronic device cooling [4]. Heat pipes are made of a tube, in the most of the cases metal tube to achieve the highest thermal conductivity, and partially charged with an operating fluid [10, 11]. Fluid evaporation in heat source and its condensation in heat sink results in two-phase heat transfer [12]. Various types of heat pipes utilize different driving forces to return condensed liquid from condenser to evaporator. Pressure instabilities in turns of pulsating heat pipes cause fluid motion [13], while capillary force, provided by wick structure, is the driving force of liquid motion inside the conventional heat pipes [14, 15]. In thermosyphons, gravity force acts as driving force for liquid return from condenser to evaporator [16]. The most influential factors on heat transfer capability of the heat pipes can be listed as structure, heat load, inclination angle, filling ratio and the applied working fluid [17–20].

Among the mentioned effective parameters, working fluid and its thermophysical specifications significantly affect thermal performance [21, 22]. By applying nanotechnology, it is possible to modify the properties of various materials [23–25]. Dispersing nanosized solid structures increases the thermal conductivity of the fluid [26, 27]. Fluids with high thermal conductivity and low dynamic viscosity are more appropriate for heat transfer augment of the heat pipes [28]. In addition, surface tension of the operating fluid is another factor, since it affects

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boiling in evaporator section of heat pipes. The surface tension of heat pipes can be reduced by using surfactants to improve thermal behavior of heat pipes [1]. The most conventional method to enhance thermal conductivity of the fluids is adding nanoparticles to them [25, 29, 30], which makes them more favorable for thermal devices [31–34]. Dispersion of nanosized solid materials in the base fluid increases the thermal conductivity due to higher thermal conductivity of the solid phase compared with the liquid. Moreover, other properties of fluid such as dynamic viscosity can be changed because of adding the solid structures. Due to the ability of nanofluids in enhancement of heat transfer, several experimental and numerical studies are carried out on the heat transfer of these types of fluids [35–39]. In addition to higher thermal conductivity of nanofluids, the existence of nanoparticles can increase nucleation sites which would result in boiling improvement. Several studies have focused on utilization of nanofluids in heat pipes to achieve higher effective thermal conductivity [40–42].

In the present study, the applications of nanofluids in various types of heat pipes are represented. The nanofluids are categorized based on the type of nanoparticles or nanosheets. The most conventional utilized nanofluids and their effects on heat transfer behavior of several types of heat pipes are reviewed, and their results are investigated.

Metal oxide nanofluids

There are several nonosized materials applicable for dispersion in the base fluids to prepare nanofluids. Metal oxide nanoparticles, such as alumina and copper oxide, are among the most conventional ones due to their stable dispersion in the base fluid. Carbonic nanostructures, such as carbon nanotubes (CNTs) are attractive for scientists due to their high thermal conductivity and ability in improving the thermophysical properties of the fluid. In the following sections, the studies carried out on the utilization of various types of the nanofluids in heat pipes are reviewed.

Alumina nanoparticles

Several nanoparticles have been added to a base fluid in order to be used in heat pipes. Alumina (Al_2O_3) are among the most conventional nanoparticles which are widely used for various heat transfer purposes. Keshavarz Moraveji and Razvarz et al. [43] added alumina nanoparticles with 35 nm average size into pure water and applied it as working fluid in a sintered wick heat pipe. The thickness of the wick was equal to 1 mm, and the concentrations of the nanoparticles in the base fluid were 0 mass%, 1 mass% and 3 mass%. Results indicated that adding the nanoparticles led to enhancement in heat transfer performance and reduction in wall temperature differences. In the most of the tested cases, nanofluid with 3 mass% concentration had better thermal performance compared with 1%. In another study [44], thermal resistances of heat pipes with different lengths including 0.3 m, 0.45 m and 0.6 m which were made of copper tube with 9.52 mm inner diameter were measured. The tested mass concentrations of alumina nanofluid in the study were 0.5, 1 and 3%. Results showed that using the nanofluid decreased the thermal resistance of the heat pipes compared with utilizing distilled water as working fluid. For instance, it was observed that at 40 W heat input, the optimal thermal performance of the heat pipes filled with the nanofluid enhanced 22.7%, 56.3% and 35.1% in the cases of 0.3, 0.45 and 0.6 m lengths, respectively.

Mashaei et al. [45] analyzed using Al_2O_3/water nanofluid in a cylindrical heat pipe which had multiple evaporators. The investigated concentrations in the study were 0 vol%, 2 vol%, 4 vol% and 8 vol%. It was found that increase in heat load and concentration of nanoparticles resulted in higher heat transfer coefficient. In addition, it was concluded that the existence of nanoparticles led to reduction in velocities of both vapor and liquid regions.

Copper oxide nanoparticles

CuO/water nanofluid preparation is relatively simple by applying two-step method which has appropriate stability and dispersion of the nanoparticles [46]. Copper oxide nanoparticles can improve thermal conductivity of the base fluid and enhance heat transfer [47]. Moreover, similar to other nanoparticles, existence of these nanoparticles can improve boiling heat transfer and nucleation sites in heat pipes. Brahim and Jemni [48] numerically investigated the thermal performance of a packed sphere wick heat pipe filled with CuO/water. It was observed that by using the nanofluid with 9% concentration, 68% reduction in thermal resistance of the heat pipe is achievable. In addition to numerical studies, experimental researches have shown that using CuO nanoparticles in the base fluid would improve thermal performance of heat pipes [49]. Manimaran et al. [50] investigated thermal performance of a conventional heat pipe which was made of copper and had two layers of screen mesh wick filled with DI water, CuO/water and TiO_2/water. Results indicated that using CuO/water nanofluid in the heat pipe resulted in the lowest thermal resistance. The thermal resistance of the heat pipe filled with CuO/water nanofluid (at 75% filling ratio and 70 W input power) was approximately 38.8% and 62% lower compared with the heat pipe filled with TiO_2/water nanofluid and DI water, respectively. In another study [51], thermal performance of a heat pipe with screen mesh wick was experimentally investigated by using CuO/water nanofluid in 0.5 mass%, 1 mass% and 1.5 mass% concentrations. As shown in Fig. 1, the heat pipe filled with the nanofluid with 1 mass% concentration had the best heat transfer.

Titania nanoparticles

Another applicable metal oxide nanoparticle in heat pipes is titania (TiO_2). Similar to other nanoparticles, adding titania can improve thermal performance of various types of heat pipes [52]. In a study [53], entropy generation of cylindrical miniature grooved heat pipe filled with TiO_2/water or Al_2O_3/water was compared with the heat pipe charged with water as working fluid. Results revealed that using the nanofluids led to reduction in generated entropy. There are several sources for entropy generation in heat pipes. By using nanofluid, the entropy generation due to existence of temperature difference between external reservoir and the vapor sharply reduced because of decrease in overall thermal resistance. Moreover, it was found that higher concentration resulted in more decrease in entropy generation as shown in Fig. 1.

Subramaniyan et al. [54] investigated thermal performance of a screen mesh heat pipe by using TiO_2/water as operating fluid. The average diameter of the utilized nanoparticles in the study was equal to 8.47 nm. Results revealed that by the adding titania nanoparticles to the working fluid can enhance heat transfer and thermal conductivity of the heat pipe. TiO_2/water has been tested in pulsating heat pipe to improve thermal performance. Based on a study conducted by Akbari and Saidi [55], it can be concluded that using stable TiO_2/water nanofluid in a pulsating heat pipe can decrease thermal resistance compared with water as operating fluid.

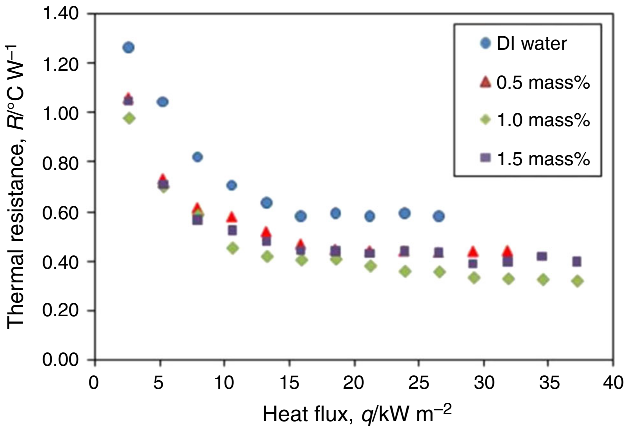


Fig. 1 Thermal resistance versus heat input [51]

Ferro-nanoparticles

Ferrofluids can significantly reduce thermal resistance of heat pipes which means higher effective thermal conductivity of these devices. Mohammadi et al. [56] performed an experimental study on a closed-loop pulsating heat pipe and compared its thermal performance in the cases of filling with water and ferrofluid. The highest observed enhancement in heat transfer was 74.8% compared with pure water which shows significant effects of adding these types of nanoparticles. In addition, the effect of magnetic field was evaluated in the study and it was concluded that applying magnetic field can improve heat transfer in the PHP. In addition to closed-loop pulsating heat pipes, ferrofluid can favorably influence thermal performance of open-loop pulsating heat pipe [57]. In addition to water, ferro-nanoparticles can be added to other base fluids and be charged to heat pipes. Goshayeshi et al. [58] investigated thermal performance of a pulsating heat pipe filled with Fe_2O_3/kerosene nanofluid. It was observed that using the nanofluid reduced the thermal resistance of the heat pipe. Moreover, similar to water-based ferrofluid, applying the magnetic field resulted in higher heat transfer.

Metallic nanoparticles

Metal nanoparticles are able to augment thermal conductivity of the fluids which makes them appropriate for heat transfer purposes. Using metallic nanofluid can improve thermal performance of heat pipes. Lin et al. [59] utilized silver nanofluid in a PHP and assessed its thermal performance. In the study, the nanofluid with two concentrations including 100 and 450 ppm was tested in heat pipe. In addition, four filling ratios from 20 to 80% were investigated. It was observed that using the nanofluid in 100 ppm concentration resulted in lower temperature difference between evaporator and condenser as shown in Fig. 2. In addition, it was found that the heat pipes had the best performance in 60% filling ratio among the tested filling ratios (20%, 40%, 60% and 80%).

In another study [60], silver and copper colloidal nanofluids were tested in a pulsating heat pipe. Thermal performance of the heat pipe filled with mentioned nanofluids was compared with the water-filled heat pipe. As shown in Fig. 3, the effective thermal conductivity of the heat pipes increased by using the nanofluids. In addition, it was concluded that the silver nanofluid was more appropriate for thermal performance enhancement (Fig. 4).

In addition to pulsating heat pipes, metallic nanofluids have been used in wick heat pipes. Kang et al. [61] utilized silver nanofluid in three concentrations, 1, 10 and

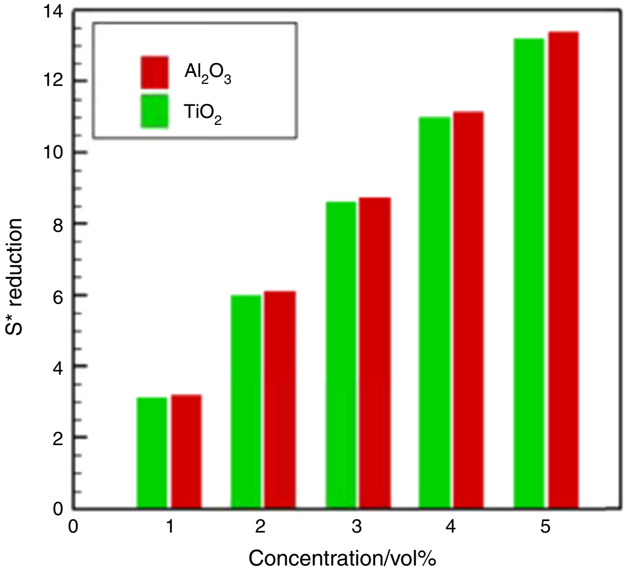


Fig. 2 Reduction in entropy generation by using nanofluids [53]

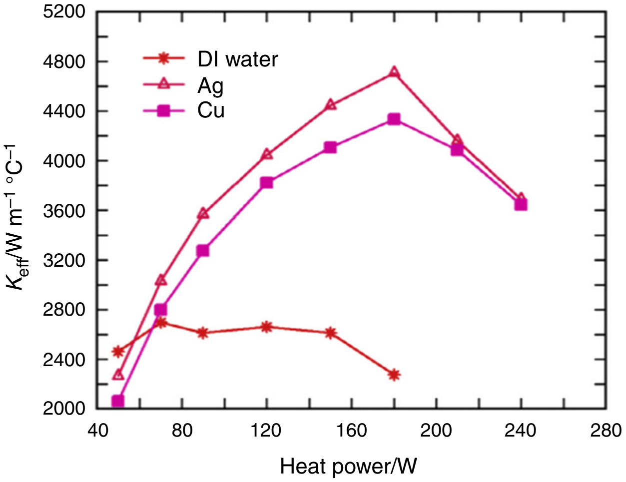
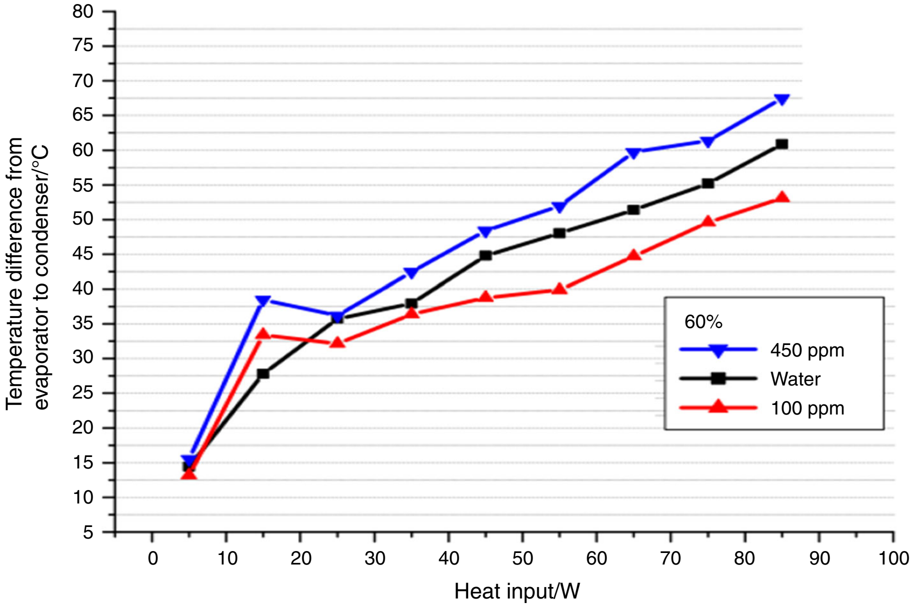


Fig. 4 Effective thermal conductivity of a pulsating heat pipe filled with nanofluids [60]

Fig. 3 Temperature difference in 60% filling ratio [59]



100 mg L^{-1}, in a circular heat pipe which had sintered wick with 1 mm thickness. It was observed that using the nanofluid led to temperature difference reduction between evaporator and condenser sections. Among the tested concentrations, 10 ppm concentration was more favorable for thermal performance enhancement. In addition, two particle sizes including 10 and 35 nm were evaluated on the heat pipe and results showed that the nanofluid with bigger particle size had better performance in the heat pipe.

Carbonic and carbon oxide-based nanofluids

Adding carbon-based nanosheets or particles can significantly enhance thermal properties of the base fluids [62, 63]. Improvement in thermal properties of heat pipes' working fluid can result in lower thermal resistance which means better thermal performance. Tharayil et al. [64] utilized graphene–water nanofluid as working fluid in a miniature loop heat pipe. The tested concentrations in the study were 0 vol%, 0.003 vol% and 0.006 vol%. Obtained results revealed that utilizing the nanofluid led to reduction in evaporator wall temperature and enhancement in heat transfer coefficient. The effect of concentration and heat

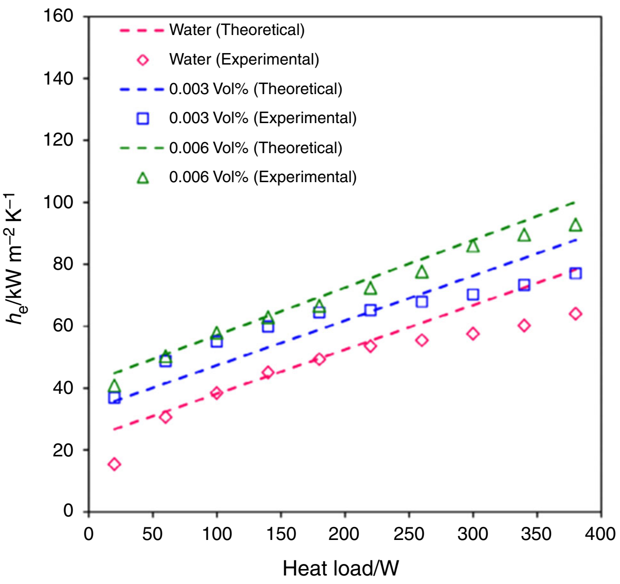


Fig. 5 Effect of graphene concentration on heat transfer coefficient [64]

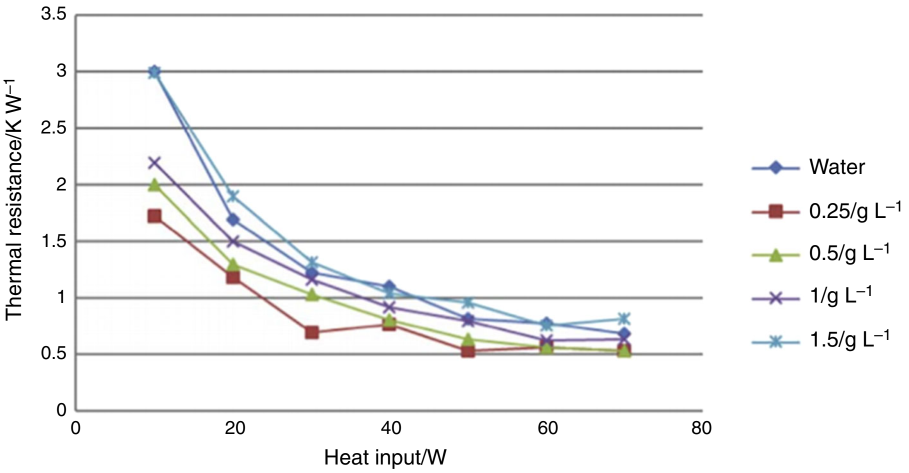
load on heat transfer coefficient of the heat pipe is shown in Fig. 1. In addition to thermal performance investigation, entropy generation analysis was performed on the heat pipe filled with the nanofluid. Based on the results, the mean decreases in total generation of entropy by using the nanofluid with 0.003 vol% and 0.006 vol% concentrations was 23.9% and 34.6%, respectively.

Graphene nanofluids can be used in other types of heat pipes such as pulsating heat pipes. Zhou et al. [65] experimentally investigated thermal performance of a pulsating heat pipes filled with graphene nanoplatelet nanofluid and compared the performance with deionized water as working fluid. Five filling ratios including 45%, 55%, 62%, 70% and 90% were tested in the study. In addition, the heat input varied between 10 and 100 W. The volumetric concentrations of nanofluid were 1.2, 2.0, 5.7, 9.1, 13.8 and 16.7%. Results showed that the optimum concentration of nanofluid for heat transfer improvement in the heat pipe was in the range of 2.0% and 13.8%. The highest decrease in thermal resistance by using the nanofluid was observed at 80 W, 62% filling ratio and 2.0% volumetric concentration which was equal to 83.6% in comparison with water-filled pulsating heat pipe [65].

Sadeghinezhad et al. [66] experimentally investigated the effect of using graphene/water nanofluid on the thermal performance of a wick heat pipe. The concentrations of the nanofluids in the study were 0.025 mass%, 0.05 mass%, 0.075 mass% and 0.1 mass%. Results indicated that using the nanofluid with 1 mass% concentration led to the best thermal performance. By using the nanofluid, the highest observed reduction in the thermal resistance was equal to 48.4%. In addition to conventional heat pipes, this nanofluid can be used in loop heat pipe for thermal performance improvement. Tharayil et al. [67], graphene/water nanofluid with 0.003 vol%, 0.006 vol% and 0.009 vol% concentrations. It was observed that the nanofluid with 0.006 vol% concentration had the best performance as working fluid in the heat pipe. The minimum thermal resistance obtained by using the nanofluid was 21.6% lower than the water-filled heat pipe at the same working conditions.

In another study, Mehrali et al. [68] utilized nitrogen doped-graphene nanofluid in a grooved heat pipe. In the study, the effects of heat load, concentration of nanosheets and inclination angle on the thermal performance of the heat pipe were investigated. Obtained results revealed that using the nanofluid enhanced the heat transfer in the heat pipe. In addition, the best thermal performance was observed in vertical orientation. By using the nanofluid with 0.06 mass% concentration, 58.6% was the highest observed reduction in thermal resistance, at vertical orientation and 120 W heat input, in comparison with using DI water as operating fluid.

Fig. 6 Thermal resistance versus heat input [70]



Kim and Bang [69] utilized graphene oxide water nanofluid in a screen mesh wick heat pipe. The volumetric concentrations of nanofluid in the study were 0.01% and 0.03%. It was observed that using the nanofluid resulted in better heat transfer. In addition, results showed that the nanofluid with 0.01% volumetric concentration had better boiling heat transfer compared with 0.03% which was attributed to deposition structure of nanoparticles layer on the wick of the heat pipe. Graphene oxide/water nanofluid has been tested in other types of heat pipes such as pulsating heat pipe. Nazari et al. [70] applied graphene oxide/water nanofluid with 0.25%, 0.5%, 1% and 1.5% g L^{-1} concentrations in a pulsating heat pipe. It was observed that by using the nanofluid, up to 42% reduction in thermal resistance was achieved. Obtained thermal resistances versus heat input for various concentrations are represented in Fig. 5.

Xing et al. [71] experimentally investigated thermal performance of a pulsating heat pipe filled with hydroxylated MWNT nanofluid. The concentration of nanofluid in the study varied in the range of 0.1–1 mass%. Obtained results revealed that using the nanofluid can sharply improve thermal behavior and heat transfer capacity of the pulsating heat pipe. For instance, it was observed that increasing the heat input up to 100 W, using the nanofluid with 0.1 mass% concentration, led to 34% reduction in thermal resistance compared with the heat pipe filled with pure water (Fig. 6).

Effect of nanofluid on flow regime

Another influential factor on thermal performance of heat pipes is the flow regime inside the tube. Increase in heat input results in higher vapor generation; consequently, the flow regime inside the tube can change from slug-plug to annular. Adding nanoparticles to the working fluid can change flow regime. Bhuwakietkumjohn and Rittidech [72] investigated the effect of adding silver nanoparticles on the flow regime of pulsating heat pipe with check valve which was filled with ethanol. It was observed that adding nanoparticle to the base fluid enhanced heat transfer rate due to increase in receiving heat surface area; moreover, the flow regime inside the tube was affected by adding nanoparticles. Flow pattern maps for both working fluids were represented in the study as shown in Fig. 7.

In another study, Gandomkar et al. [73] experimentally investigated the effect of heat input on pulsating heat pipes filled with ferro-nanofluid. Two heat pipes were considered in the study which were made of copper and Pyrex. Results revealed that by increasing the power from 5 to 25 W (in copper heat pipe) or 10–60 W in the Pyrex heat pipe, the flow regime inside the tubes changed from slug-plug to annular.

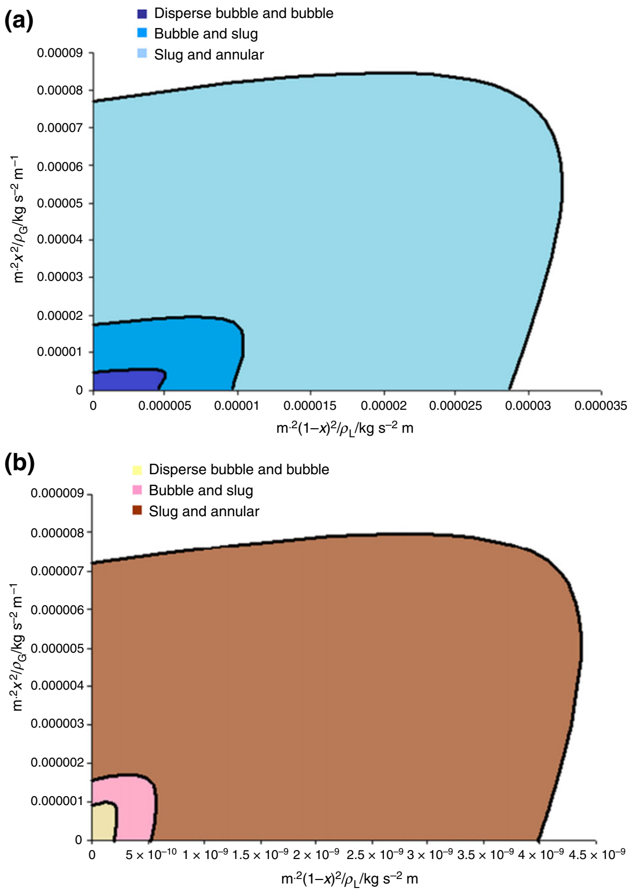


Fig. 7 Flow pattern for the PHP filled with **a** silver–nano-ethanol mixture, **b** ethanol [72]

Conclusions

In the current study, effect of using nanofluid in various types of heat pipes are reviewed. Based on the literature review, applying nanofluid to the heat pipes can improve thermal performance and heat capacity. Several specifications of nanofluids are influential in heat transfer behavior in heat pipes. Stability, concentration and the type of nanoparticles are among the most important factors. More stable nanofluids would have better performance in heat pipes. In addition, concentration of nanoparticles in the base fluid plays a key role in the thermal behavior of heat pipes. Most of the studies have shown that there is an optimal concentration for nanofluids to achieve the best thermal performance. Enhancement in thermal performance of heat pipes by using nanofluid is mainly attributed to higher thermal conductivity of the nanofluids compared with pure fluids and increase in nucleation sites.

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