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A Review of Nanofluid Boiling Heat Transfer and Its Applications in Heat Pipes

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Nanofluid is a new type of heat transfer medium formed by adding metal or non-metal in liquid medium in a certain proportion and manner, which has many advantages over the traditional working fluid. Combining heat pipes with nanofluids and using nanofluids as the working material of heat pipes can reduce thermal resistance and effectively improve the heat transfer performance of heat pipes. This paper provides a relevant overview of heat pipes and nanofluids, and introduces the relevant classifications of heat pipes, the working principle and the relevant research on nanofluid-enhanced boiling heat transfer. It conducts a literature review on the application of nanofluids in heat pipes, and finally proposes possible future research directions.

Key Words: Boiling heat exchange; Heat pipe; Nanofluid; Classification; Working principle

Introduction

Heat pipe (HP) is an efficient heat transfer device, where the high thermal conductivity of a heat pipe allows it to transfer a higher amount of heat compared to conventional materials for the same area. Since the theory of the heat pipe principle was first proposed in 1944 by Gaugler [1] of General Motors, Ohio, USA. It was not until 1964 that Grover *et al.* [2] first introduced the concept of the heat pipe, made a simple heat pipe, and experimentally proved that the thermal conductivity of the heat pipe far exceeded that of any known metal. Since then, the research of heat pipe technology has attracted a large number of researchers, and the theory and application of heat pipes have shown a high-speed development trend. Immediately after, Cotter [3] proposed a simplified heat pipe model and conducted experimental research on the velocity of steam and liquid in the heat pipe, which greatly improved the consistency of heat management theory between the heat transfer limit part and the workpiece pressure. In 1967, American scientists first successfully applied heat pipes to spacecraft cooling [4]. Since then, countries around the world have increased their investment in heat pipe research, and heat pipe technology has made great progress. Nowadays, heat pipes have many applications in the fields of computers, automotive engineering, medicine, aerospace engineering, traffic engineering, etc., and have become one of the main energy-saving and emission-reduction utilization tools.

Heat pipe (HP) is a passive cooling device that, in most cases, does not consume any external energy [5]. In addition to being widely used in various fields due to its high thermal conductivity and excellent isothermal properties, the heat pipe also has unique features such as compact structure, low mass, low noise, and no transmission element.

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Factors affecting the heat transfer performance of the heat pipe include the inner and outer diameter size of the heat pipe, the heat pipe material, the length of the evaporation section, the adiabatic section and the condensation section, the thermal properties of the working fluid, the liquid filling rate, etc. [6].

A heat pipe is an element that utilizes a phase change for efficient heat transfer, and usually consists of a shell, a suction core, and an internal working fluid. The suction core portion (a porous capillary material immediately adjacent to the tube wall), which is the core component that facilitates antigravity heat transfer, is available in sintered, grooved, and reticulated types. It provides a capillary force to drive the closed circulation of the working fluid and also serves as an interface for use in liquid-gas phase changes [7]. As can be seen from the working principle diagrams of axial flat plate heat pipe in Fig. 1 and radial flat plate heat pipe in Fig. 2, according to the construction of the heat pipe, the working part of the heat pipe can be divided into three parts: evaporation section, condensation section and adiabatic section. The evaporation section is generally in direct contact with the heat source, the wall and the heat source through the role of thermal conductivity between the heat transfer to the tube mass, so that the temperature of the mass increases to reach the boiling point of evaporation. Adiabatic section has two roles, first of all, with the evaporation of the mass of heat from the evaporation section to the condensing section for the transfer of heat, and secondly, the adiabatic section can be in contact with the evaporation section of the heat source and the condensing section of the cold source of isolation, which makes the heat pipe can be made into the various types of shapes that we need to meet a variety of working conditions. There is no heat exchange between the working fluid and the outside world in the adiabatic section, so the adiabatic section, as a mass transport path, is also called the transport section [8]. After the evaporation, the workpiece flows to the condensing section. The condensation section dissipates the heat carried by the workpiece through cooling paths such as convection heat transfer. The workpiece in the tube changes from gas to liquid, and the heat in the tube is also taken away. After the workpiece in the tube is liquefied, it flows along the tube wall and condenses into water droplets, which flow back to the evaporation section under the action of capillary pressure [9]. The normal operation of the heat pipe will have a closed cycle of evaporation of liquid, flow of high temperature vapor, condensation of vapor, and condensation of the work mass into a liquid reflux, which is the reason why the heat pipe can be regarded as a superconductor of heat [10].

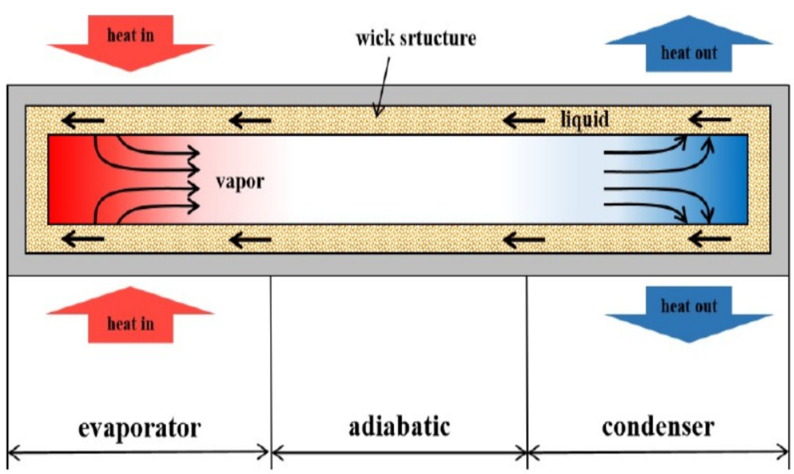

Fig. 1. Working principle diagram of axial flat heat pipe

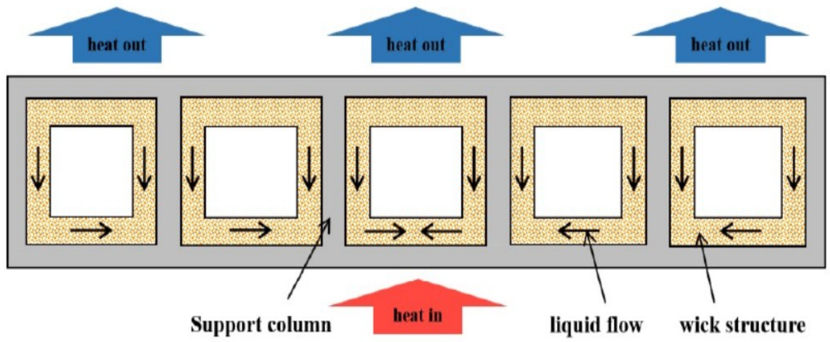

Fig. 2. Schematic Diagram of Working Principle of Radial Flat Heat Pipe

Nanofluid is a colloidal nanoscale suspended liquid formed by adding metallic or non-metallic nanoparticles with an average diameter of less than 100 nm, dispersed in a certain proportion into liquid media such as water, motor oil or ethylene glycol [11]. The thermal conductivity of metal and non-metal nanoparticles can reach dozens or even hundreds of thousands times that of pure liquid materials. According to the comparison table of thermal conductivity of common substances (Table 1), it can be seen that at room temperature, the thermal conductivity of carbon nanotubes is about 7.5 times that of copper, 37.5 times that of iron, 4,893 times that of pure water, and 11,718 times that of ethylene glycol. Therefore, adding nanoparticles to pure liquid to form nanofluid can significantly improve the thermal conductivity of the liquid, and it is not easy to wear and clog the instrument. These excellent properties have made a large number of scholars at home and abroad have invested in the study of nanofluids. Nanofluid technology has gradually been used in the fields of chemical industry, energy, aerospace, shipbuilding, automobile, air conditioning and refrigeration, electronics, computers and so on. Especially, nanofluids show broad application prospects in the field of enhanced heat transfer [12].

Table 1. Comparison table of thermal conductivity of common substances.

Materialistic	Densities (g/cm^3)	Thermal conductivity (W/(m·K))
Carbon nanotube	1.2	3000
Purified water	0.998	0.613
Ethylene glycol	1.11	0.256
Oil	0.88	0.145
Iron	7.86	80
Copper	8.92	401

Advantages of nanofluidic media over other media include: 1. Compared with millimetre and micrometre particles, nanoparticles are smaller in size and lighter in mass. Due to the small size effect of nanoparticles and their strong Brownian motion, their behaviour is closer to that of liquid molecules and less prone to wear and clogging. Therefore compared to liquids with millimetre or micron sized particles added, nanofluids have more potential for practical applications [13]. 2. The small size of nanoparticles can be used in microelectronics and micro heat pipes and other micro heat exchangers. 3. Nanofluids make the flow boundaries of the flow layer disrupted due to inter-particle, particle-liquid, particle-wall interactions, which results in a reduction of the thermal resistance and an enhancement of the heat transfer. 4. The surface area and heat capacity of nanoparticles are much larger than that of millimetre or micron-sized particles when the same volume share of solids is added to the fluid. Accordingly, the available heat transfer surface area of nanoparticles is larger and the thermal conductivity is greater.

For enhanced heat transfer in heat pipe, since the main heat transfer mechanism of heat pipe is boiling heat transfer, the improvement of boiling performance will improve the heat transfer performance of heat pipe [14]. It has been shown that the thermal conductivity of nanofluids is much larger than that of pure fluids, while nanofluids are outstanding in improving the performance of boiling heat transfer. Therefore, the application of nanofluids to heat pipes to improve the heat transfer efficiency of the heat pipe also came into being, nanofluids, a new type of work material combined with heat pipes can significantly improve the heat transfer efficiency of the heat pipe. Nanofluid heat pipe combines the advantages of both, and has a broader application prospect in the field of heat transfer, which is of great significance [15].

Boiling Heat Transfer Theory

The heat transfer process when the liquid boils on the heating surface is a two-phase flow heat transfer characterized by a phase change. The latent heat generated by the internal phase change of the liquid carries away a large amount of heat [16]. Boiling heat transfer mainly consists of two forms: 1. Large vessel boiling (also known as pool boiling) refers to boiling above the saturation temperature of the hot wall immersed in a liquid with a free surface [17]. 2. Flow boiling is also known as boiling in the tube, in which the fluid is heated by the hot wall in the process of flow. The flow of fluid can be a natural circulation, or the forced circulation by the pump drive [18].

Flow boiling differs from pool boiling in that the fluid is heated while it is flowing. The heat transfer zones of flow boiling in tubes mainly include single-phase liquid convection zone, nucleate boiling zone, liquid film forced convection zone and single-phase steam convection zone. Figure 3 shows the schematic diagram of the pipeline flow boiling bubble formation process: The single-phase liquid convection zone is when the fluid just enters the pipe. The fluid is heated by the hot wall of the pipe but has not yet reached the saturation temperature. The bubbles generated are difficult to break away from the pipe wall, but grow by sliding along the pipe wall. The nucleate boiling zone refers to the period when the mainstream temperature of the fluid reaches the saturation temperature and the bubbles generated no longer condense and disappear. After the nucleate boiling zone is the liquid film forced convection zone. The characteristic of this zone is that no bubbles are generated on the wall and a liquid film is formed on the wall. In the nucleate boiling region and the liquid film forced convection region, the wall temperature remains basically unchanged, and the fluid is always at the saturation temperature. As the liquid film attached to the wall evaporates, all the liquid turns into steam. After the fluid temperature leaves the saturation temperature, it begins to rise rapidly. At this time, the wall temperature in the single-phase steam convection zone also rises accordingly [19].

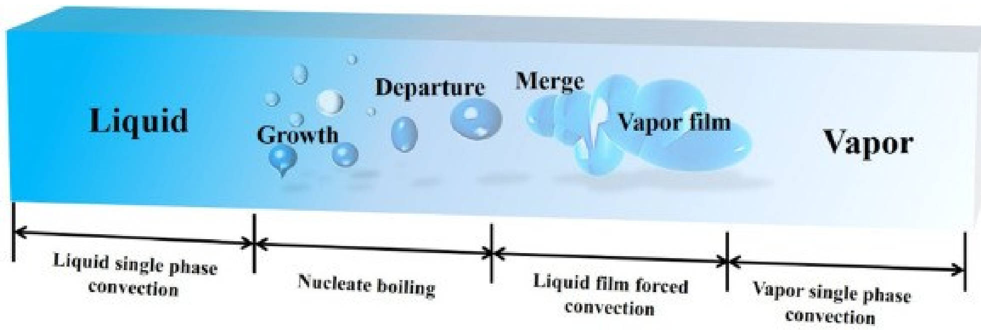

Fig. 3. Flow boiling bubble formation process diagram in the pipeline [16]

To study pool boiling, it is first necessary to analyze the heat transfer curves related to pool boiling. It can be seen from the pool boiling heat transfer curve in Figure 4 that the pool boiling process mainly includes four heat transfer zones: natural convection zone, nucleate boiling zone, transition boiling zone and film boiling zone. Point A is the boiling start point (ONB). Before point A, there are no bubbles on the heating surface, and heat transfer is carried out in the form of thermal conduction. The heat transfer performance is weak, and this area is the natural convection zone. Later, point A is the nucleate boiling area, and bubbles begin to form on the heated surface. The generation and detachment of bubbles cause strong disturbances, which greatly improves the convective heat transfer coefficient. At this time, it can be seen from Figure 4 that the heat flux density begins to rise rapidly, but the wall temperature does not increase much. The maximum value of the heat flux at point C is the critical heat flux (CHF), also known as the burnout heat flux. In actual work, in order to prevent the equipment wall temperature from rising rapidly and burning after reaching the critical heat flux density, the deviation from nucleate boiling point (DNB) is often used as the maximum heat flux density point. After point C, when the wall temperature continues to rise, the bubbles cannot fall off in time, resulting in a layer of steam film covering the heating surface. Due to the relatively low thermal conductivity of steam, the heat transfer resistance increases and the heat flux density is in a decreasing state. Due to the low thermal conductivity of steam, the heat transfer resistance increases and the heat flux density is in a reduced state. This area is the transition boiling zone. When the heating surface is completely covered by the steam film, the heat flux reaches the q_{min} point. As the wall temperature further increases, the radiation heat transfer is enhanced, the heat flux rises again, and then enters the stable film boiling zone [20].

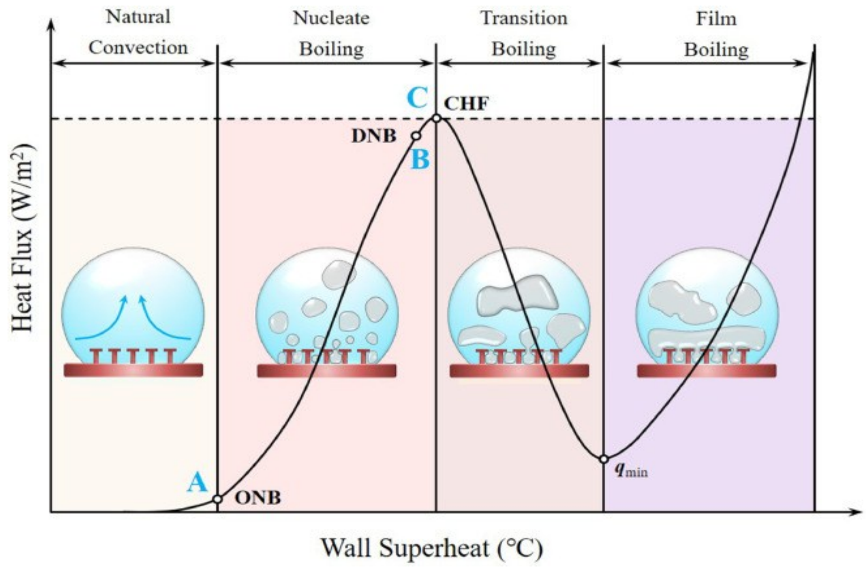

Fig. 4. Pool boiling curve [16]

Case Studies of Nanofluid-Based Boiling Heat Transfer

He *et al.* [21] conducted a boiling heat transfer study on two nanofluids made of zinc oxide (ZnO) nanoparticles dissolved in deionized water and ethylene glycol, respectively, in a cylindrical vessel. The results showed that the increase in heat flux leads to a significant increase in the heat transfer coefficient of the nanofluids.

Sharma & Unune [22] enhanced pool boiling performance by using silver (Ag)/zinc oxide (ZnO) nanofluids at concentrations of 0.02%, 0.06% and 0.1% on three heater surfaces by using the electro discharge machining (EDM) method. The results showed that the critical heat flow density (CHF) and heat transfer coefficient of the surfaces containing silver/ZnO nanofluids at a concentration of 0.1% increased by 80.43% and 252.98%, respectively, compared to the combination of deionized water and normal surfaces. It can also be concluded that the EDM method increased the nucleation sites, and the deposition of the nanoparticles lowered the contact angle of the surfaces, and the performance of pool boiling was enhanced.

Ramakrishna *et al.* [23] compared the pool boiling critical heat flow density (CHF) of nanofluids with copper oxide (CuO) nanoparticles with deionized water. The results showed that the optimum volume fraction of copper oxide nanoparticles was 0.2%, while the critical heat flow density of copper oxide nanofluids with volume fractions ranging from 0.01% to 0.5% were elevated higher than 60% compared to deionized water.

Karimzadehkhouei *et al.* [24] conducted pool boiling heat transfer experiments on a flat plate using different concentrations of TiO_2 and CuO nanofluids and found that the enhancement effect of TiO_2 nanofluids on the boiling heat transfer decreases with the increase in concentration, but not with CuO nanofluids.

Xing *et al.* [25] experimentally investigated the pool boiling heat transfer coefficients of covalently and non-covalently functionalized multi-walled carbon nanotube nanofluids at different volumetric concentrations on a flat plate surface. The results showed that the maximum pool boiling heat transfer coefficient of covalently functionalized nanofluids increased up to 53.4% compared to conventional fluids.

The pool boiling phenomenon of aluminium trioxide (Al_2O_3) nanofluids with an average particle size of 10 nm on the surface of a copper sheet was investigated by Manetti *et al.* [26]. They investigated the pool boiling of aluminum oxide (Al_2O_3) nanofluid on a smooth surface with a surface roughness of Ra = 0.05 µm using aqueous Al_2O_3 nanofluids with volume concentrations of 0.0007% and 0.007%, respectively, and compared it with the pool boiling on a smooth surface with a surface roughness of Ra = 0.23 µm on a rough copper surface. The results show that the pool boiling heat transfer coefficients on smooth and rough copper surfaces increased by 75% and 15%, respectively, compared to deionized water for heat fluxes ranging from 100 to 800 kW/m^2.

Suriyawong & Wongwises [27] experimentally investigated the pool boiling heat transfer of titanium dioxide (TiO_2)-water (H_2O) nanofluids with volume concentrations of 0.00005%, 0.0001%, 0.0005%, 0.005%, and 0.01%, respectively, under two types of heating surfaces (*i.e.*, copper and aluminum tubes with different surface roughness). The results show that at a concentration of 0.0001 vol%, the heat transfer coefficient decreases for aluminum tubes as the heating surface and increases for copper tubes.

The flow boiling heat transfer of refrigerant nanofluid in a horizontal smooth tube was experimentally investigated by Hao *et al.* [28]. They used CuO nanofluid based on R113 refrigerant in which the mass fraction of CuO nanoparticles was 0~0.5 wt%. The results showed that the maximum enhancement in heat transfer coefficient of the refrigerant-based nanofluid was about 29.7% compared to the pure refrigerant.

Kim *et al.* [29] investigated the critical heat flow density (CHF) of aluminum trioxide (Al_2O_3) nanoparticles and reduced graphene oxide (RGO) nanofluids at atmospheric pressure using pool boiling experiments and compared it with deionized water. The results show that the CHF increases with concentration up to 54% for Al_2O_3 nanofluids at concentrations above 0.001 vol%. In RGO nanofluids with a concentration of 0.00005-0.005 vol%, the CHF enhancement ranges from 10%~37% with increasing concentration.

Wang & Su [30] investigated the flow-boiling heat transfer of γ-Al_2O_3/H_2O nanofluids in a vertical tube. The results show that for γ-Al_2O_3/H_2O nanofluids with an average particle size of 20 nm and volume concentrations of 0.1% and 0.5%, the flow boiling Nusselt number increases with the increase of surface heat flux, nanoparticle volume concentration and pressure, and the average Nusselt number of the two concentrations of nanofluids increases by 23% and 45%, respectively. Compared with deionized water, γ-Al_2O_3/H_2O nanofluids have an enhancing effect on flow boiling heat transfer, and the maximum enhancement rate can reach about 86%.

Current Research Status of Nanofluidic Heat Pipes

There are many ways to classify the heat pipe. According to the working temperature, the heat pipe can be divided into: low-temperature heat pipe (-273 ~ 0 °C), room temperature heat pipe (0 ~ 250 °C), medium-temperature heat pipe (250 ~ 450 °C), high-temperature heat pipe (450 ~ 1,000 °C) and so on. According to the structure form, it can be divided into traditional heat pipe, gravity heat pipe, loop heat pipe, pulsating heat pipe, flat plate heat pipe and so on. According to the different flow modes of the working fluid in the pipe, the heat pipe can be divided into thermal siphon heat pipe, oscillating heat pipe, and core heat pipe (mesh core heat pipe, sintered core heat pipe, and channel heat pipe) [31]. Combining the application and research of heat pipes by a large number of scholars, this article will mainly illustrate the four major types of heat pipes, namely loop heat pipes, gravity heat pipes, slot channel heat pipes and pulsating heat pipes, as relevant research examples.

Loop Heat Pipe

As shown in Figure 5, Loop Heat Pipe (LHP) refers to a loop closed-loop type heat pipe. It generally consists of an evaporator, condenser, vapor piping, liquid piping and a compensation chamber. The main driving force to induce liquid reflux is capillary force.

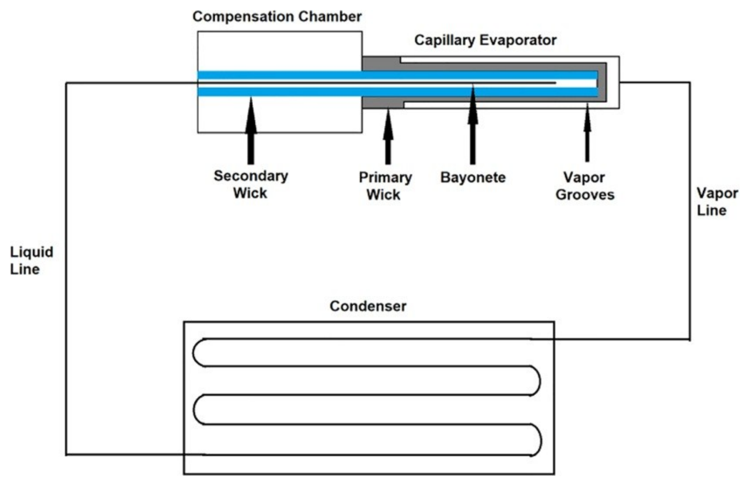

Fig. 5. Schematic Diagram of Loop Heat Pipe [32]

Tharayil *et al.* [33] applied nanofluids mixed with graphene and water to loop heat pipes. The results show that as the volume concentration of graphene nanofluid increases from 0.006 vol%, the thermal resistance of the loop heat pipe gradually decreases. Compared with pure water, at a concentration of 0.006 vol% and a heating power of 380 W, the thermal resistance of the loop heat pipe is reduced by 30.4% and the thermal efficiency is increased by 93%. Veeramachaneni *et al.* [34] applied graphene and water nanofluid to a copper loop heat pipe with a thermal load of 4~320 W and fluid filling ratio of 0.1-0.2% were experimentally investigated for copper and graphene hybrid nanofluid loop heat pipe. It has been shown that the thermal resistance reduction and thermal conductivity enhancement using 0.02 vol% (30% (Cu) + 70% (graphene)) hybrid nanofluidic phase is 24.42% and 32.4%, respectively, compared to deionized water. As shown in Figure 6, through experiments they concluded that in addition to the enhancement of the thermal conductivity of the fluid, the deposition of nanoparticles on the inner surface of the evaporator increases the effective heat transfer area of the evaporator and increases the boiling heat transfer nucleation sites, which is the main reason for the enhancement of the heat transfer performance of the loop heat pipe.

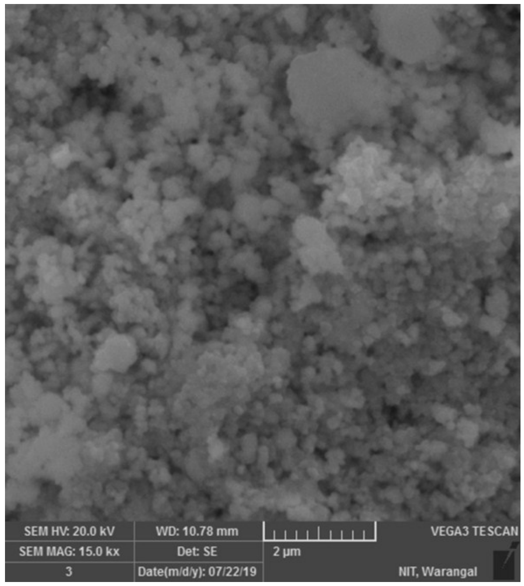

Fig. 6. The SEM image of Copper–GnP nanoparticles [34]

Thermosyphon Heat Pipe

Gravity heat pipes are also called thermosyphon heat pipes (THP). As shown in Figure 7, unlike traditional heat pipes, gravity acceleration needs to be applied, that is, the condensation section is placed directly below the condensate, and the condensate is refluxed by gravity. Therefore, gravity heat pipes do not require capillary structures, have a simpler structure, and have relatively low processing costs.

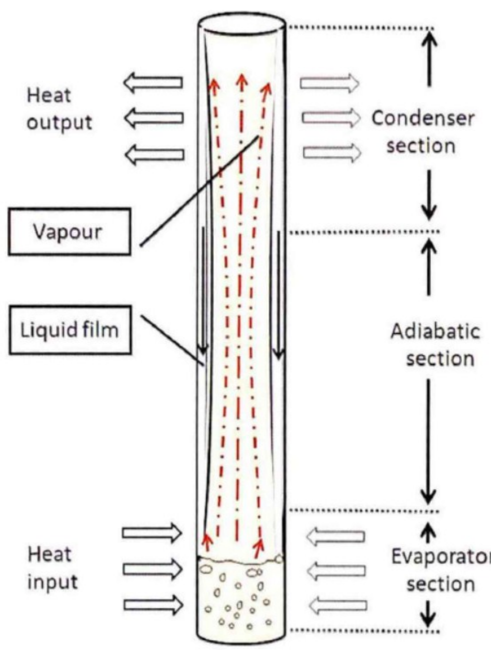

Fig. 7. Schematic Diagram of Gravity Heat Pipe

Çiftçi [35] conducted an experimental study on the heat transfer performance of gravity heat pipe with 2.0 vol% aluminum nitride and zinc oxide hybrid nanofluid in the range of 150-450 W heat load and the experimental setup is shown in Figure 8. The results show that (50% (Aluminium Nitride) + 50% (Zinc Oxide)) hybrid nanofluid has the best heat transfer performance at a thermal load of 150 W. The maximum thermal resistance is reduced by about 40.79%. The main reason for the improvement of heat transfer performance of heat pipes is that the suspended nanoparticles reduce the contact angle of the solid-liquid interface and the suspended nanoparticles perform Brownian motion in nucleation boiling and collide with large bubbles formed in the working fluid, causing a reduction in thermal resistance.

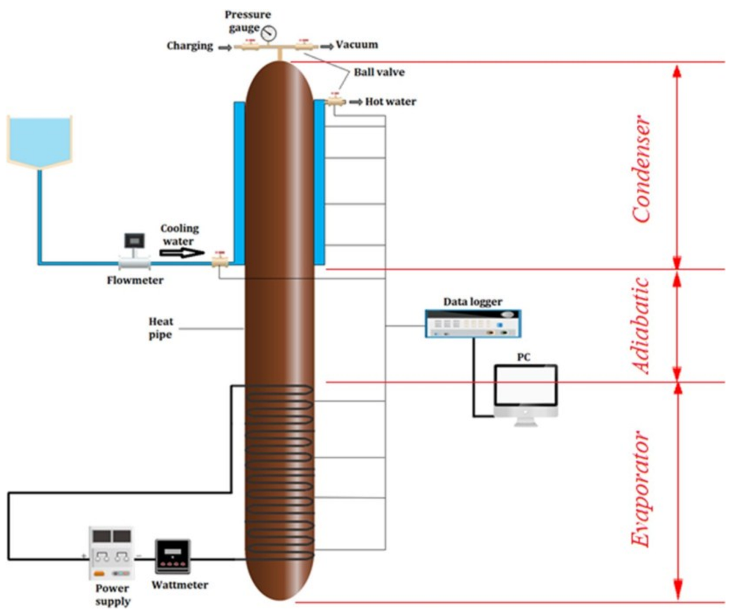

Fig. 8. Schematics of the heat pipe test rig [35]

Herrera *et al.* [36] visualized the boiling heat transfer performance of graphene nanofluid ring siphon heat pipes using inflated aluminum plates at 70% filling ratio, different heating powers (30 W, 60 W, 90 W), and concentrations (0.3 wt%, 0.5 wt%, 1 wt%). The results show that graphene nanofluid with a concentration of 0.5 wt% has a lower nucleation site for boiling heat transfer compared to pure water, indicating that the temperature reaches the boiling point faster. Furthermore, a portion of the graphene is deposited on the surface of the upper wall, which results in a clogging on the liquid surface. This affects the liquid level in the evaporation section to be lower than the liquid level in the condensation section. The lack of liquid in the upper heat source section resulted in an increase in thermal resistance as shown in Figure 10. When the concentration of graphene nanofluid was increased from 0.5 wt% to 1 wt%, the thermal resistance was significantly higher compared to the graphene nanofluid with a concentration of 0.5 wt% due to clogging as shown in Figure 11, despite the fact that more bubbles could be generated compared to pure water.

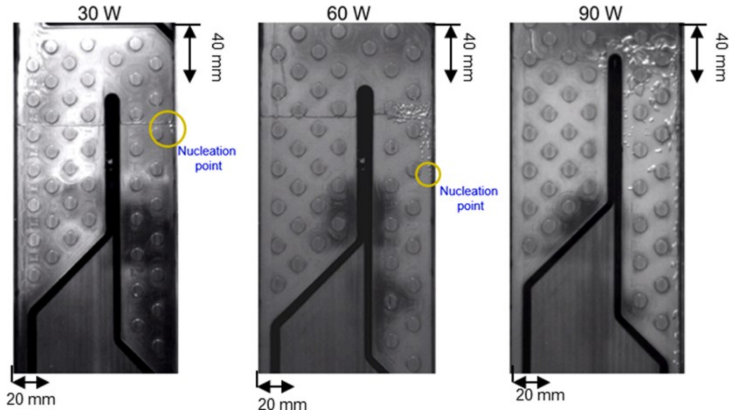

Fig. 9. (a) Pure water fluid visualisation for 30 W (b) 60 W (c) 90 W input power [36]

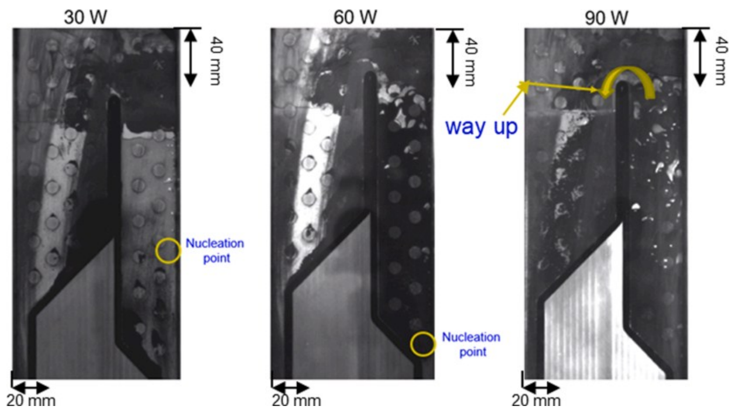

Fig. 10. (a) Visualisation of graphene nanofluid with a concentration of 0.5 wt% graphene nanofluid at 30 W (b) 60 W (c) 90 W input power [36]

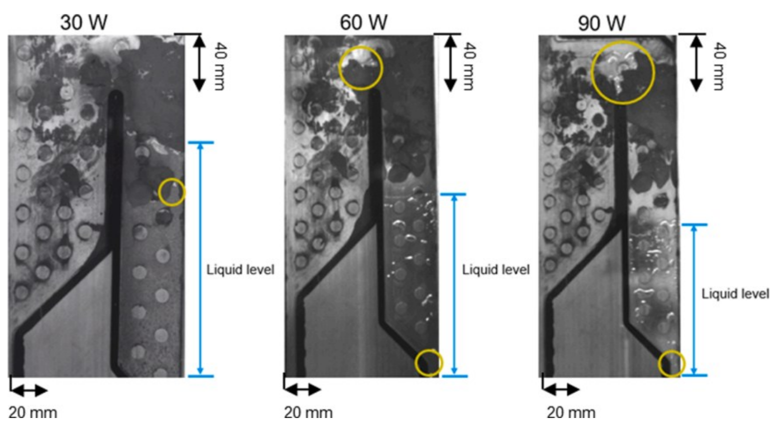

Fig. 11. (a) Visualisation of graphene nanofluid with 1 wt% graphene nanofluid concentration at 30 W (b) 60 W (c) 90 W input power [36]

Grooved Heat Pipe

Grooved Heat Pipe (GHP) is a heat pipe with suction core by capillary action of the groove structure on its inner wall surface, which makes the work mass flow spontaneously to the evaporation section. As shown in Figure 12, the rectangular grooved heat pipe cross-section is schematic, where δ is the heat pipe wall thickness and σ is the depth of the groove. Due to the existence of the slot channel structure, the heat transfer area inside the tube is increased, which greatly reduces the heat pipe thermal resistance. And because the vapor flows in the core of the tube, the liquid returns through the channel. The gas-liquid two phases basically do not have a carrying effect; it is more favorable to the heat pipe work than the gravity heat pipe.

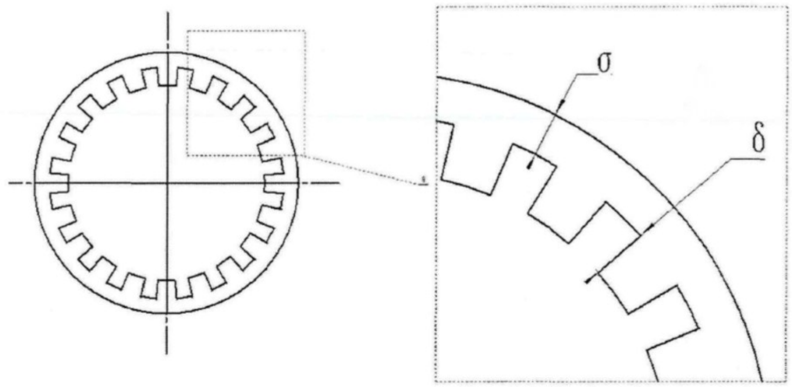

Fig. 12. Section Diagram of Channel Heat Pipe

Pandya *et al.* [37] investigated the heat transfer performance of axial fluted heat pipe with CeO_2-MWCNT hybrid nanofluid using numerical modeling method. The results showed that the best heat transfer performance of the fluted heat pipe was achieved when 1.25 vol% of hybrid nanofluid was used, with an enhancement of about 61.27% and a reduction in maximum thermal resistance of about 30% as compared to the base fluid. Liu *et al.* [38] investigated the heat transfer performance of a cylindrical micro fluted heat pipe using different types of nanofluids. The results showed that copper (Cu) nanofluids and copper oxide (CuO) nanofluids improved the heat transfer performance of the slot heat pipe. However, silicon oxide (SiO) nanofluid deteriorates the heat transfer performance. It was shown to be due to the different surface structure of the nanoparticles forming a coating on the inner surface of the evaporation section thereby weakening the boiling heat transfer performance of the evaporation section. As shown in Figure 13, the coating structure of Cu and CuO nanofluids is a compact porous structure formed by tightly aggregated nanoparticles, which is not easy to come off. However, the coating of SiO nanofluid appears to be a slurry layer without any porous reorganization layer and the coating is easily removed by water flushing. It can be seen that the surface structure formed by Cu and CuO nanoparticles provides a better capillary structure, while the slurry surface structure formed by SiO nanoparticles reduces its heat transfer performance.

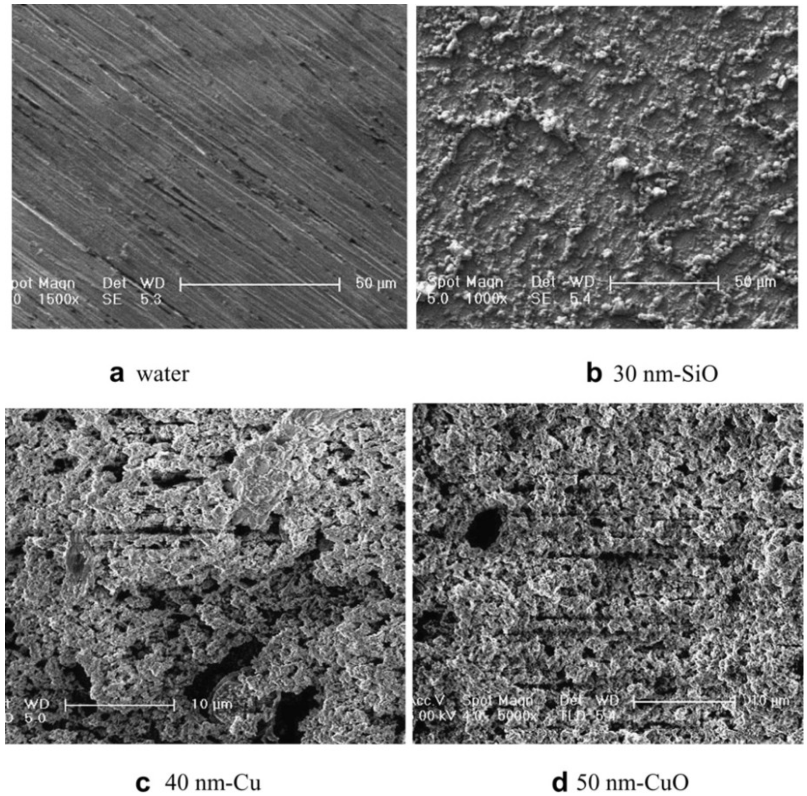

Fig. 13. TEM of the coating layer after the test using CuO nanoflfluid [38]

Pulsating Heat Pipe

Pulsating heat pipe (PHP) (also known as oscillating heat pipe, self-excited oscillating flow heat pipe) is a unique new type of heat transfer element improved on the basis of ordinary heat pipe. Pulsating heat pipe is usually made of a long capillary tube bent into multiple elbows, which can be divided into closed, open and valve-closed pulsating heat pipes by observing the presence or absence of loop formation and one-way valves inside the pulsating heat pipe [39], and its structure is shown in Figure 14. The pulsating heat pipe has no capillary structure, and it is driven by the unbalanced pressure difference between the air plugs to return the liquid to form a loop.

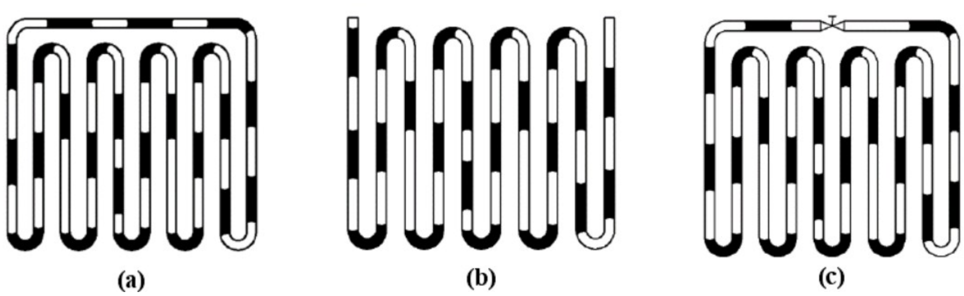

Fig. 14. (a) Closed pulsating heat pipe (b) Open pulsating heat pipe (c) Closed pulsating heat pipe with valve

Zhang *et al.* [40] used SiO_2-H_2O nanofluids with mass concentrations of 0.5%, 1.0%, 1.5% and 2.0%, respectively, to visualize the pulsating heat pipe employing the nanofluids using a high-speed camera. The results show that the addition of nanoparticles increases the transient driving force of the workpiece, promotes the phase change of the workpiece of the pulsating heat pipe, facilitates the condensate reflux, and the performance of the heat pipe is improved. As shown in Figure 15, the maximum heat transfer efficiency enhancement of the heat pipe can reach 40.1% at a heating power of 50 W and a concentration of 1.0 wt%.

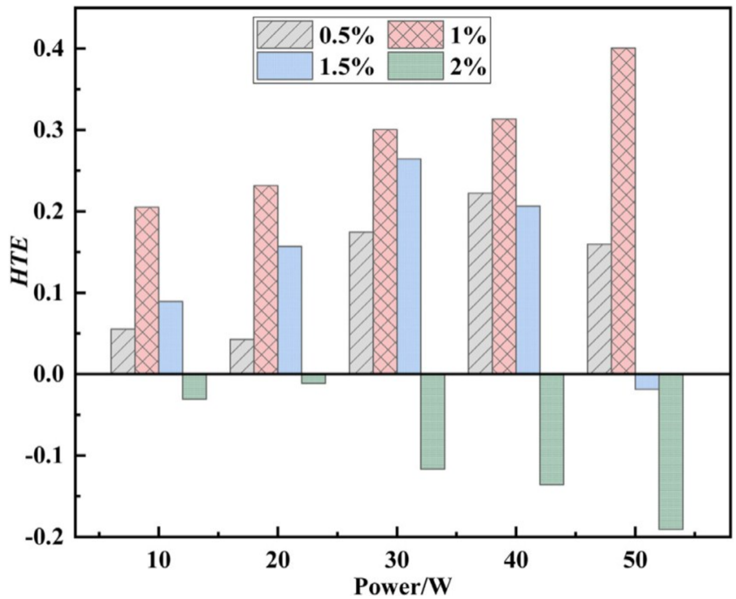

Fig. 15. The HTE Variation of PHP with different concentration [40]

Zhou *et al.* [41] used an ethanol-water solution of carbon nanotubes as the working fluid of an oscillating heat pipe and investigated the thermal resistance and heat transfer performance of the heat pipe. The results showed that the vertically oscillating heat pipe using carbon nanofluid had better startup and heat transfer performance compared to the oscillating heat pipe using ethanol-water mixture, and the wall temperature and thermal resistance were reduced by about 18.5% and 80.8%, respectively, by using 2 wt% carbon nanotube nanofluid in the heat pipe. From the transmission electron microscope image of the carbon nanotube nanofluid and the deposition of carbon nanotubes on the inner surface of the evaporator section (Figure 16), it can be seen that the thermal resistance of the heat pipe is reduced and the heat transfer performance is improved mainly due to the increase in thermal conductivity and the deposition of the carbon nanotube fibers on the surface of the evaporator, which increases the nucleation sites and enhances the boiling heat transfer.

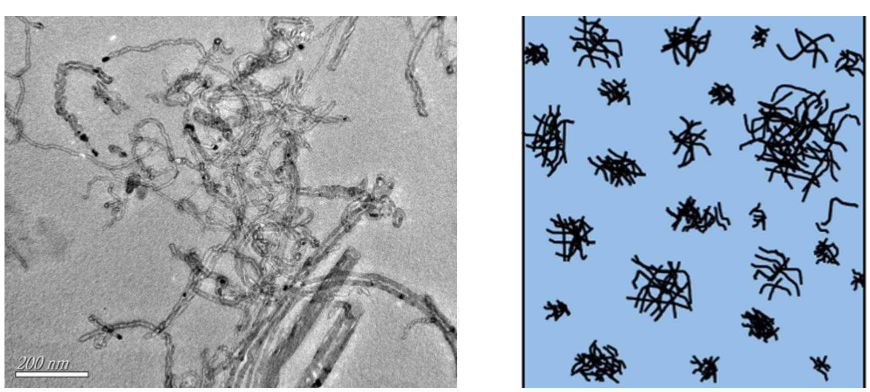

Fig. 16. (a) Schematic of CNT fibre deposition on the inner surface of the oscillating heat pipe

evaporator (b) Transmission electron microscopy image of a carbon nanotube nanofluid [41]

CONCLUSIONS

Heat pipe is an efficient heat transfer device, the high thermal conductivity of the heat pipe makes it possible to transfer higher heat compared to traditional materials, which has a wide range of application fields and great application potential. This paper provides a relevant review on the classification, working principle, application cases and nanofluid-enhanced boiling heat transfer and enhanced heat transfer performance of heat pipes. The open literature suggests that nanofluids show great potential for enhancing heat transfer in heat pipes.

Meanwhile, the research on nanofluid heat pipes has made great progress in recent years, but there is still much room for improvement, and many key problems need to be solved: 1. The measurement results of the thermal conductivity of nanofluids by different researchers lack consistency, so it is necessary to improve the corresponding research program and test system to facilitate more accurate measurement of the heat transfer coefficient of nanofluids. 2. The research on the heat transfer performance of heat pipes by nanofluids is mainly based on experiments, and the research on the mechanism of enhanced heat transfer after nanofluids are applied to heat pipes is not deep enough, and the theoretical analysis needs to be improved. 3. The current research on heat pipes with nanofluids is mainly focused on a single nanofluid, and the research on the application of mixed nanofluids to heat pipes is relatively small. 4. The cost of nanofluid preparation is high, and it is a priority to promote the research on nanofluids in the future to make nanofluid cheaper or to find the preparation method that saves the cost. 5. research on nanofluids is a priority.

CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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