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Nanofluids and heat pipe limitations

Maroua Mekcem
Faculty of engineer science, Department of Electromechanical, Badji Mokhtar Annaba University, Algeria

Abstract

Given the high efficiency of heat pipes as heat transfer devices, which work with phase changing principle (evaporation and condensation) and without requiring any external energy input, the heat pipes have been utilized for many years in several areas. However, heat transfer in heat pipes is limited by physical phenomena which appear during its operation, called heat pipe limitations; these can limit and reduce its performance. At this state, the use of nanofluids instead of conventional fluids come a solution after that Choi and Eastman (1995) confirmed the feasibility of enhancing the thermal conductivity of fluids by adding nanoparticles.

This paper represents a general description of heat pipes, including a brief historical perspective, principle of operation and explanation of main heat transfer limitations. The work shows the contribution of nanofluids in pushing back the heat transfer limitations

Key words: Heat pipe, heat pipe limitations, heat transfer, thermal conductivity, nanofluids

1. Introduction

Heat pipe has been utilized for many years in different engineering fields. Heat pipe is a heat transfer device with high efficiency and reliability, it works with phase changing principle and it transfers heat with a very low thermal resistance and high heat rates over considerable distances with small temperature drops without requiring any external energy input or moving parts. It is also known by the design and manufacturing simplicity.

Heat pipe can operate over a large interval of temperature with a high thermal exchange depending on its various application areas which include the electronic cooling, aerospace thermal control, solar systems, automotive industry, permafrost stabilization, medicine and human body temperature control

However, heat transfer in the heat pipe is limited by different factors, so the nanotechnology was introduced in this case to exceed these limitations, in such a way that the feasibility and effectiveness of thermal enhancement of fluids with nanoparticles were introduced by Choi and Eastman in (1995). Actually, the idea of utilizing nanoparticles within the working fluid of a heat pipe to enhance the heat transfer and the performance has become a subject of interest for scientists and engineers. Furthermore, Heat pipe science provides an opportunity to apply a variety of fundamental laws of different disciplines such as, heat transfer, fluid mechanics, thermodynamics and solid mechanics to a rather simple system, such as the heat pipe.

*Corresponding author: Address: Faculty of engineer science, Department of Electromechanical, Badji Mokhtar Annaba University, Algeria. E-mail address: maroua03mekcem@gmail.com , Phone: +213662039336

2. Heat pipes and their working limits

2.1 Brief history of heat pipe

The predecessor of heat pipe is the Perkins tube, whose main initiative appeared by the American Angier March Perkins in the mid-19th century in UK, then it was developed by the Perkins family through a series of patents, and the closest design of Perkins tube was introduced by Jacob Perkins (Father of Angier March Perkins) in 1836 and expanded by Gaugler (1944) and other scientists to be the actual heat pipe. Perkins tube was a gravity assisted heat pipe, also known as thermosyphon. The working principle of thermosyphon is that the fluid at the bottom of the tube is heated, and after vaporization the fluid moves to the upper part of the tube where it is condensed and the condensate returns to the bottom through the assist of gravity. [2]

2.2 Principle of operation of heat pipe

The heat pipe is a metal sealed tube (shape of tube can be bent or flattened) containing a wick (capillary structure) tacked on the inner surface, and it is filled with a small quantity of a vaporizable liquid called working fluid such as water.

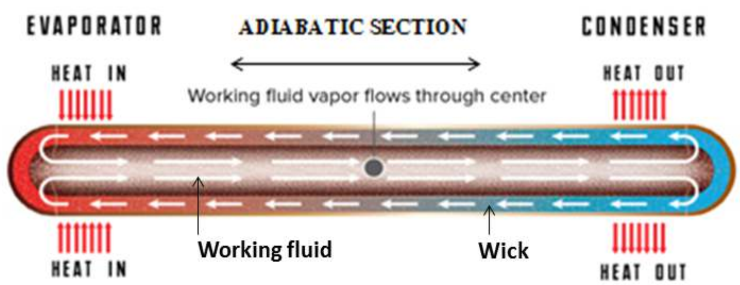

Figure 1. Schematic showing the principle of operation and circulation cycle of the working fluid in a conventional heat pipe

As shown in Fig 1, the length of heat pipe is divided into three sections, the evaporator section, adiabatic section and condenser section. Firstly, the heat input in the evaporator section vaporizes the working fluid, and then the vapor spreads in the adiabatic section toward the condenser where it condenses releasing its latent heat of vaporization to provide the heat sink. Thereafter, the condensed fluid returns back to evaporator section by the pumping effect created by the capillary structure of the wick, and by this process the heat pipe works passively and continuously.

Due to the wide range of heat pipe applications, there are different types of it according to the range of operation temperature as the low temperature range is from 200 to 550 K and most heat pipe applications fall within this range, commonly used fluids are ammonia, acetone, the Freon compounds, and water. The medium temperature range is from 450 to 750 K, and the working fluids are mercury and sulphur. For the high Temperature Range from 750 K and above, Sodium, lithium, cesium, silver are often used. Also there are the cryogenic heat pipes which operate between 4 to 200 K with typical working fluids that include helium, argon, oxygen, and krypton [1]. Furthermore, there are other criteria of classification as size and shape (as micro heat pipes with 30 μm width × 80 μm depth and 19.75 mm in length, and heat pipes as large as 100 m in length), also combination shell-fluid (regarding the compatibility between container and wick materials and working fluid), in other words there is freedom of design. Faghri [1] reviewed types of heat pipe and Capillary Wick Designs and Structures.

2.3 Heat transfer limitations

The operation and performance of heat pipe depend on the size and shape of the pipe, wick structure, working fluid, filling ration, tilt angle and operating temperature [17, 22]. The heat transport in heat pipe is limited under some conditions. Thus, the inappropriate use of these parameters reliant to the application of heat pipe can stands constraints that reduce and limit its efficiency. Major limitations, which are physical phenomena, are briefly presented below.

2.3.1 Capillary Limit

Capillarity is the ability of a particular structure to provide the absorption and the circulation of the working fluid, and this parameter is limited by the wick during the operation of heat pipe. This limit is called capillary limitation or hydrodynamic limitation. The latter appears when the total pressure drop in heat pipe exceeds the maximum capillary pressure of the wick structure. In this case the pumping rate is insufficient to pump back the liquid to the evaporator section, so any attempt to increase the heat transfer above the capillary limit by augmentation of heat input will cause dry out in the evaporator section. In order for a heat pipe to operate, the following condition must be satisfied:

$$\Delta P_{cap} \geq \Delta P_v + \Delta P_l + \Delta P_g$$

Where:

- ΔP_{cap} = capillary pressure (Pa)
- ΔP_v = pressure drop of vapor flow (Pa)
- ΔP_l = pressure drop of liquid flow (Pa)
- ΔP_g = pressure drop due to gravity (Pa)

2.3.2 Boiling Limit

When the radial heat flux is too high in the evaporator, it causes the boiling of liquid in the evaporator wick and the appearance of vapor bubbles which prevent the liquid from wetting the inner wall and provide a supplementary thermal resistance resulting the dry out of the heat pipe, this limitation is called boiling limit.

2.3.3 Sonic Limit

The vapor flow system in the heat pipe is similar to that of a converging diverging nozzle with a constant mass flow rate, where the evaporator exit corresponds to the throat of the nozzle. The vapor velocity increases along the evaporator and reaches to the maximum at the end of the evaporator section where the vapor flow is choked. The sonic limit occurs when the vapor velocity reaches the sonic velocity at this point. However, it does not represent a serious failure, but it can provide a perturbation on the system.

2.3.4 Flooding Limit

The flooding or entrainment limit has its origin in the interfacial interaction between the vapor and liquid flows. When the vapor velocity is too high, it produces shear force effects on the condensate. Consequently, liquid droplets are torn from the interaction surface and entrained into the vapor. The droplets flow to the condenser with the vapor, and leads to a flooding condition in the condenser section and causes a dry out in the evaporator.

2.3.5 Viscous Limit

Viscous limit (Vapor Pressure Limit) is confronted when a heat pipe operates at temperatures below its normal operating range or especially during the frozen startup. In this case, the vapor pressure is not sufficient to overcome the viscous forces. Consequently, the vapor does not start to flow from the evaporator to the condenser, and the circulation cycle doesn't initiate.

3. Heat transfer with nanofluids in heat pipes

3.1 Heat transfer enhancement using nanofluids

One of the variables that determine the performance of heat pipe is the thermo physical proprieties of the working fluid, so the enhancing of its thermal potency leads to increase the heat transfer without extending the heat transfer surface (appending fins) which increases the cost and the size of the equipment significantly.

The effective conductivity of a solution could be enhanced through the addition of supplemental high-conductivity particles, the feasibility and effectiveness of thermal enhancement of fluids with nanoparticles was introduced by Choi and Eastman [5].The suspensions of metal or metal oxide or nonmetallic (CNT: Carbon Nanotubes) particles with an average size of about 1–100 nm in base fluid are known under the name of “Nanofluids”.

Many experimental and analytical studies have been performed on different types of heat pipes using nanofluids, the most common nanoparticles used in researches are Aluminia (Al_2O_3) and copper oxide (CuO), Titanium oxide (TiO_2), Gold and Silver, graphene quantum dots (GQD) and hybrid nanofluids as well. Studies also show that the behavior of thermo physical proprieties of nanofluids such as thermal conductivity, viscosity, density and specific heat are dependent on various factors such as particles volume fraction (concentration) , particles material, size, shape and type of base fluid and temperature [21]. The main effects of nanofluids on heat pipes performance are summarized below.

3.2 Main effects of nanofluids on heat pipes

The first research about the application of nanofluids in heat pipe was published by Chien et al. [9].Since then; many articles about different types of heat pipe using nanofluids have been published. One of the most important results of these studies [3-20], is an increase in the maximum heat load and decrease in the thermal resistance in heat pipe. Maryam Shafahi et al. [3,10], showed that the use of nanofluids in the flat-shaped heat pipe and cylindrical heat pipe decreases the temperature difference along the heat pipe, and reduces the speed of the liquid, and also it provides the possibility of reduction in heat pipe size under the same condition.

It exists an optimum nanoparticle concentration and wick thikness to maximize the heat transport capacity in the heat pipe, Maryam Shafahi et al. [3] established it for flat-shaped heat pipe. Hussein Kavusi and Davood Tghraie [6], showed that nanoparticle concentration has great effect on the thermal conductivity of nanofluid as working fluid in heat pipe. Leonard M.Poplaski et al. [4] determined the optimal nanoparticle concentration of Al_2O_3, TiO_2 and CuO corresponding to the capillary limit for a conventional nanofluid-filled heat pipe, and also a decrease in total thermal resistance was observed to be 83%, 76%, 97% for Al_2O_3, TiO_2 and CuO respectively. In other words, after a certain increase in nanoparticle concentration, the resulting fluid becomes so viscous that it negates any other gains. In practice, high concentration of nanoparticles also leads to sedimentation and blocking of the wicking material. Furthermore, the existence of nanoparticles within the working fluid provides nucleation sites and the bombardment of vapor bubbles, which improves heat transfer rates and pushes back the boiling limit [16,13,15].

nanofluids improve the wettability and the capillary pumping pressure, so the capillary limit is pushed back by using nanofluids as working fluid. [14,15,12]. Grab et al. [11] concluded that only extraordinarily small portion of the nanoparticles suspended in the working fluid is transported by the vapor phase. Therefore, a deposition of nanoparticles on the condenser surface seems rather unlikely.

Conclusions

This paper summarizes the main results of many studies performed on different types of heat pipe using nanofluids. Replacing the conventional fluid by nanofluid enhances the heat transfer capacity, and reduces the dry out problems in heat pipe by pushing back the boiling and the capillary limits which represent a big constraint for the heat pipe performance. Many factors affect the heat pipe thermal performance and should be acquired with optimal values, such as nanoparticles concentration. However, heat transfer mechanisms in heat pipes using nanofluids are somewhat controversial, thus further theoretical and experimental investigations are needful to understand the behavior of nanofluids and their effects on heat pipes.

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