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"A REVIEW ON HEAT PIPE EFFICIENCY ENHANCEMENT USING NANOFLUIDS AND GLASS MATERIALS"

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ABSTRACT

Heat pipes are passive thermal transport devices that operate through evaporation, vapour movement, condensation, and liquid return. Their ability to transfer large quantities of heat with a small temperature difference makes them highly suitable for thermal management in electronics, solar thermal systems, energy recovery units, and industrial cooling applications. However, conventional heat pipes may show performance limitations under high heat flux, restricted operating temperature, and material compatibility conditions. Nanofluids have emerged as advanced working fluids because the dispersion of nanoparticles in base fluids can improve thermal conductivity, boiling behaviour, surface wettability, and heat transfer rate. At the same time, glass materials are important in heat pipe systems where transparency, corrosion resistance, chemical stability, and solar radiation transmission are required. This review discusses the basic operation of heat pipes, the role of nanofluids in improving heat pipe efficiency, the application of glass materials in heat pipe systems, and the major research gaps associated with their combined use. The review concludes that nanofluids and glass materials can support efficient and application-specific heat pipe development when stability, compatibility, geometry, and operating conditions are properly optimized.

Key Words: *Heat pipe; thermal efficiency; nanofluids; glass materials; thermal conductivity; passive cooling; solar thermal system .*

I. INTRODUCTION

Heat pipes are highly efficient passive heat transfer devices that are widely used for thermal management in engineering, energy, electronic, aerospace, solar, and industrial systems. A heat pipe transfers heat from one region to another by using the combined mechanisms of evaporation, condensation, and capillary-driven return of the working fluid. Due to this phase-change-based operation, heat pipes can transport a large amount of heat with a very small temperature difference between the evaporator and condenser sections. This makes them more effective than many conventional solid heat conductors, especially in applications where compact design, high heat flux removal, low maintenance, and silent operation are required. The increasing demand for miniaturized electronic devices, high-performance cooling systems, renewable energy technologies, and efficient heat recovery units has created a strong need to improve the thermal efficiency of heat pipes [1], [2].

The basic operation of a heat pipe involves three main regions: the evaporator, adiabatic section, and condenser. Heat is supplied at the evaporator section, where the working fluid absorbs thermal energy and changes into vapour. The vapour then travels through the inner core of the pipe towards the condenser section due to pressure difference. At the condenser, the vapour releases latent heat and returns to the liquid state. The condensed liquid is transported back to the evaporator either by gravity, capillary action through a wick structure, or a combination of both. This continuous cycle allows the heat pipe to transfer heat efficiently without requiring any external pumping device. Therefore, heat pipe efficiency depends strongly on the thermophysical properties of the working fluid, pipe material, wick structure, filling ratio, inclination angle, operating temperature, heat input, and compatibility between the fluid and container material [3].

In conventional heat pipes, working fluids such as water, ethanol, methanol, acetone, ammonia, and refrigerants are commonly used depending on the operating temperature range. However, the thermal performance of these fluids is limited by their natural thermophysical properties. As heat flux requirements increase, conventional fluids may not be sufficient to maintain low thermal resistance and high heat transfer efficiency. This limitation has encouraged researchers to explore advanced working fluids such as nanofluids. Nanofluids are prepared by dispersing nanoparticles into a base fluid in very small concentrations. These nanoparticles may include metal oxides, metals, carbon-based particles, or hybrid nanoparticles. Common examples include Al2O3, CuO, TiO2, SiO2, ZnO, graphene, carbon nanotubes, and hybrid nanomaterials. Due to their improved thermal conductivity and heat transfer characteristics, nanofluids have shown strong potential for enhancing heat pipe performance [4].

The use of nanofluids in heat pipes can improve efficiency through several mechanisms. First, nanoparticles increase the effective thermal conductivity of the working fluid, which improves heat absorption and heat transport inside the pipe. Second, nanoparticles can enhance nucleate boiling at the evaporator surface by increasing the number of active nucleation sites. Third, deposition of nanoparticles on the inner surface or wick structure may modify surface wettability, which can improve capillary pumping and liquid return. Fourth, nanofluids can reduce overall thermal resistance, resulting in a lower temperature difference between the evaporator and condenser. These improvements are useful in applications where rapid heat removal is necessary. However, the performance of nanofluids is not always positive. Higher nanoparticle concentration may increase viscosity, reduce fluid mobility, cause particle agglomeration, block the wick pores, and reduce long-term stability. Therefore, the selection of nanoparticle type, size, shape, concentration, base fluid, and dispersion method is very important for achieving reliable improvement in heat pipe efficiency.

Along with the development of nanofluids, material selection for the heat pipe container also plays an important role in determining thermal performance and durability. Metals such as copper, aluminium, and stainless steel are commonly used for heat pipe fabrication due to their high thermal conductivity and mechanical strength. However, glass materials are also important in specific heat pipe applications. Glass heat pipes are especially useful in experimental visualization, solar thermal systems, chemical environments, and applications where transparency and corrosion resistance are required. Borosilicate glass is one of the most commonly used glass materials because it has good chemical stability, acceptable thermal resistance, and relatively low thermal expansion. The transparent nature of glass allows direct observation of boiling, condensation, bubble formation, liquid film movement, dry-out conditions, and two-phase flow behaviour inside the heat pipe. This makes glass heat pipes valuable for research and educational purposes.

Glass materials also have potential in solar heat pipe systems because they can allow solar radiation to pass through while supporting the internal working fluid circulation. In evacuated tube solar collectors, glass-based systems are widely used to absorb and transfer solar energy. When combined with suitable working fluids or nanofluids, glass heat pipe systems may improve the thermal conversion efficiency of solar thermal devices. Nanofluids can absorb solar energy more effectively than conventional fluids due to improved thermal conductivity and optical absorption characteristics. Therefore, the combination of glass materials and nanofluids may be useful for improving heat pipe performance in solar energy applications, transparent thermal devices, and low-to-medium temperature heat transfer systems.

Despite these advantages, glass materials also have certain limitations. Glass has lower thermal conductivity than metals, which can reduce heat transfer through the pipe wall. It is also brittle and more sensitive to mechanical shock, thermal stress, and sudden temperature changes. These limitations restrict the use of glass heat pipes in high-pressure, high-load, and severe industrial environments. Therefore, glass heat pipes are generally more suitable for controlled thermal systems, laboratory studies, solar applications, and low-pressure thermal devices. The challenge is to balance the benefits of transparency and corrosion resistance with the limitations of mechanical strength and thermal conductivity.

II. FUNDAMENTALS OF HEAT PIPE OPERATION AND EFFICIENCY

A heat pipe is a passive thermal transport device that works on the principle of phase change heat transfer. It is designed to transfer heat from a hot region to a cold region with very small temperature difference. The high thermal performance of a heat pipe is mainly due to the evaporation and condensation of the working fluid inside a sealed container. Unlike conventional solid conductors, where heat transfer occurs only by conduction, a heat pipe uses latent heat of vaporization to transport a large quantity of heat. This makes heat pipes suitable for applications where compact size, high heat transfer rate, and reliable operation are required. The efficiency of a heat pipe depends on how effectively heat is absorbed at the evaporator, transported through the vapour core, released at the condenser, and returned back to the evaporator as liquid [5].

A typical heat pipe consists of three main zones: evaporator section, adiabatic section, and condenser section. The evaporator section receives heat from an external source. Due to this heat input, the working fluid present near the evaporator absorbs thermal energy and changes from liquid phase to vapour phase. This phase change process is very effective because the fluid absorbs latent heat during vaporization. The vapour generated in the evaporator region creates a pressure difference inside the pipe. As a result, the vapour moves towards the condenser section, where the temperature is lower. In the condenser section, the vapour releases heat to the surroundings or cooling medium and condenses back into liquid. The condensed liquid then returns to the evaporator section through capillary action, gravity, or wick-assisted flow. This continuous cycle of evaporation, vapour transport, condensation, and liquid return allows the heat pipe to operate as an efficient heat transfer system.

The wick structure plays an important role in many heat pipe designs. The main function of the wick is to provide capillary pressure for returning the condensed liquid from the condenser to the evaporator. Common wick structures include screen mesh wick, sintered powder wick, grooved wick, fibre wick, and composite wick. The selection of wick structure affects liquid permeability, capillary pumping capability, thermal resistance, and dry-out limit. If the wick cannot return sufficient liquid to the evaporator, dry-out may occur, which causes a sudden increase in evaporator temperature and reduces heat pipe efficiency. Therefore, the design of the wick must provide a proper balance between capillary pressure and liquid flow resistance. A wick with smaller pores can generate higher capillary pressure, but it may also increase flow resistance. On the other hand, a wick with larger pores may allow easier liquid flow but may not provide sufficient capillary pumping force [6].

The working fluid is another important factor that controls the thermal performance of a heat pipe. The working fluid must be selected according to the operating temperature range, compatibility with the container material, chemical stability, latent heat, surface tension, viscosity, vapour pressure, and thermal conductivity. Water is commonly used for medium-temperature applications because it has high latent heat and good thermal properties. Other fluids such as methanol, ethanol, acetone, ammonia, and refrigerants are used when different temperature ranges are required. A good working fluid should evaporate easily at the operating temperature, transport heat efficiently in vapour form, condense effectively at the condenser, and return smoothly to the evaporator. If the working fluid is not suitable for the temperature range, the heat pipe may show poor start-up behaviour, high thermal resistance, or unstable operation.

Heat pipe efficiency is commonly related to the ratio between useful heat transferred at the condenser and heat supplied at the evaporator. However, in practical analysis, the performance of a heat pipe is often evaluated using thermal resistance, temperature difference, heat transport capacity, start-up time, heat transfer coefficient, and evaporator wall temperature. Lower thermal resistance indicates better heat pipe performance because it means that heat is transferred with a smaller temperature difference. The thermal resistance of a heat pipe can be affected by conduction resistance through the pipe wall, evaporation resistance at the liquid-vapour interface, vapour flow resistance, condensation resistance, and liquid return resistance in the wick. Therefore, the total performance of a heat pipe is not controlled by one single parameter but by the combined effect of material, fluid, geometry, and operating condition.

The container material of the heat pipe also influences thermal efficiency. Copper, aluminium, stainless steel, and glass are commonly used depending on the application. Copper is widely preferred because of its high thermal conductivity and good compatibility with water. Aluminium is lightweight and useful in aerospace and electronic applications, but fluid compatibility must be considered. Stainless steel provides strength and corrosion resistance, but its thermal conductivity is lower than copper. Glass materials are used when transparency, chemical resistance, or solar radiation transmission is required. However, glass has lower thermal conductivity and lower mechanical strength compared with metals. Therefore, the selection of container material should be based on heat transfer requirement, operating pressure, chemical compatibility, mechanical safety, and application environment.

The filling ratio has a strong effect on heat pipe efficiency. Filling ratio refers to the amount of working fluid charged inside the heat pipe. If the filling ratio is too low, there may not be enough liquid to maintain continuous evaporation, leading to dry-out at the evaporator. If the filling ratio is too high, excessive liquid may block vapour flow and increase thermal resistance. An optimum filling ratio is necessary to maintain stable evaporation, smooth vapour movement, and proper liquid return. The optimum value depends on the internal volume of the heat pipe, wick type, working fluid, heat input, and orientation. In many experimental studies, the thermal performance first improves with increasing filling ratio and then decreases after exceeding the optimum level.

The inclination angle also affects the operation of heat pipes. In gravity-assisted heat pipes or thermosyphons, the return of condensed liquid depends strongly on gravity. When the condenser is placed above the evaporator, liquid return becomes easier and thermal performance improves. However, when the heat pipe is operated horizontally or against gravity, capillary action becomes more important. In wickless heat pipes, improper inclination may cause poor liquid return and unstable operation. In wicked heat pipes, capillary pumping can support liquid return even in horizontal or inclined positions, but the performance still depends on wick structure and heat load. Therefore, heat pipe orientation must be considered carefully during design and application.

Heat input is another key parameter affecting thermal efficiency. At low heat input, the evaporation rate may be insufficient, resulting in slow start-up and poor heat transfer. As heat input increases, evaporation becomes more active and thermal resistance generally decreases. However, after a certain limit, excessive heat input may cause dry-out, boiling instability, sonic limit, entrainment limit, capillary limit, or viscous limit. These limitations restrict the maximum heat transport capacity of the heat pipe. The capillary limit is one of the most important limits in wicked heat pipes because it occurs when the wick cannot provide enough capillary pressure to return liquid to the evaporator. Once this limit is reached, the evaporator temperature rises sharply and the heat pipe efficiency decreases significantly [7].

III. ROLE OF NANOFLUIDS IN HEAT PIPE PERFORMANCE ENHANCEMENT

Nanofluids have received significant attention in heat pipe research because they can improve the thermal performance of conventional working fluids. A nanofluid is prepared by dispersing very small solid nanoparticles into a base fluid such as water, ethanol, methanol, acetone, ethylene glycol, or refrigerant. The nanoparticles generally have higher thermal conductivity than the base fluid, and therefore their addition can improve the effective heat transfer capability of the working medium. In heat pipes, the working fluid plays a central role in absorbing heat at the evaporator, transporting energy through vapour movement, and releasing heat at the condenser. Therefore, any improvement in the thermal behaviour of the working fluid can directly affect the overall heat pipe efficiency. Nanofluids are mainly used to reduce thermal resistance, improve evaporator heat absorption, increase heat transfer rate, enhance boiling characteristics, and improve the stability of the evaporation-condensation cycle [8].

The enhancement of heat pipe efficiency by nanofluids is strongly related to their improved thermophysical properties. When nanoparticles are added to a base fluid in suitable concentration, the effective thermal conductivity of the fluid increases. This helps in faster heat absorption at the evaporator section and better heat distribution inside the heat pipe. Metal and metal oxide nanoparticles such as Cu, Ag, Al2O3, CuO, TiO2, ZnO, Fe2O3, and SiO2 are commonly used because of their thermal stability and availability. Carbon-based nanoparticles such as graphene, graphene oxide, carbon nanotubes, and diamond nanoparticles have also been investigated due to their excellent thermal conductivity. In recent studies, hybrid nanofluids containing two or more types of nanoparticles have been considered for further improving heat transfer performance. However, the actual improvement depends not only on the thermal conductivity of nanoparticles but also on their size, shape, volume fraction, dispersion quality, and compatibility with the base fluid.

One of the major benefits of nanofluids in heat pipes is the reduction of thermal resistance. Thermal resistance represents the difficulty faced by heat while moving from the evaporator to the condenser. A lower value of thermal resistance indicates better heat pipe performance. Nanofluids can reduce thermal resistance by improving heat absorption at the evaporator and increasing the rate of heat rejection at the condenser. At the evaporator, the presence of nanoparticles can promote active boiling and increase the number of nucleation sites. These nucleation sites help in faster vapour generation, which improves heat transport through the vapour core. At the condenser, improved thermal properties of the working fluid support effective condensation and heat release. As a result, the temperature difference between the evaporator and condenser decreases, and the heat pipe operates more efficiently [9].

Nanoparticles can also influence the surface characteristics inside the heat pipe. During operation, some nanoparticles may deposit on the inner wall or wick surface of the evaporator section. This deposition can change the surface roughness and wettability of the heated surface. Improved wettability helps the liquid spread more uniformly on the evaporator surface, which supports continuous evaporation and reduces the possibility of dry-out. A thin and stable nanoparticle layer may also increase the surface area available for heat transfer. This can improve boiling heat transfer and enhance liquid-vapour interaction. However, excessive deposition can block wick pores, reduce permeability, and disturb the liquid return path. Therefore, nanoparticle deposition may be beneficial or harmful depending on the concentration, operating time, particle stability, and wick structure.

The concentration of nanoparticles is one of the most important parameters in nanofluid-based heat pipes. At low or moderate concentration, nanoparticles can improve thermal conductivity and reduce thermal resistance. However, after a certain optimum concentration, the performance may start decreasing. This happens because higher nanoparticle concentration increases viscosity and reduces the fluid's ability to flow easily through the wick structure. High concentration may also cause agglomeration, sedimentation, and clogging. Agglomeration occurs when nanoparticles join together and form larger clusters. These clusters reduce the stability of the nanofluid and may block the small pores of the wick. Sedimentation reduces the uniform distribution of particles in the base fluid, leading to non-uniform thermal properties. Therefore, the selection of optimum nanoparticle concentration is necessary for achieving maximum heat pipe efficiency.

The stability of nanofluids is a major issue for long-term heat pipe operation. A stable nanofluid should maintain uniform particle distribution for a long duration without settling or forming large clusters. Stability is usually improved by using ultrasonication, surfactants, pH control, or surface functionalization of nanoparticles. Ultrasonication helps break particle clusters and improves dispersion in the base fluid. Surfactants reduce the attractive forces between particles and help them remain suspended. However, surfactants may degrade at high temperature and may also affect boiling behaviour. In heat pipes, long-term stability is more important than short-term thermal enhancement because unstable nanofluids can reduce reliability. If nanoparticles settle in the evaporator or wick, they may increase thermal resistance and cause poor liquid return. Therefore, stability evaluation is essential before using nanofluids in practical heat pipe systems [10].

The type of base fluid also affects the performance of nanofluid heat pipes. Water-based nanofluids are widely used due to the high latent heat, good thermal properties, and environmental safety of water. However, water is suitable mainly for moderate temperature ranges. Alcohol-based nanofluids such as ethanol or methanol are useful for lower temperature applications because they have lower boiling points. Acetone-based nanofluids may be used where quick evaporation and low-temperature operation are required. The compatibility between base fluid, nanoparticle, wick, and container material must be carefully considered. For example, copper heat pipes with water-based nanofluids are common because copper and water have good compatibility. In glass heat pipes, fluid compatibility and thermal expansion behaviour should also be considered. If the fluid reacts with nanoparticles or container material, gas generation, corrosion, or performance degradation may occur.

Different types of nanoparticles affect heat pipe efficiency in different ways. Metal oxide nanoparticles such as Al2O3, CuO, and TiO2 are commonly used because they are chemically stable and relatively easy to disperse. Al2O3 nanofluids generally show good stability and moderate thermal enhancement. CuO nanofluids may provide better thermal conductivity but can suffer from agglomeration if not properly dispersed. TiO2 and SiO2 nanoparticles are useful where chemical stability and corrosion resistance are important. Carbon nanotubes and graphene-based nanofluids can provide high thermal conductivity, but they may require special dispersion techniques due to their tendency to form clusters. Hybrid nanofluids are also promising because they can combine the advantages of two different nanoparticles. For example, a hybrid nanofluid may provide better thermal conductivity, stability, and surface interaction than a single-particle nanofluid.

The operating conditions of the heat pipe also determine the effectiveness of nanofluids. At low heat input, the effect of nanofluids may be limited because evaporation is not very strong. At moderate heat input, nanofluids generally show better performance because enhanced thermal conductivity and improved boiling support effective heat transport. However, at very high heat input, dry-out, entrainment, or capillary limits may occur. In such cases, nanofluids may not always prevent performance degradation. Similarly, inclination angle affects the movement of liquid and vapour inside the heat pipe. In gravity-assisted heat pipes, liquid return is easier when the condenser is above the evaporator. In horizontal or inclined heat pipes, the wick structure and fluid viscosity become more important. If the nanofluid has high viscosity, liquid return may be difficult, especially in long or small-diameter heat pipes.

Nanofluids are particularly useful in applications where high heat flux removal is required. These applications include electronic cooling, solar thermal collectors, battery thermal management, heat exchangers, refrigeration systems, and waste heat recovery systems. In electronic devices, nanofluid heat pipes can help maintain lower operating temperatures and improve device reliability. In solar thermal systems, nanofluids can enhance solar energy absorption and improve thermal output. In battery systems, heat pipes using nanofluids can help distribute heat more uniformly and reduce thermal hotspots. In industrial systems, nanofluid heat pipes may improve heat recovery efficiency and reduce energy losses. However, practical application still requires detailed study of long-term stability, manufacturing cost, maintenance, compatibility, and environmental impact.

Although nanofluids offer many advantages, their use in heat pipes also creates several challenges. The most important challenges include particle agglomeration, sedimentation, wick clogging, increased viscosity, erosion, corrosion, and uncertain long-term reliability. The preparation method of nanofluids is also important because poor dispersion can reduce performance. In addition, there is no universal optimum nanoparticle concentration because the best concentration depends on the type of nanoparticle, base fluid, wick structure, heat pipe geometry, and operating condition. Some studies have reported improvement in heat pipe efficiency with nanofluids, while others have reported limited or even negative effects at higher concentrations. This indicates that nanofluid heat pipes require careful optimization rather than simple addition of nanoparticles. In the context of glass heat pipes, nanofluids are especially interesting because glass allows visual observation of internal flow and phase change behaviour. Transparent glass heat pipes can help researchers directly observe bubble formation, boiling intensity, condensation patterns, liquid film movement, and nanoparticle deposition. This is useful for understanding the actual mechanism of heat transfer enhancement. In solar glass heat pipe systems, nanofluids may improve both thermal conductivity and solar absorption. However, the lower thermal conductivity of glass compared with metals may limit the total heat transfer rate. Therefore, the combination of nanofluids and glass materials should be designed carefully to balance transparency, heat transfer efficiency, fluid stability, and mechanical safety. Overall, nanofluids can improve heat pipe efficiency by enhancing thermal conductivity, reducing thermal resistance, improving boiling behaviour, modifying surface wettability, and supporting faster heat transport. However, their performance depends on many factors such as nanoparticle type, concentration, size, shape, base fluid, stability, wick structure, heat input, inclination angle, and container material. The improvement is usually highest when the nanofluid is stable and used at an optimum concentration. Excessive nanoparticle loading may reduce performance due to higher viscosity and clogging. Therefore, future development of nanofluid-based heat pipes should focus on stable nanofluid preparation, hybrid nanoparticle systems, long-term reliability testing, and performance comparison under real operating conditions [11].

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