Recent advances in loop heat pipes: A review

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Abstract: Among the various technologies available today heat pipes can be considered as an efficient heat transfer device. A heat pipe is a device which can transfer heat though long distances. Heat pipes (HPs) have gained importance in recent years, mainly in the field of cooling electronic components, since they need heat removal from limited volumes to the environment. Small HPs are widely used in electronic applications, which are normally limited by the compact structure and dimensions of the electronic device. Among small heat pipes, loop heat pipes (LHPs) are usually preferred due to high efficiency and compact size. Nano fluids also have attracted attention due to their superior heat transfer properties in recent years. The lower thermal conductivity of conventional working fluids puts a limit on heat transfer. The thermal performance of heat pipes may be improved by using nano fluids as working fluids. This review presents an investigation on the design, operating principle, advantages and applications of loop heat pipes. Furthermore, emphasis is given on the effect of the nano fluid in the thermal performance of LHPs.

Key words: Loop heat pipe, nano fluid, thermal performance

1. Introduction

The loop heat pipe (LHP) is a device that operates on a multi phase fluid-flow cycle, maintained by a capillary medium in the evaporator. It is a heat transfer device which can transport a large amount of heat over a long distance with negligible temperature difference. It utilizes boiling and condensation to transfer heat, and the surface tension force developed at the liquid/vapor interface on the evaporator wick to maintain the flow circulation. The schematic of loop heat pipe is shown in figure 1. The operation of a LHP may be summarised as follows. At start-up, the liquid load is sufficient to fill the condenser and the liquid and vapour lines and there is sufficient liquid in the evaporator and compensation chamber to saturate the wick. When a heat load is applied to the evaporator, fluid evaporates from the surface of wick. Since the wick has considerable thermal resistance, the temperature and pressure within the compensation chamber will be less than that in the evaporator. The capillary forces in the wick obstruct the flow of the vapour from evaporator to compensation chamber. When the pressure difference between compensation chamber and evaporator rises, the liquid is displaced from the vapour line and the condenser and it enters the compensation chamber.
1.1. Advantages of loop heat pipes
Along with the features of a heat pipe, the LHP has the following additional advantages:
- High heat flux capability
- Ability to transfer energy over long distances
- Ability to operate over a range of environments
- Wick is not provided in the transport lines
- Chance of entrainment is very low

1.2. Applications
LHPs can be used in thermoelectric generators. Thus it avoids the use of power consuming fan and results in noise free operations. They are also used in LED street lights for heat dissipation. In solar water heaters the LHP is considered as an integral component due to its better performance. In 1989, LHP was first adopted for space application in a Russian spacecraft. Even now they are being used for space applications. In the thermal management of electronic components also LHPS are widely used.

2. Literature review
A pie-chart demonstrating the literature explored for the present review is shown in figure 2. This paper is an attempt to review recent advances in loop heat pipes with special emphasis on nano based loop heat pipes as of 2017. A total of 32 papers are taken for this study. Out of these seventeen papers focus on experimental, eight on numerical, three on combined experimental and numerical investigations, and four explaining various reviews of loop heat pipes.
2.1. Experimental Investigations

The thermal performance of a loop heat pipe has been experimentally investigated by many researchers. Pauken et al. [2] experimentally studied the heat transfer characteristics of LHP with two working fluids i.e., ammonia and propylene. The constant conductance performance of the LHP was found to be 170 W/K with ammonia and 44 W/K for propylene. The thermal performance of an LHP with acetone as working fluid was experimentally studied by Riehl et al. [3]. Results showed that the system could present reliable performance in all situations with power level as low as 1 W. Also higher operating temperatures could be obtained when evaporator was above the condenser. Bai et al. [4] developed a model for start-up process on the basis of node network method. These nodes were mainly classified into two, namely fluid nodes and wall. Zhao et al. [5] introduced a solar water heater based on LHP technology. It resulted in the reduction of fossil fuel consumption and carbon emissions associated with hot water production and supply. Vlassov et al. [6] developed a considerably precise condenser and transient nodes in the compensation chamber and evaporator. It was found that his model was able to predict transient behaviour of LHP within 3 - 4°C of accuracy. Guiping et al. [7] conducted a fundamental study of a dual compensation chamber. The experimental results showed that a V-shaped operational curve was obtained for heat loads above 50 W. Thermal behaviour of a cryogenic LHP was experimentally studied by Philippe et al. [8] for space applications. Results indicated that a small heating load applied to the cold reservoir allowed maintenance of a constant sub cooling and the system behaved as a capillary loop. Leonid et al. [9] developed a LHP for cooling of high power electronic components. The experimental results suggested that when high power dissipation levels were available low conductivity wick should be adopted for LHP applications.

Huang et al. [10] categorised the start-up phenomenon of LHP into four modes i.e., oscillation, failure, normal and overshoot. In the failure mode, evaporator temperature couldn’t reach a steady state instead it continued to rise. In oscillation mode, evaporator temperature increased due to the continued heat input and vapourisation of the fluid. Zhang et al. [11] developed a solar photovoltaic heat pump system for generating hot water. After the experimental investigations the thermal, electrical and overall efficiency of the module were 40%, 10% and 50% respectively. The system’s overall performance coefficient was 8.7. Shen et al. [12] experimentally studied the application of self rewetting fluid to LHP. It was concluded that total thermal resistance reduced by 60% and heat transfer characteristics improved. A LHP using flat evaporator with biporous wick was investigated by Chen et al. [13]. The wick was made from nickel powder. The LHP showed a very quick response to variable heat load and operated steadily without temperature oscillation. Zhao et al. [14] developed a LHP with liquid guiding holes and the performance characteristics were analysed. The results showed that LHP could start successfully with heat loads from 70 W to 220 W. The thermal performance of a
A miniature LHP was investigated with graphene nano fluid by Trijo et al. [15]. The results showed that thermal conductivity and thermal efficiency of the LHP increased. Zhao et al. [16] also studied the thermal performance of a double compensation chamber LHP for anti icing system in aircrafts. The results indicated that surface temperature of the aircraft wing increased with increase of heat load on the evaporator. Zhenping et al. [17] experimentally investigated the influence of a copper nano fluid on the heat transfer characteristics of a miniature loop heat pipe. It was concluded that performance enhancement of the loop heat pipe using the nano fluid resulted in the reduction of the contact angle, improvement in boiling heat transfer and deposited nanoparticle coat on the boiling surface.

2.2. Numerical investigations
Alekey et al. [18] conducted 3D numerical investigation of flow and conjugate heat and mass transfer in a model TacSat-4 satellite LHP evaporator. The simulation results showed that evaporation mainly occurred at the vapour groove corners near the evaporator. In order to determine thermodynamic behaviour of LHP a steady state model was developed by Benjamin et al. [19]. Simulation results showed the major effect of evaporation coefficient and wick conductivity on the LHP evaporator temperature and its temperature field. Esarte et al. [20] developed a new model for cooling high power emitting diodes through loop heat pipes. It was based on the steady state energy balance equations for each component. Several parameters such as tube radius and length and their effects were also studied. Mariya et al. [21] developed a 3D model of heat and mass transfer in the flat evaporator of an LHP. EFD Lab software package was used for numerical simulation. The simulation results were analysed for getting heat transfer dependences of heat load for different orientations of the evaporator. Hui et al. [22] numerically investigated the steady state model of an anti-gravity LHP. It was found that anti-gravity length and condensation length influenced the circulation of working fluid. The thermal characteristics of LHP evaporator were analysed by Masahito et al. [23]. It was done by using a 3D pore network model with a dispersed pore size wick. It was inferred that optimum shape can be achieved by varying the three phase contact line. Masahito et al. [24] also developed a mathematical model to study the heat transfer characteristics of evaporator in LHP with a small gap between case and wick. Also the effect of this gap on the thermal properties was discussed. After the numerical investigation it was concluded that micro gap was an efficient approach for improving thermal performance. Riehl [25] studied the effect of nickel - water nano fluid in a LHP. Result showed that heat transfer coefficient was lower at the evaporator side and operating temperatures were higher throughout the LHP.

2.3. Combined experimental and numerical investigations
Gunnasegaran et al. [26, 27] conducted experimental and numerical investigations on LHPs with alumina and silica as nano fluids. It was found that the thermal resistance decreased when using silica - water nano fluid. The LHP charged with alumina - water nano fluid yielded lower wall temperature difference between evaporator and condenser and steady state was attained faster. Nookaraju et al. [28] experimentally and numerically investigated the enhancement in thermal performance of a copper sintered wick heat pipe with deionised water. From the results it could be concluded that as heat input increased the efficiency value decreased. The investigations on loop heat pipes with nano fluids can be summarized as shown in the table 1.
Table 1. Investigations on LHPs with nanofluids

| Authors             | Parameter analysed     | Nanoparticle | Conclusions                                                                 |
|---------------------|------------------------|--------------|-----------------------------------------------------------------------------|
| Trijo Tharayil et al. [15] | Thermal conductivity | Graphene     | The thermal conductivity and thermal efficiency increased. Very low concentrations of nanofluid gave improvement in heat transfer. |
| Zhenping et al. [17] | Contact angle          | Copper       | Results from the reduction of the contact angle, the enhancement of boiling heat transfer. Water recirculation rate of nanofluid is more than that of pure water during boiling. |
| Reihl [25]          | Heat transfer coefficient | Nickel      | Heat transfer coefficient is lower at the evaporator side and operating temperatures are higher throughout the LHP. |
| Gunnasegaran et al. [26] | Thermal resistance | Silica       | Thermal resistance of LHP decreased. Therefore, the presence of nanoparticles could greatly enhance the cooling of LHP. |
| Gunnasegaran et al. [27] | Thermal resistance | Alumina      | It reaches steady state faster than pure water. Thermal resistance of LHP decreased. |

2.4. Reviews on loop heat pipes

Zhangyuan et al. [29] conducted a review on solar water heating application of LHP. This review also discussed the problems that still existed in the solar water heaters and identified new research subjects to improve the performance of solar water heaters. Stephane et al. [30] focused the review on parametric analysis of LHP operation. It was shown that LHP operation was mainly affected by the boiling and capillary limitations. The LHP performance was characterized by their thermal resistance and maximum heat transport capability. A review on the development of cryogenic LHPs was presented by Lizhan et al. [31]. This work contributed to a better understanding of the development
and operating characteristics of cryogenic LHPs. Maydanic et al. [32] conducted a review on the development of LHPs using flat evaporators. It was concluded that stainless steel – nickel – ammonia was the most efficient combination for 40 – 70 °C and Copper – copper – water combination was the most efficient for 70 – 100 °C.

2.5. Application domains of loop heat pipes

Loop heat pipes can be used for a wide variety of applications like aircraft anti – icing system, cooling of electronic components, solar water heating etc. The specific applications and corresponding literature are listed in table 2.

| Sl. no | Literature | Applications |
|-------|------------|--------------|
| 1     | [3], [6], [8], [16], [30] | Cryogenics, future space missions, aircraft anti-icing system |
| 2     | [5], [11], [28] | Solar water heating, photovoltaics |
| 3     | [9], [17], [20], [25] | Cooling and thermal management of electronic components |

3. Conclusions

This paper reviews recent findings related to loop heat pipes and factors affecting their performance. It is observed that thermal efficiency and thermal resistance are two important factors which determine the thermal performance of a loop heat pipe. Nano fluid based LHPs form a recent area of investigation with promising results. The thermal resistance of loop heat pipes reduces with increase in nano particle concentration. Thermal efficiency of loop heat pipes can be improved by using nano fluids. There are only limited investigations on loop heat pipes with nano fluids. The three dimensional numerical investigations on loop heat pipes are scarce. Also a few researchers have considered combined experimental and numerical investigations. Various parameters, such as wick materials, structure factors of evaporator and heat conduction through the tube wall, on heat transfer performance and fluid flow properties are yet to be analysed in full detail. Furthermore, theoretical and experimental investigations are required to determine the thermal characteristics of nano fluid based loop heat pipes.

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