Heliyon 5 (2019) e01627

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.heliyon.com

Review Article

Current research aspects in mono and hybrid nanofluid based heat pipe technologies

Rakesh K. Bumataria [a], N.K. Chavda [b], Hitesh Panchal [c,*]

[a] *Gujarat Technological University, Ahmedabad, Mechanical Engineering Department, Government Polytechnic, Porbandar, Gujarat, India*
[b] *Gujarat Technological University, Ahmedabad, Mechanical Engineering Department, A.D. Patel Institute of Engineering and Technology, New V. V. Nagar, Anand, Gujarat, India*
[c] *Mechanical Engineering Department, Government Engineering College Patan, Gujarat, India*

ARTICLE INFO

Keywords:
Nanotechnology
Mechanical engineering

ABSTRACT

Technological development has leads to need of more compact thermal management system especially in electronic cooling systems. Heat pipe with the use of mono and hybrid nanofluids are recent trends to satisfy the need of enhanced heat transfer and miniaturization in size. In this article, a state-of-the-art review on different types of heat pipe s, nanofluids preparation and characterization techniques have been carried out. The study begins with an overview of heat pipe and discussed about heat pipe with sintered, grooved and mesh wick structures, applications, mono nanofluids and hybrid nanofluids. The research works carried out for last decade are analyzed in terms of types of heat pipe, working medium, nanofluids preparation and characterization techniques. Effect of operating variables like nanoparticle size, shape and concentration, filling ratio, inclination angle and heat load are also presented. In last, the possible future research thrusts are presented.

1. Introduction

Due to increase of work frequency and heat flux of electronic system, the dissipation of heat from it become major problem in electronic component design. Miniaturization of electronic system need more heat dissipation from compact thermal devices. Effective heat transfer using compact system is essential for modern thermal management system, especially for cooling application of CPUs, LEDs, rectifiers, thyristors, transistors, travelling wave collectors, audio and RF amplifiers and high density semiconductors. Since the reliability electronic components is sensitive to their operating temperature, it is important to optimize the thermal management components with higher cooling flux. Step have been taken to improve heat dissipation by using heat pipe technology is one of key solution for such a problem. In this article mono and hybrid nanofluids based heat pipe including cylindrical, flat, pulsating, rotating, loop and thermosyphon are considered for analysis. The related research work carried out for the past 10 years are reviewed in term of types of heat pipe, size, material and application, types of working medium, its filling ratio and operating condition, preparation methods, characterization techniques, performance characteristics and variables etc. The main segment deals with a comprehensive review on major research carried out in various aspects of nanofluids based heat pipe technology. The final phase discussed the current issues, future trends and their research direction for nanofluids based heat pipe technology.

1.1. Heat pipe

Heat pipes is passive device that transfer heat form heat source to heat sink over relatively long distance via latent heat of vaporization of working fluid [1]. Heat pipe is divided into three sub sections (1) evaporator, (2) adiabatic and (3) condenser section as shown in Fig. 1.

Different structures such as different types of grooves, wire mesh, sintered powder metal and fiber/spring are provided at inner wall of heat pipe as shown in Fig. 2. Proper quantity of working fluid is filled inside the heat pipe and sealed after creating required vacuum [2]. There are many configurations of heat pipe are observed in open literature like cylindrical heat pipe, flat heat pipe, thermosyphon, pulsating heat pipe, oscillating heat pipe, loop heat pipe, rotating heat pipe etc.

1.2. Working medium

A fluid which filled inside the heat pipe and sealed after creating required vacuum is known as working medium. The primary need of working medium is to absorb latent heat of evaporation from evaporator

* Corresponding author.
E-mail address: engineerhitesh2000@gmail.com (H. Panchal).

https://doi.org/10.1016/j.heliyon.2019.e01627
Received 7 March 2019; Received in revised form 11 April 2019; Accepted 30 April 2019

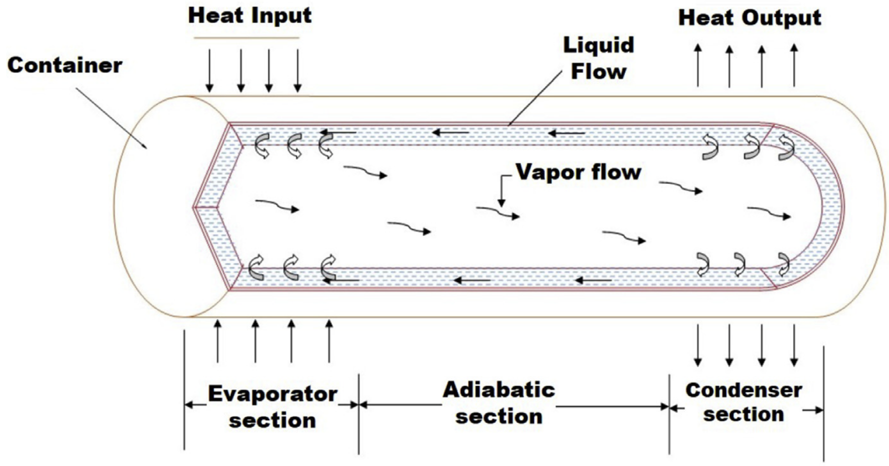


Fig. 1. Heat pipe.

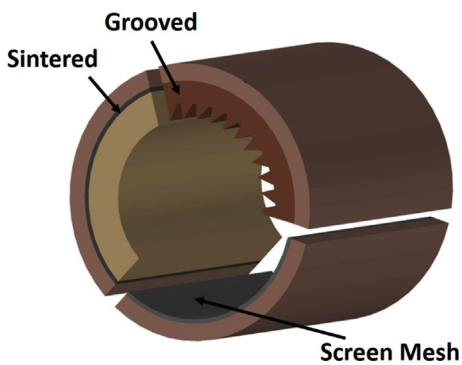


Fig. 2. Different wick structures.

section and reject it as latent heat of condensation at condenser section. Due to pressure difference, working medium moves from evaporator section to condenser section in gaseous phase and return back in liquid form through wick structure using capillarity action. Various types of working medium are widely used in heat pipe as shown in Fig. 3. This article is specially focused on mono and hybrid nanofluids as working fluid in heat pipe technology.

1.3. Nanofluids

A fluid suspended with nanoparticles (less than 100nm size) of metallic or non-metallic substance uniformly and stably suspended in conventional fluid is known as nanofluids [3]. Wide range of nanoparticles in various shapes such as spherical, cylindrical etc. is manufactured from pure metals (Au, Ag, Cu, Fe), metal oxides (CuO, SiO_2, Al_2O_3, TiO_2, ZnO, Fe_3O_4, Fe_2O_3, MgO), carbides (SiC, TiC), nitrides (AlN, SiN) and different types of carbon (diamond, graphite, single/multi wall carbon nanotubes) by different chemical processes. Traditional liquids used as base fluids are water, ethylene glycol, refrigerants and engine oil. Nanoparticles can be mixed with different base fluids in different concentration ratio. Hence, enhancement of thermal performance of heat pipe using nanoparticles mainly depends upon parameters such as type, size, shape and concentration of nanoparticles and base fluid [2].

The concise published review articles related to nanofluids [4, 5, 6, 7, 8, 9, 10] are shown in Table 1. Major reviews are related to preparation of nanoparticles, nanofluids preparation methods, characterization, challenges like stability and aggregation, properties and applications of it.

1.4. Hybrid nanofluids

Earlier studies of single-component nanofluids have shown a huge potential for thermal conductivity augmentation. However, progress in such research has been limited due to the more need for enhanced properties of heat transfer fluids. Thermal conductivities of ceramic oxides such as Al_2O_3, SiO_2 and TiO_2 are lower than those of metals like silver, copper and gold or carbon compounds such as diamond, carbon nanotubes and graphene. Aggregation of pure metal like Ag, Cu and oxides like CuO are higher than oxides like Al_2O_3 due to higher mass density. In recent years, as nanotechnology has rapidly developed, low thermal conductivity and stability issues of nanofluids could be overcome by combination of more than one component nanoparticle to achieve synergetic effect which is termed as composite/hybrid nano-additive. A

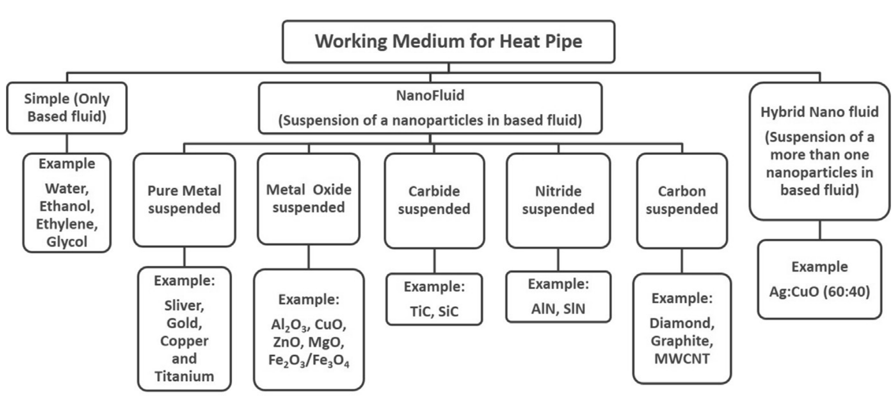


Fig. 3. Various types of working medium used in heat pipe.

Table 1
List of various review articles related to nanofluids.

Author	Title	Journal	Year
Li et al. [4]	A review on development of nanofluid preparation and characterization	Powder Technology	2009
Haddad et al. [5]	A review on how the researchers prepare their nanofluids	International Journal of Thermal Sciences	2014
Sidik et al. [6]	A review on preparation methods and challenges of nanofluids	International Communications in Heat and Mass Transfer	2014
Babita et al. [7]	Preparation and evaluation of stable nanofluids for heat transfer application: A review	Experimental Thermal and Fluid Science	2016
Devendiran et al. [8]	A review on preparation, characterization, properties and applications of nanofluids	Renewable and Sustainable Energy Reviews	2016
Ali et al. [9]	Preparation Techniques of TiO2 Nanofluis and Challenges: A Review	Applied Science	2018
Sajid et al. [10]	Recent advances in application of nanofluids in heat transfer devices: A critical review	Renewable and Sustainable Energy Review	2019

suspension with compositions of hybrid nano-additives termed as 'hybrid nanofluid' leads to an increased thermal conductivity and stability which facilitates heat transfer enhancement [11].

Suresh et al. [12], presented synthesis of Al_2O_3-Cu/DI water (90:20 weight proportion) hybrid nanofluids with sodium lauryl sulphate (SLS) as dispersant. They investigated the thermal conductivity and viscosity of hybrid nanofluids by experiments. Maximum enhancement in thermal conductivity was 12.11% at 2% volume concentration. Madhesh et al. [13] had experimentally, studied the tube in tube type counter flow heat exchanger using Cu-TiO_2/water as working medium. Convective heat transfer coefficient, Nusselt number and overall heat transfer coefficient were increased by 52%, 49% and 68% respectively as compare with water. Hung et al. [14] evaluated the performance of air cooled heat exchanger system using Graphene oxide, and graphite-2H/amorphous carbon as working fluid. Thermal conductivity, density, specific heat, and viscosity of the HCNFs (Hybrid Carbon Nanofluid) were higher than water mean while pumping power and cooling system also increased. They conclude that HCNFs are more suitable for heat exchange at a higher flow rate. Sundar et al. [15] had experimentally, investigated the circular heat tube using MWCNT (Multi-Wall Carbon Nanotubes)–Fe_3O_4/water as working fluid. As compared to base fluid, the Nusselt number was enhanced by 31.10%. Pumping power was increased by 1.18 times for the particle loading of 0.3% at a Reynolds number of 22,000. Yarmand et al. [16] had experimentally, investigated heat transfer enhancement in circular tube using Graphene Nanoplatelets -Silver (GNP-Ag)/DI water hybrid nanofluid. Thermal conductivity was improved by 22.22% and viscosity enhanced by 1.3-times at 0.1% particle weight concentration and 40 °C temperature. Esfe et al. [17], Presented thermal conductivity of Cu-TiO_2/Water/EG (Ethylene Glycol) hybrid nanofluid with the help of experimental data and modelling using artificial neural network. The properties of nanofluids were measured at various concentrations (0.1–2.0 %) and temperature range from 30 to 60 °C. In ANN (Artificial Neural Network), MSE (Mean Square Error) and correlation coefficient were 2.62e-5 and 0.999 respectively. Suresh et al. [18] had experimentally, studied circular tube using Al_2O_3–Cu/water hybrid nanofluids. Nusselt number and Reynold number were enhancement by13.56% and 1730 as compared to water.

The concise published review articles related to hybrid nanofluids [19, 20, 21, 22, 23, 24, 25, 26] are shown in Table 2. Major reviews are related to recent research, hybrid nanofluids preparation methods, characterization, applications, thermal conductivity challenges like stability, enhancement in viscosity, various heat transfer and fluid properties of it.

Table 2
List of various review articles related to hybrid nanofluids.

Author	Title	Journal	Year
Sarkar et al. [19]	A review on hybrid nanofluids: Recent research, development and applications	Renewable and Sustainable Energy Reviews	2015
Sidik et al. [20]	Recent progress on hybrid nanofluids in heat transfer applications: A comprehensive review	International Communications in Heat and Mass Transfer	2016
Babu et al. [21]	State-of-art review on hybrid nanofluids	Renewable and Sustainable Energy Reviews	2017
Minea et al. [22]	Influence of hybrid nanofluids on the performance of parabolic trough collectors in solar thermal systems: Recent findings and numerical comparison	Renewable Energy	2017
Sidik et al. [23]	A review on preparation methods, stability and applications of hybrid nanofluids	Renewable and Sustainable Energy Reviews	2017
Sundar et al. [24]	Hybrid nanofluids preparation, thermal properties, heat transfer and friction factor – A review	Renewable and Sustainable Energy Reviews	2017
Sajid et al. [25]	Thermal conductivity of hybrid nanofluids: A critical review	International Journal of Heat and Mass Transfer	2018
Babar et al. [26]	Viscosity of Hybrid Nanofluids: A Critical Review	J. Thermal Science	2019

1.5. Preparation methods

Nanofluids can be prepared by two methods, (i) one step method, and (ii) two step method. In one step method, the nano size particles are made and dispersed in to a base fluid simultaneously. In two step method, the nano size particles are produced in first step and dispersed into base fluid in second step. These methods should prepare a homogeneous and stable solid liquid mixture by avoiding agglomeration, possible erosion and clogging of nanaofluids.

1.6. Characterization techniques

The nanofluids are characterized by the following techniques: SEM, TEM, XRD, FT-IR, DLS, TGA Raman and Zeta potential analysis. SEM (Scanning Electron Microscopy) analysis is carried to study the micro structure and morphology of nanoparticles or nanostructured materials. TEM (Transmission Electron Microscopy) is similar to SEM but it has much higher resolution than SEM. Images taken by XRD (X-ray Diffraction) technique are help full to identify and study the crystal behavior of nanoparticles. FT-IR (Fourier-Transform Infrared Spectroscopy) is use to study the surface chemistry of solid particles and solid-liquid particles, DLS (Dynamic Light Scattering) analysis is performed to estimate the average size of nanoparticles which are dispersed in the base liquid media. TGA (Thermo-gravimetric Analysis) is used to study the influence of heating and melting on the thermal stabilities of nanoparticles. Raman spectroscopic technique is used to provide a structural fingerprint by which molecules can be identified. Zeta potential value is related to the stability of nanoparticles in base fluid [27].

2. Main text

2.1. Review of experimental and theoretical work related to use of mono and hybrid nanofluids in heat pipe

2.1.1. Thermosyphon

Noie et al [28], experimentally, studied the heat transfer enhancement in two phase closed thermosyphon using Al_2O_3/water. 1000 mm long copper pipe was used as container material. Al_2O_3 nanoparticles

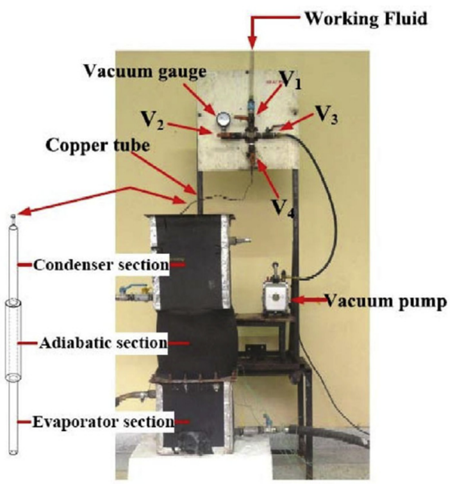


Fig. 4. Schematic of initially the filling of working fluid (Parametthanuwat et al. [30]).

Reprinted from Nanoscale Research Letters, 6:315, Thanya Parametthanuwat, Sampan Rittidech, Adisak Pattiya, Yulong Ding and Sanjeeva Witharana, Application of silver nanofluid containing oleic acid surfactant in a thermosyphon economizer, Pages No.04, Copyright (2011), with permission from Springer Nature

were dispersed in distillate water by ultrasonication without using dispersed for 1–3 v% concentration. Huminic et al. [29], experimental studied the thermal performance of thermosyphon heat pipe using iron oxide/DI water nanofluid. Nanofluids were prepared by one step method. XRD and HRTEM (High Resolution Transmission Electron Microscopy) technique were used for characterization.

Parametthanuwat et al. [30], experimentally, studied the application of silver nanofluids in two phase closed thermosyphon. Nanofluids were prepared by suspending nanoparticles of Ag in base fluid using ultrasonic vibrator for 5 hour in ultrasonic bath. Experiment was conducted at 30, 50 and 80% filling ratio of evaporator section volume and using water, water based silver nanofluid at 0.5 wt%, and nanofluid mixed with 0.5, 1 and 1.5 wt% of oleic acid. Experimental set up for the same is shown in Fig. 4. The relation between filling ratios and effectiveness are shown in Fig. 5. Results show that for each and every working medium, the filling ratio of 50% had achieved highest effectiveness.

Huminic et al. [31], experimentally and numerically, studied the heat transfer characteristics of thermosyphon heat pipe using Fe_2O_3/water

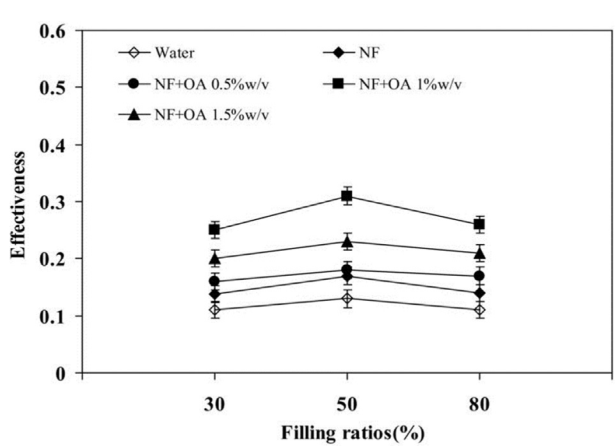


Fig. 5. Relationship between filling ratios and effectiveness (Parametthanuwat et al. [30]).

Reprinted from Nanoscale Research Letters, 6:315, Thanya Parametthanuwat, Sampan Rittidech, Adisak Pattiya, Yulong Ding and Sanjeeva Witharana, Application of silver nanofluid containing oleic acid surfactant in a thermosyphon economizer, Pages No.08, Copyright (2011), with permission from Springer Nature

nanofluid. Nanofluid was prepared by two step method. XRD, SAED and HRTEM techniques were performed for characterization. Kamyar et al. [32], experimentally, studied the effects of Al_2O_3/DI water and $TiSiO_4$/DI water nanofluids on heat transfer characteristics of a two phase closed thermosyphon. Nanofluids were prepared by two step method using ultrasonic homogenizer at 50 kHz sound frequency. TEM technique was used for characterization of both nanofluids. Liu et al. [33], experimentally, studied the thermal performance of an open thermosyphon using CuO/DI water nanofluid for evacuated tubular high temperature air solar collector. Nanofluid was prepated by direct dispersing CuO particles in base fluid and than oscillated continuously for about 10 hour in ultrasonic bath with working frequency of 25–40kHz. SEM technique was used to analyse the nanoparticle suspension in nanofluid. Menlik et al. [34], experimentally, investigated the thermosyphon type heat pipe using MgO/water nanofluids. One step method was used for nanofluids preparation (see Table 3).

Table 3
Summary of experimental and theoretical works related to Thermosyphon using nanofluids.

Literature	Desc. of Working Medium	Desc. of operating parameters	Critique Outcome	Year
Noie et al. [28]	Types of nanofluids: Al_2O_3/water % concentration: 1–3 v% Particle size (nm): 20	Heat Load (W): 50, 100, 150, 200 Surface temperature (°C): 28-58	o Efficiency was increased up to 14.7% as compared with pure water.	2009
Huminic et al. [29]	Types of nanofluids: Iron oxide/DI Water % concentration: 2.0, 5.3 % Filling ratio: 12% HP Particle size (nm): 4-5	Orientation (Deg.): 45, 90 Surface temperature (°C): 25-65	o Thermal resistance of thermosyphon with iron oxide nanofluid had lower than DI water. o Thermal resistance was decreased by increasing concentration.	2011
Parametthanuwat et al. [30]	Types of nanofluids: Ag/water % concentration: 0.5, 1.0, 1.5 w % Filling ratio: 30, 40, 80 % $V_{Evap.}$	Heat Load: 0–4 kW/m2 Surface temperature (°C): 60, 70, 80	o Highest heat flux of 25 kW/m^2 and highest effectiveness of 0.3 were achieved at 50 % filling ratio and 1 wt% concentration.	2011
Huminic et al. [31]	Types of nanofluids: Fe_2O_3/water % concentration: 2, 5.3 v% Particle size (nm): 4-5	Orientation (Deg.): 60, 70, 80, 90 Heat Load (W): 60, 70, 80, 90 Surface temperature (°C): 60-90	o Experimental and numerical results showed better heat transfer characteristics of thermosyphon using nanofluid as compared with water.	2013
Kamyar et al. [32]	Types of nanofluids: Al_2O_3, $TiSiO_4$/water % concentration: 0.01, 0.02, 0.05, 0.075 v%	Heat Load (W): 40, 70, 120, 180, 210 Surface temperature (°C): 20-80	o Thermal resistance was decreased by 65% with 0.05 v% Al_2O_3 and 57% with 0.075 v%	2013

(continued on next page)

Table 3 (*continued*)

Literature	Desc. of Working Medium	Desc. of operating parameters	Critique Outcome	Year
Liu et al. [33]	Particle size (nm): 13, 50 Types of nanofluids: CuO/DI Water % concentration: 0.8–1.5 wt% Filling ratio: 60% $V_{Evap.}$ Particle size (nm): 20-50	Pressure: -0.9 bar Heat Load (W): 300-1200 Surface temperature (°C): 0-40°	$TiSiO_4$ nanofluids. o Air outlet temperature and system collecting efficiency of the solar air collector using nanofluid was higher than water.	2013
Menlik et al. [34]	Types of nanofluids: MgO/Water % concentration: 1–5 v% Filling ratio: 33.3% HP Particle size (nm): 40	Heat Load (W): 200, 300, 400 Surface temperature (°C): 20-80	o Heat transfer rate was enhanced by 26% at 200 W heating power and 7.5 g/s flow rate.	2015

2.1.2. *Cylindrical grooved heat pipe*

Do et al. [35], prepared mathematical model to study the thermal performance of heat pipe with rectangular groove weak using water based Al_2O_3 nanofluid. Nanofluids were prepared by two step method using oscillated ultrasonic homogenizer for 12 hrs. Liu et al. [36], experimentally, studied the thermal performance of inclined grooved heat pipes using CuO/water nanofluid at 1.0 wt% concentration. Nanofluids were prepared by direct dispersing CuO particles in DI water and oscillated for 10 hr in an ultrasonic water bath with a frequency of 25–40 kHz. Wang et al. [37], experimentally, studied the operational characteristics of cylindrical miniature grooved heat pipe using CuO/DI water nanofluids. Nanofluids were prepared by two step method using oscillation it for 10 hr in an ultrasonic bath with a working frequency of 25–40 kHz. SEM technique was implemented to characterization the heat pipe using water and nanofluids as working medium. Han et al. [38], studied thermal characteristics of grooved (square) heat pipe (SS tube) with hybrid ($Ag:Al_2O_3$/water) nanofluids. Nanofluids were prepped by two step method using ultrasonic bath fot 16–20 hrs. SEM technique was used to visualize the particle deposition on pipe inner surface. Liu et al. [37], studied the effect of Cu/DI water, CuO/DI water and SiO/water nanofluids on thermal performance of cylindrical micro grooved heat pipe using nanofluids. Each types of nanoparticles were dispersed in DI water and oscillated in an ultrasonic bath for 12 h with working frequency of 40 kHz. TEM technique was used for characterization of nanofluids and grooved heat pipe. Latibari et al. [39], experimentally, investigated the effect of aqueous nitrogen dropped graphene nanofluid on thermal performance of grooved copper heat pipe. Nanofluid was prepared using one step method. FESEM (Field Emission Scanning Electron Microscopy) technique was used for characterization (see Table 4).

Table 4
Summary of experimental and theoretical works related to cylindrical heat pipe with grooved wick structure using nanofluids.

Literature	Desc. of Working Medium	Desc. of operating parameters	Critique Outcome	Year
Do et al. [35]	Types of nanofluids: Al_2O_3/Water % concentration: 0–1.2 v% Particle size (nm): 10–60	Surface temperature (°C): 75–100	o Thermal resistance tends to decrease with particle size. o 1.0 v% is optimum concentration for better performance.	2010
Liu et al. [36]	Types of nanofluids: CuO/Water % concentration: 0.5–2.0 wt% Filling ratio: 50% $V_{Evap.}$ Particle size (nm): 50	Orientation (Deg.): 0, 30, 60, 75, 90 Heat Load (W): 0-180 Surface temperature (°C): 25–70 Pressure: 7.45, 12.38, 19.97 kPa	o 45° inclination angle is optimum angle. o Maximum heat flux and HTC (Heat Transfer Coefficient) was enhanced by using nanofluids. o Performance was increased by increasing pressure.	2010
Wang et al. [37]	Types of nanofluids: CuO/DI Water % concentration: 0.5–2.0 wt% Filling ratio: 50% $V_{Evap.}$ Particle size (nm): 50	Heat Load (W): 0-100 Surface temperature (°C): 35–180 Pressure: 0.086 Pa	o Heat resistance and maximum heat removal capacity of heat pipe could reduce by 50% and increased by 40% as compared to water respectively.	2010
Han et al. [38]	Types of nanofluids: Ag-Al_2O_3/Water % concentration: 0.005–0.05 v% Particle size (nm): 27, 89	Orientation (Deg.): 5, 45, 90 Heat Load (W): 50–300 W (dW = 50W)	o Use of mono and hydrid nanofluids leads to worse thermal performance.	2011
Liu et al. [40]	Types of nanofluids: Cu, CuO, SiO_2/water % concentration: 0.5, 1.0, 1.2 wt% Particle size (nm): 20, 30, 40, 50	Heat Load (W): 0–70 Surface temperature (°C): 40, 50, 60 Pressure: 7.45, 12.38, 19.97 kPa	o Smaller size nanoparticles had better heat transfer rate as compare to larger size. o 1.0 wt% mass concentration was optimum for better performance.	2011
Latibari et al. [39]	Types of nanofluids: NDG/Water % concentration: 0.01, 0.02, 0.04, 0.06 wt%	Orientation (Deg.): 0–90 Heat Load (W): 0–120 W Surface temperature (°C): 15-40 Pressure: 1 kPa	o Thermal resistance was decrease by 58.6 % and heat transfer coefficient was enhanced by 99% at 0.06 wt% concentration, 90° inclination angle and 120 W heat loads.	2016

2.1.3. *Cylindrical screen mesh heat pipe*

Shukla [41] studied experimental performance of cylindrical copper heat pipe with DI water, DI water-Ag and DI water Cu working fluid. Nanofluids were prepared using one step method and characterized using SEM technique. Liu et al. [42], experimentally, studied mesh heat pipe using CuO/DI water nanofluid. Evaporating heat transfer coefficient averagely increased by 2.5 times at 1.0 wt% concentration. Two step method by 10 hrs oscillation in ultrasonic bath was used for nanofluids preparation and TEM technique was used for characterization. Mousa [1], experimentally, studied circular heat pipe with 2-layer screen mesh using Al_2O_3/water. Two step method was used for nanofluids preparation. Hajian et al. [3], experimentally, investigated thermal performance of cylindrical heat pipe with screen mesh using nanofluid (Suspended silver nanoparticles in DI water). For characterization, TEM technique was used and one step method was used to produce nanofluids. Putra et al. [43], experimentally, studied the performance of screen mesh wick heat pipe using Al_2O_3/Water, Al_2O_3/EG, TiO_2/Water, TiO_2/EG and ZnO/EG nanofluid. Nanofluids were prepared by two step method using ultrasonicating for 60 min. SEM and XRD techniques were used for characterization. Senithkumar et al. [44], experimentally, investigated the effect of inclination angle in cylindrical heat pipe performance using Cu/DI water nanofluid. Two step method using ultrasonic homogenization was used for nanofluids preparation. Solomon et al. [45], experimentally investigated the thermal performance of 4-layered screen wick heat pipe with nanoparticles coated wick and without coated one. 1 gm copper nanoparticles with 1 litre DI water were mixed using ultrasonic vibrator for 30 min. SEM technique was used for characterization of nanofluids. The measurement scheme of experiment for measuring different parameters and thermocouple tappings on heat pipe are shown in Fig. 6.

Wang et al. [46], experimentally, studied the thermal performance of inclined miniature mesh heat pipe using Water-CuO nanofluid. Nanofluids were prepared by two step method using ultrasonic water bath for 10 hour. Asirvatham et al. [47], experimentally, studied the heat transfer performance of screen mesh wick heat pipe using Ag/water nanofluid for removal of heat from power transistor in electronics and processors in computers. Nanofluids were prepared using dispersion of Ag nanoparticles in DI water and sonicated well for bout 1 hour in ultrasonicater of 50–60 kHz frequency. Nanofluids and screen mesh wick structure were characterized using SEM technique. Kole et al. [48], experimentally, studied the thermal performance of screen mesh wick heat pipe using Cu/DI water nanofluids for different concentration and inclination angles of heat pipe. Nanofluids were prepared using two step method by sonication and homogenization and characterized using TEM and DLS measurement. Kumar et al. [49], experimentally, studied heat transfer enhancement in screen mesh type cylindrical heat pipe using DI water, TiO_2/water and TiO_2/n-Butanol as working medium. Saleh et al. [50], experimentally investigated the thermal conductivity of screen mesh wick heat pipe using ZnO/ethylene glycol nanofluids. Nanofluids were prepared by two step method using ultrasonic irradiation for dispersing nanoparticles in ethylene glycol and characterized using XRD patterns. Saleh et al. [51], experimentally studied the transport properties of TiO_2 nanoparticles dispersed in DI water with 1.0 % volume concentration and 10–600 °C temperature range using SS screen mesh wick heat pipe. Two step method by dissolving nanoparticles in DI water was used for nanofluids preparation and XRD pattern and FESEM image were used for

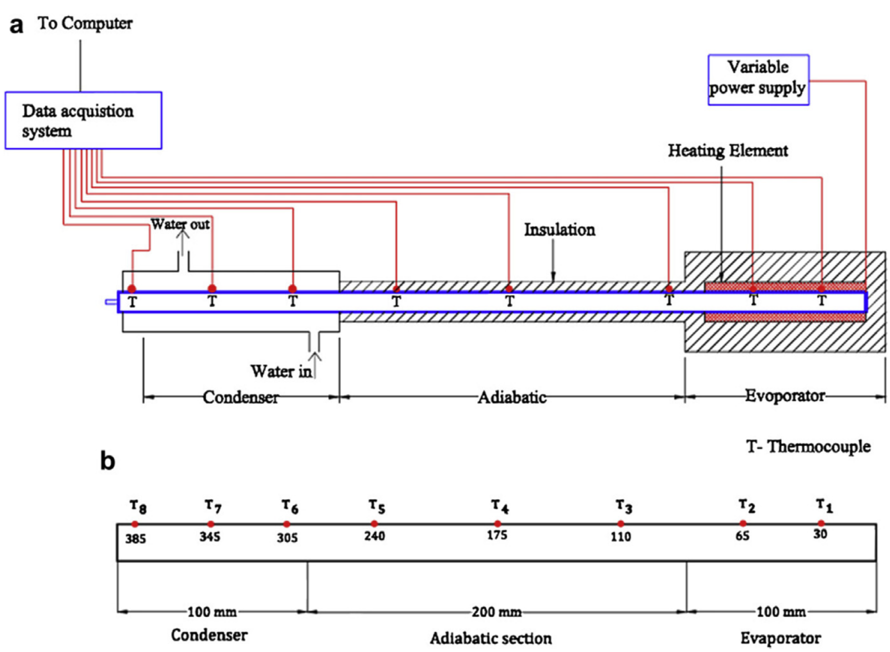


Fig. 6. (a) Measurement scheme of the heat pipe (b) Arrangement of thermocouples on the heat pipe (Solomon et al. [45]).
Reprinted from Applied Thermal Engineering, 36, A. Brusly Solomon, K. Ramachandran, B.C. Pillai, Thermal performance of a heat pipe with nanoparticles coated wick, Pages No.106-112, Copyright (2011), with permission from Elsevier

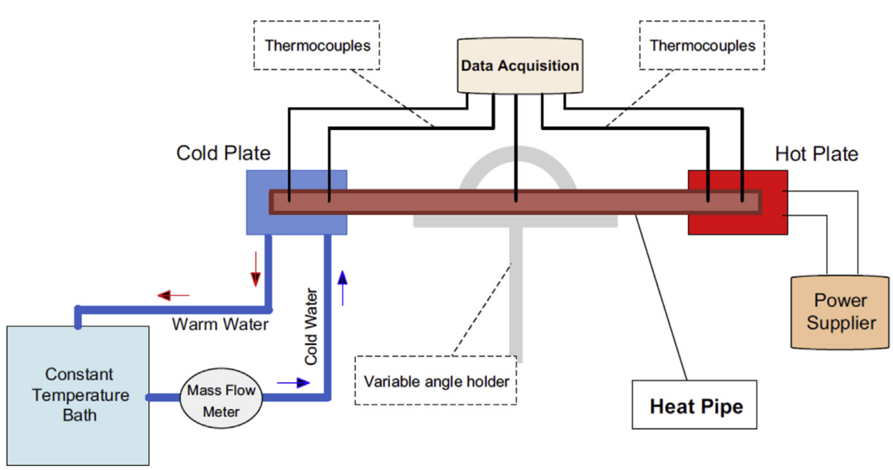
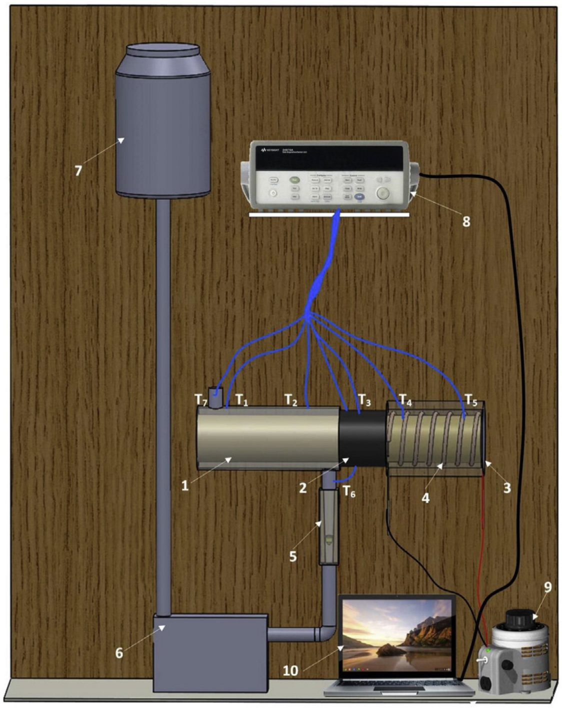


Fig. 7. Diagram of the experimental system (Ghanbarpour. [57]).
Reprinted from Experimental Thermal and Fluid Science, 66, M. Ghanbarpour,N. Nikkam,R. Khodabandeh,M.S. Toprak,M. Muhammed, Thermal performance of screen mesh heat pipe with Al2O3 nanofluid, Pages No.213-220, Copyright (2015), with permission from Elsevier



T_1, T_2, T_3, T_4, T_5 – T-type thermocouples located at the surface of the Heat pipe, T_6, T_7, T-type thermocouples to measure the inlet and outlet cooling temperature, 1- Condenser section, 2-Adiabatic section, 3-Evaporator section, 4-Heating coil, 5-Rotameter, 6-Chiller unit, 7-Overhead tank, 8-Data Acquisition System, 9-Auto transformer, 10-Computer

Fig. 8. Experimental Setup (Ramachandran et al. [60]).
Reprinted from International Communications in Heat and Mass Transfer, 76, R. Ramachandran,K. Ganesan,M.R. Rajkumar,L.G. Asirvatham,S. Wongwises, Comparative study of the effect of hybrid nanoparticle on the thermal performance of cylindrical screen mesh heat pipe, Pages No.294-300, Copyright (2016), with permission from Elsevier

characterization. Ghanbarpour et al. [52], experimentally, investigated 2-layered copper screen mesh heat pipe using SiC/DI water nanofluids. Two step method with ultrasonic mixing was used for nanofluids preparation. XRD and SEM techniques were used for characterization. Kim et al. [53], experimentally, compared the thermal performance of SiC/-water nanofluid filled heat pipe and water filled heat pipe with SiC nanoparticle coated screen mesh wick. SiC/water nanofluids were prepared by dispersing weighted particles into base fluid and sonicated for 3 hr. The SEM images of prepared nanoparticles and wicks coating are taken to support the thermal characteristics. Mortezza et al. [54], experimentally, investigated the thermal performance of 2 layer screen mesh type cylindrical heat pipe (copper made) using Al_2O_3/DI water nanofluid. Nanofluids were prepared by two step method and characterized using TEM. After test, heat pipe was tested using SEM. Venkatachalapathy et al. [55], experimentally, analysed the performance of cylindrical heat pipe using CuO/DI water nanofluids. Two step method by ultrasonic homogenized of 40kHz for 60 min was used for nanofluids preparation. HRTEM technique was used for characterization. Wang et al. [56], experimentally, studied screen mesh heat pipe using SiO_2 nanofluids for high power LED (Light emitting diodes). Suspending SiO_2 nanoparticles in DI water and stirred for ultrasonic vibration bath about 10 hrs was used for preparation (Two step method). Ghanbarpour et al. [57], studied the thermal performance of screen mesh heat pipe with Al_2O_3 nanofluid. Nanofluid was prepared using two step method and TEM technique was used for characterization. Fig. 7, shows the schematic diagram of experimental set up.

Kim et al. [58], experimentally, studied the effects of graphene oxide/water nanofluids on screen mesh heat pipe performance and capillary limits. Nanofluids were prepared by a two step method dispersing weighted nanoparticles into distilled water and sonicating the mixture continuously for 6 hour. SEM technique was used to characterized the nanofluid. Chavda [59], experimentally, investigated two layer screen mesh, cylindrical copper heat pipe using silver nanofluid. Two step method was used to prepare nanofluids. Different nanoparticles size, concentration, filling ratio were investigated. Ramachandran et al. [60], experimentally, studied cylindrical, screen mesh heat pipe using Al_2O_3-CuO/DI water hybrid nanofluids.

Fig. 8, shows the schematic diagram of experimental set up. Two step method by ultrasonic disruptor for 1 hour was used for nanofluids preparation. XRD and TEM techniques were used for nanofluids characterization and SEM technique was used for heat pipe microstructure analysis. Senthil et al. [61], experimentally, investigated the thermal

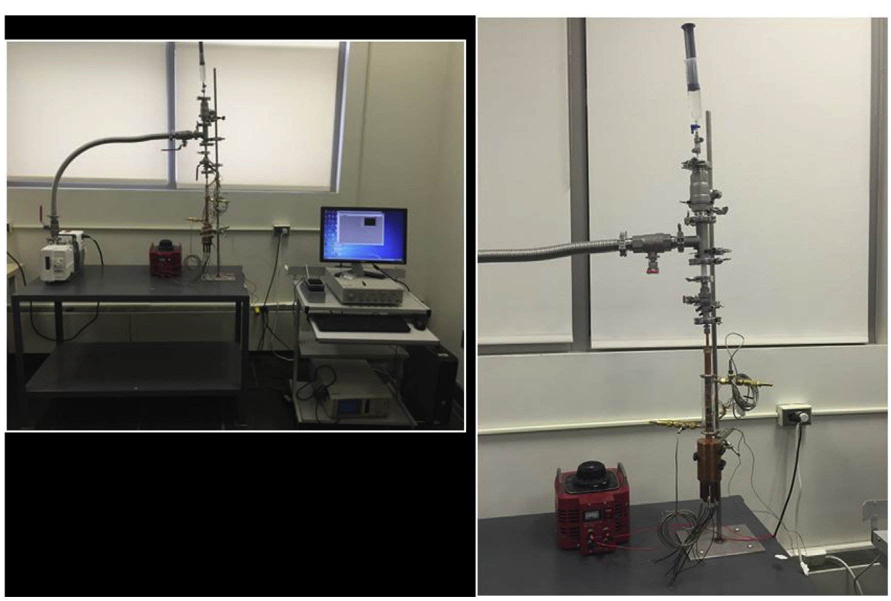


Fig. 9. Charging and evacuation system (Mahdavi et al. [63]).
Reprinted from Experimental Thermal and Fluid Science, 93, Mahboobe Mahdavi, Saeed Tiari, Sven De Schampheleire, Songgang Qiu, Experimental study of the thermal characteristics of a heat pipe, Pages No.292-304, Copyright (2018), with permission from Elsevier

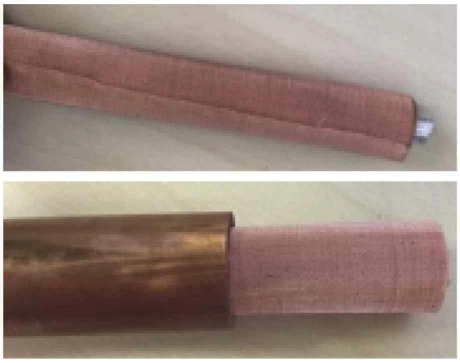


Fig. 10. Wick insertion for the cylindrical containers (Mahdavi et al. [63]). *Reprinted from Experimental Thermal and Fluid Science, 93, Mahboobe Mahdavi, Saeed Tiari, Sven De Schampheleire, Songgang Qiu, Experimental study of the thermal characteristics of a heat pipe, Pages No.292-304, Copyright (2018), with permission from Elsevier*

characteristics by filling ratio of Al_2O_3/DI water nanofluid in wire mesh heat pipe. Nanoparticles were dispersed in water by using ultrasonic vibrator for 6 hour to obtain 1v% concentration and characterized using SEM technique. Kavusi et al. [62], numerically, investigated the thermal efficiency of copper made cylindrical heat pipe by varying % charge volume, inclination angle, % nanoparticle volume concentration and using Al2O3, Ag, CuO/water nanofluids. Mahdavi et al. [63], experimentally studied the thermal characteristics of heat pipe. Charging and evacuation system of heat pipe are well established and presented in their article which is shown in Fig. 9.

Over filling of heat pipe leads to increase the thermal resistance due to excess liquid interfering with evaporation and condensation process. Four layered copper mesh was used as a wick structure in their analysis, the wick insertion in cylindrical container is shown in Fig. 10.

Specially designed variable angle stand was prepared for the analysis of angle variation on performance of heat pipe. Mounted heat pipe in horizontal orientation, inclined with 60° angle and vertical orientation were as per shown in Fig. 11.

Gravity opposes orientation leads to deterioration in performance as compared with horizontal orientation (see Table 5).

Table 5
Summary of experimental and theoretical works related to cylindrical heat pipe with screen mesh type wick structure using nanofluids.

Literature	Desc. of Working Medium	Desc. of operating parameters	Critique Outcome	Year
Shukla [41]	Types of nanofluids: Ag, Cu/ Water % concentration: 0.01,-0.15 wt%	Heat Load (W): 100–250 Surface temperature (°C): 10–85	o Efficiency was enhanced by 8% using Ag/DI water and 14% using Cu/DI water nanofluids as compare with DI water.	2010
Liu et al. [42]	Types of nanofluids: CuO/DI Water % concentration: 0.5–2.0 wt % Filling ratio: 60 % $V_{Evap.}$ Particle size (nm): 50	Heat Load (W): 20–150 Surface temperature (°C): 60, 50, 40 Pressure: 19.97, 12.38, 7.45 kPa	o Evaporating heat transfer coefficient averagely increased by 2.5 times at 1.0 wt % concentration. o Total heat resistance decrease by 60% using 1.0 wt% CuO nanofluid.	2011
Mousa [1]	Types of nanofluids: Al_2O_3/ Water % concentration: 0.25–1.5 v % Filling ratio: 20–100% Particle size (nm): 40	Heat Load (W): 0–60 W Surface temperature (°C): 34–44 Pressure: 0.01 bar	o Optimum filling ratio was 0.45–0.50. o Thermal performance was decreased by increasing concentration.	2011
Hajian et al. [3]	Types of nanofluids: Ag/DI Water % concentration: 50, 200, 600 ppm Filling ratio: 250 ml Particle size (nm): 50	Heat Load (W): 300–500 Surface temperature (°C): 20-90 Pressure: 10-2 torr	o The thermal resistance and response time of heat pipe was decreased by 30% and 20% respectively as compared with DI water.	2012
Putra et al. [43]	Types of nanofluids: Ag/DI Water % concentration: 1–5 v%	Heat Load (W): 10, 20, 30 W Surface temperature (°C): 20–90 Pressure: 137.8 kPa	o 5 v% concentrations had given best thermal performance using Ag/water nanofluid.	2012
Senthilkumar et al. [44]	Types of nanofluids: Cu/DI Water % concentration: 100 mg/lit. Particle size (nm): 40	Orientation (Deg.): 0–90 Heat Load (W): 30–70	o 30° and 45° are optimum angles for DI water and copper respectively. o Thermal efficiency was enhanced by 10% using copper nanofluid compare with DI water.	2012
Solomon et al. [45]	Types of nanofluids: Cu/DI Water Particle size (nm): 80-90	Heat Load (W): 100, 150, 200 Surface temperature (°C): 30–90	o Thermal resistance was reduced by 40% and heat transfer coefficient was enhanced by 40% using coating in heat pipe. o Total resistance was decreased by 19%, 15% and 14% at heat load of 100, 150 and 200 W respectively.	2012
Wang et al. [46]	Types of nanofluids: CuO/ Water % concentration: 0.5, 1.0, 2.0 wt% Filling ratio: 50% $V_{Evap.}$ Particle size (nm): 50	Orientation (Deg.): 30, 45, 60, 90 Heat Load (W): 0–180 W Surface temperature (°C): 40, 50, 60 Pressure: 7.45, 12.38, 19.97 kPa	o Evaporator and condenser HTC were improve by 22% and 5% at 45° inclinations. o Heat removal capacity of heat pipe was increase by 40% using 1.0 wt% CuO.	2012
Asirvatham et al. [47]	Types of nanofluids: Ag/ water % concentration: 0.003, 0.009 v%	Heat Load (W): 20–100 Surface temperature (°C): 20-160	o Thermal conductivity was increased by 42.4%, 56.8% and 73.% for 0.003, 0.006 and 0.009 v% respectively. o A thermal resistance was reduced by 76.2% for 0.009 v%.	2013

(continued on next page)

Table 5 (*continued*)

Literature	Desc. of Working Medium	Desc. of operating parameters	Critique Outcome	Year
	Filling ratio: 30 % Hp Particle size (nm): 58.35			
Kole et al. [48]	Types of nanofluids: Cu/DI Water % concentration: 0.0005, 0.005, 0.05, 0.5 wt% Particle size (nm): 40	Orientation (Deg.): 45, 60, 90 Heat Load (W): 10, 40, 70, 100 Surface temperature (°C): 24-32	o Maximum thermal conductivity was enhanced by 15% with 0.5 wt% concentration of nanofluids. o Vertical orientation with 0.5 wt% concentration had 27% reduction in thermal resistance.	2013
Kumar et al. [49]	Types of nanofluids: TiO_2/DI Water % concentration: 100 mg/lit. Filling ratio: 30 ml Particle size (nm): 50	Orientation (Deg.): 0, 15, 30, 45, 60, 75, 90 Heat Load (W): 30, 40, 50, 60, 70 Surface temperature (°C): 20-100	o Thermal efficiency of nanofluids was higher than base fluid due to dilute aqueous solution of n-Butanol which have positive surface gradient with temperature.	2013
Saleh et al. [50]	Types of nanofluids: ZnO/EG	—	o Wall temperature was reduced by 60 °C using nanofluids as compare to base fluid.	2013
Saleh et al. [51]	Types of nanofluids: TiO_2/DI Water % concentration: 0.05, 0.1, 0.5, 1.0 10 v% Particle size (nm): 33	Orientation (Deg.): 0, 45, 90 Heat Load (W): 8, 16, 24 Surface temperature (°C): 22–190	o 45° inclination angle and 60% charge volume ratio had best thermal performance.	2014
Ghanbarpour et al. [52]	Types of nanofluids:SiC/ Water % concentration: 0.35, 0.7, 1.0 wt% Particle size (nm): 35	Orientation (Deg.): 0–90 Heat Load (W): 50–160 W Temperature difference dT = 3–9 °C	o Maximum heat removal capacity of the heat pipe was increases by 29% at mass concentration of 1.0 wt.%.	2015
Kim et al. [58]	Types of nanofluids: SiC/ water % concentration: 0.01–0.1 v % Filling ratio: 100 % of wick vol.	Heat Load (W): 120–1120 Surface temperature (°C): 45–65 Pressure: 12.5 kPa	o Evaporation thermal resistance of SiC coated wick and SiC/water filled heat pipes had higher compared to uncoated water heat pipe.	2015
Mortezaa et al. [54]	Types of nanofluids: Al_2O_3/ DI Water % concentration: 5–10 wt% Particle size (nm): 100-200	Heat Load (W): 5, 15, 25, 35, 45 Surface temperature (K): 295–330	o 5wt% concentration had improved thermal performance whereas 10wt% concentration had deteriorated the performance.	2015
Venkatachalapathy et al. [55]	Types of nanofluids: CuO/DI Water % concentration: 0.5, 1.0, 1.5 wt% Particle size (nm): 50	Orientation (Deg.): 090 Heat Load (W): 40-120 Surface temperature (°C): 30-80 Pressure: 7.45 kPa	o Evaporation and condensation HTC were improved by 30.50% and 23.54% respectively at 60° inclination angle.	2015
Kim et al. [58]	Types of nanofluids: Graphene Oxide/water % concentration: 0.01, 0.03 v % Filling ratio: 100% of wick volume Particle size (nm): 350	Heat Load (W): 25–450 Surface temperature (°C): 0–140 Pressure: 14.5 kPa	o Thermal resistance was decreased by 25%. o 0.03 v% concentration showed lower heat transfer than 0.01 v%.	2016
Chavda [59]	Types of nanofluids: Ag/DI Water % concentration: 0.1, 0.2, 0.3 v% Filling ratio: 40% Particle size (nm): 15, 25, 35	Orientation (Deg.): 0–90 Heat Load (W): 10–140 W Surface temperature (°C): 50–120 Pressure: 10–3 torr	o 35nm size silver nanoparticles, 0.3% volume concentration, 45° inclination angle and 120–140 W heat input had given best thermal performance.	2016
Ramachandran et al. [60]	Types of nanofluids: Al_2O_3-CuO/DI Water % concentration: 0.1 v% Filling ratio: 5.12 ml Particle size (nm): 50	Heat Load (W): 50-250 Pressure: 10–4 torr	o Thermal resistance of hybrid nanofluid with Al_2O_3 25%-CuO 50% shows 44.25% reduction in thermal resistance.	2016
Senthil et al. [61]	Types of nanofluids: Al_2O_3/ DI Water % concentration: 1 v% Filling ratio: 25, 50, 75, 100% Particle size (nm): 50	Orientation (Deg.): 0, 30, 60, 90	o 75% filling ratio and 30° inclination angle showed better thermal efficiency as compared with DI water.	2016
Kavusi et al. [62]	Types of nanofluids: Al_2O_3, Ag, CuO/Water % concentration: 2, 5, 10 V% Particle size (nm): 10, 20, 40	Heat Load (W): 455, 1184, 2000	o Thermal efficiency was enhanced by 10.60% by using 0.10v% concentration. o Optimum angles were 60° and 45° for DI water and alcohol respectively.	2017

2.1.4. *Cylindrical sintered heat pipe*

Kang et al. [64], experimentally, investigated circular copper sintered heat pipe performance using nanofluid. Pure water with silver used as nanofluids and prepared by two step method using ultrasonic homogenizer. TEM analysis was used to study micro structure. Kumaresa et al. [65], experimentally, investigated thermal characteristics of copper sintered wick heat pipe using DI water-CuO nanofluid. Working medium was prepared by ultrasonic homogenizer at 40kHz

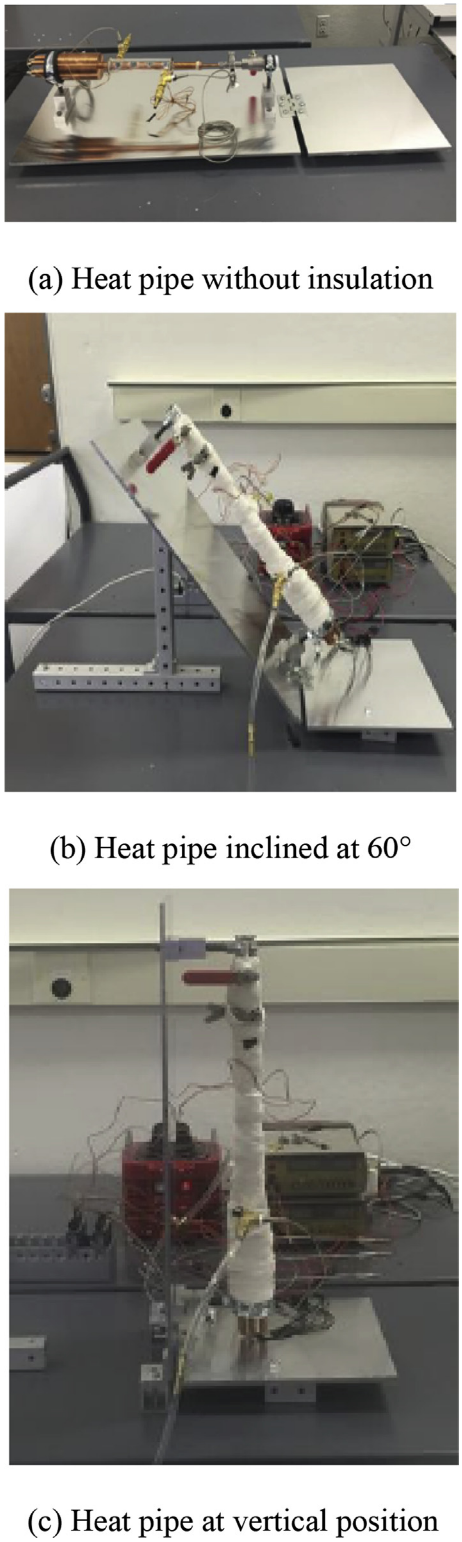


Fig. 11. Heat pipe mounted on a base plate (Mahdavi et al. [63]).
Reprinted from Experimental Thermal and Fluid Science, 93, Mahboobe Mahdavi, Saeed Tiari, Sven De Schampheleire, Songgang Qiu, Experimental study of the thermal characteristics of a heat pipe, Pages No.292-304, Copyright (2018), with permission from Elsevier

frequency for 60 min and characterized using XRD and HR TEM technique. Khalili et al. [66], experimentally and numerically investigated and compared the thermal performance of simple and novel (partly sintered) sintered wick heat pipe. Variation of thermal resistance with heat input in annularly sintered wick heat pipe is shown in Fig. 12 for various filling ratio.

Sadeghinezhad et al. [67], experimentally, investigated thermal performance of sintered heat pipe using Graphene Nanoplatelets (GNP)/Water. Nanofluids were prepared by two step method using ultrasonication probe. FESEM and TEM techniques were used for characterization. Vijaykumar et al. [68], experimentally, studied thermal characteristics of cylindrical sintered wick heat pipe using CuO and Al_2O_3 nanofluid. Nanofluids were prepared by two step method using ultrasonic homogenizer for 60 min. Micro structure was observed by TEM and crystalline pattern was investigated using XRD technique. Vijaykumar et al. [69], experimentally, studied heat transfer characteristics of copper sintered wick heat pipe using CuO and Al_2O_3 nanofluids. Actual image of experimental set up along with all necessary measuring devices was as per shown in Fig. 13.

Nanoparticles were dispersed in DI water by two step method using ultrasonic homogenizer at 40kHz frequency for 60 min. XRD and HRTEM techniques were used for characterization. Effect of temperature on surface tension and specific heat for various concentration were as per shown in Fig. 14 (see Table 6).

Table 6
Summary of experimental and theoretical works related to cylindrical heat pipe with sintered wick structure using nanofluids.

Literature	Desc. of Working Medium	Desc. of operating parameters	Critique Outcome	Year
Kang et al. [64]	Types of nanofluids: Ag/Water % concentration: 1, 10, 100 ml/lit. Particle size (nm): 10, 35	Heat Load (W): 30, 40, 50, 60, 70 W Surface temperature (°C): 40-70	o As compare with water at 20W, using nanofluids 70W heat load can be applied to heat pipe. o Non linear relation with nanoparticles size and concentration.	2009
Kumaresa et al. [65]	Types of nanofluids: CuO/DI Water % concentration: 0.5, 1.0, 1.5 wt % Filling ratio: 34% of HP Particle size (nm): 39.1	Orientation (Deg.): 0-90 Heat Load (W): 10–160 W Surface temperature (°C): 0-80 Pressure: 13.46 kPa	o Optimum title angle and weight concentration were 45° and 1.0 wt % respectively. o Reduction in thermal resistance, enhancement in HTC and thermal conductivity were 66.1%, 29.4 % and 63.5 % respectively.	2014
Khalili et al. [66]	Filling ratio: 10, 20, 30, 45	Orientation (Deg.): 0, 90, 270 Heat Load (W): 0-150	o Optimum filling ratio was 20%. o Thermal resistance of partly sintered wick heat pipe was lower by 28%, 17% and 47% as compare with annular sintered wick heat pipe for vertical, horizontal and reverse-vertical orientation.	2016

(continued on next page)

Table 6 (*continued*)

Literature	Desc. of Working Medium	Desc. of operating parameters	Critique Outcome	Year
Sadeghinezhad et al. [67]	Types of nanofluids: Graphene/Water % concentration: 0.025, 0.05, 0.075 wt%	Orientation (Deg.): 0, 30, 60, 90 Heat Load (W): 20, 40, 60, 80 Surface temperature (°C): 10-40	o 0.1wt% concentration gives best performance.	2016
Vijaykumar et al. [68]	Types of nanofluids: CuO, Al_2O_3/DI Water % concentration: 0.5, 1.0, 1.5 % Particle size (nm): 50	Orientation (Deg.): 0, 30, 45, 60, 75, 90 Heat Load (W): 10-160	o Optimum inclination angle was 45°. o Optimum concentrations were 1.0 wt% for CuO and 1.5 wt% for Al_2O_3. o HTC was increased by 32.99% and 24.59% for CuO and Al_2O_3 respectively.	2016
Vijaykumar et al. [69]	Types of nanofluids: CuO, Al_2O_3/DI Water % concentration: 0.5, 1.0, 1.5 wt % Particle size (nm): 20, 50	Orientation (Deg.): 0-90 Heat Load (W): 30-150 Surface temperature (°C): 0-30	o Max. thermal efficiency of Heat pipe filled with CuO was 30.42 % at 1.0 wt% concentration and Al_2O_3 was 26.17 % at 1.5 wt% concentration.	2017

2.1.5. Flat heat pipe

Alizad et al. [70], prepared analytical model of flat shaped heat pipe to investigate the thermal performance and operational attributes using CuO, Al_2O_3 and TiO_2 nanofluids. Transient behaviour, performance and operational characteristics of flat heat pipe using nanofluids were investigated. Higher concentration of nanoparticles increases the thermal performance.

2.1.6. Loop heat pipe

Putra et al. [71], experimentally, studied thermal performance of biomaterial wick loop heat pipe with Al_2O_3/water nanofluid for electronic equipment cooling. Massive, tabulate, foliose, branching and S. powder of Cu were used as wick material. Nanofluids were prepared by dispersing

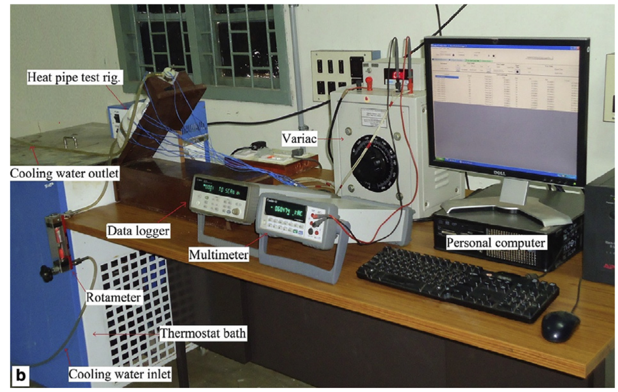


Fig. 13. Experimental set up (Vijaykumar et al. [69]).
Reprinted from Journal of the Taiwan Institute of Chemical Engineers, 81, M. Vijayakumar,P. Navaneethakrishnan,G. Kumaresan,R. Kamatchi, A study on heat transfer characteristics of inclined copper sintered wick heat pipe using surfactant free CuO and Al2O3 nanofluids, Pages No.190-198, Copyright (2017), with permission from Elsevier

Al_2O_3 nanoparticles in DI water using ultrasonication at concentration of 1 v%, 3 v% and 5 v%. Biomaterial structure of wicks was investigated using SEM photograph. Thermal resistance of biomaterial wick was reduced by 56.3% as compared with sintered wick. Tharayil et al. [72], experimentally, investigated loop heat pipe using grapheme oxide/water nanofluids. Nanofluids were prepared by two step method using ultrasonic homogenization. The lowest thermal resistance value was 21.6% observed for optimum concentration as compare with DI water.

2.1.7. Oscillating heat Pipe(OHP)

Ji et al. [73], experimentally, investigated the effect of Al_2O_3 particle size on heat transfer performance in an oscillating heat pipe (6 turns). 50nm, 80nm, 2.2 um and 20 um diameter particles were used in study. Nanofluids of 0.5 wt% were prepared by direct dispersion of nanoparticles in base fluid and stirred by using ultrasonic oscillator for 1 hr. SEM technique was used for characterization. Nanoparticles with 80 nm size had best heat transfer performance among all four. Ji et al. [74], Experimentally, investigated the heat transfer performance in polydimethylsiloxane (PDMS-one type of transparent material) oscillating heat pipe (5 turns) using ethanol and Al_2O_3/ethanol as working medium with 70% filling ratio as shown in Fig. 15. The dimensions are as shown in Fig. 16. Electric field was also applied on it. Cylindrical shaped alumina nanoparticles wee added in to the based fluid and mixed using magnetic stirrer for 1 day and sonicated using ultrasonic oscillator for one hour. TEM technique was applied to study the characteristics of

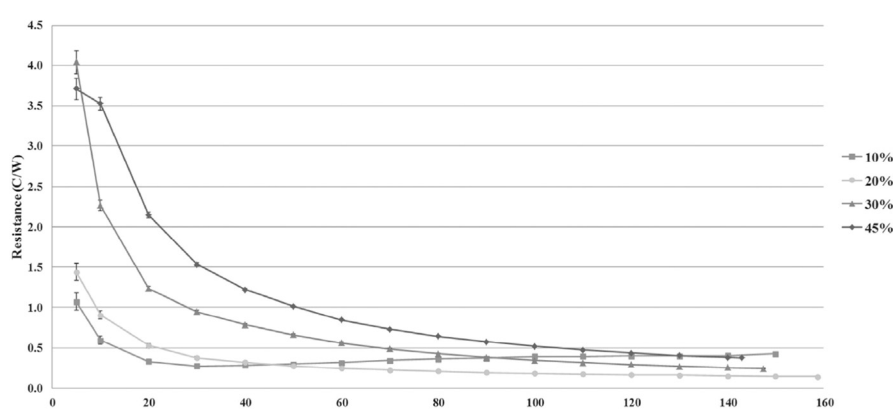


Fig. 12. Thermal resistance v.s. heat input for the annularly sintered wick heat pipe (Khalili et al. [66]).
Reprinted from Applied Thermal Engineering, 94, M. Khalili,M.B. Shafii, Experimental and numerical investigation of the thermalperformance of a novel sintered-wick heat pipe, Pages No.59-75, Copyright (2016), with permission from Elsevier

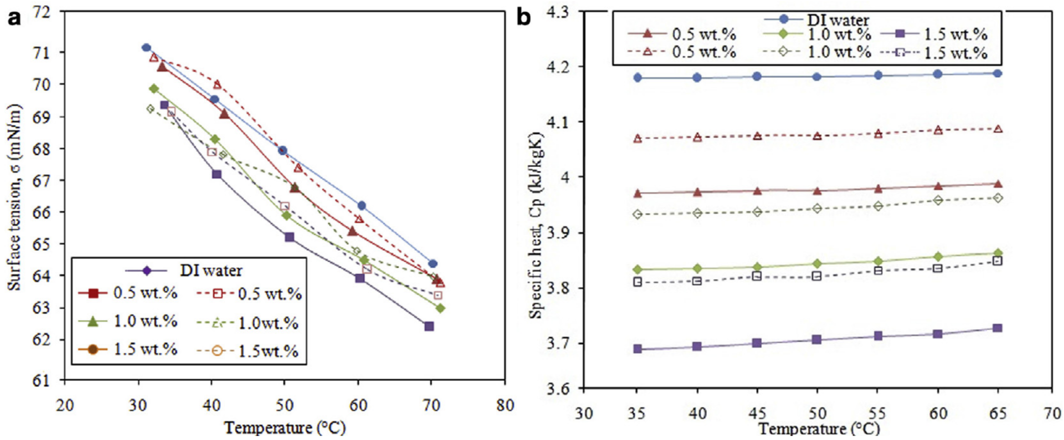


Fig. 14. (a) Surface tension and (b) specific heat of CuO (Continious line) and Al_2O_3 (Dashed line) nanofluids under varying concentrations (Vijaykumar et al. [69]). *Reprinted from Journal of the Taiwan Institute of Chemical Engineers, 81, M. Vijayakumar,P. Navaneethakrishnan,G. Kumaresan,R. Kamatchi, A study on heat transfer characteristics of inclined copper sintered wick heat pipe using surfactant free CuO and Al2O3 nanofluids, Pages No.190-198, Copyright (2017), with permission from Elsevier*

nanoparticles. Results shows negligible effect of electric field on heat transfer performance of heat pipe.

Su et al. [75], Experimentally, studied the heat transfer performance of an oscillating heat pipe with Graphene oxide/self rewetting nanofluid. Self rewetting nanofluid was prepared by mixing graphene oxide dispersion solution with n-butanol alcohol solution. Nanofluids were prepared by mixing self rewetting fluids and graphene oxide dispersion solution. Heat transfer in self rewetting nanofluid was enhanced by 16% to that self rewetting fluid and 12% to that of nanofluid.

2.1.8. Pulsating heat pipe (PHP)

Goshayeshi et al. [76], had experimentally investigated the heat transfer rate and temperature distribution without and with magnetic field in pulsating heat pipe (5 turns) using Fe_2O_3/Kerosene. Two step method using stirring for 5 hrs in sonicator bath was used for nanofluids preparation. DLS analysis was used for characterization. Magnetic field had decreased the thermal resistance by 12%. Kang et al. [77], investigated pulsating heat pipe (5 turns) with magnetic field and without magnetic field by using Fe_3O_4/DI Water nanofluids. Magnetic field had improved thermal performance of PHP at lower heat input but effect was dominant at higher heat input. Xing et al. [78], experimentally, investigated closed loop PHP using pure water and MWNTs nanofluid. One step method was used for nanofuid preparation. At 100 W heat input, thermal resistance of 0.1 wt% nanofluid was decreased by 34% as compare with pure water. Nazari et al. [79], experimentally, investigated pulsating heat pipe using Graphene oxide/water nanofluids. Hammer (One Step) method was used for nanofluids preparation. XRD analysis was used to characterize the nanofluids. Graphene oxide sheets had increased thermal conductivity and viscosity of the base fluid. Thermal resistance of PHP was decreased as comparison with pure water.

2.1.9. Rotating heat pipe

Hassan et al. [80], had investigated the performance of rotating heat pipe using Cu, CuO and Al_2O_3/Water nanofluids using mathematical model. The test was conducted with 5 and 10 nm size particles and 0.2 and 4 v% concentration. Heat load was varied by 40–140W. The heat

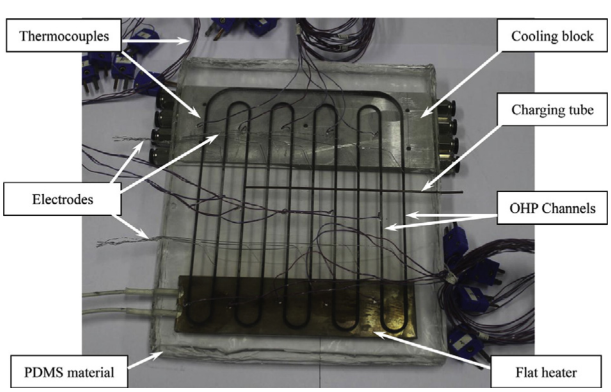


Fig. 15. Photo of the PDMS OHP (Ji et al. [74]).
Reprinted from Applied Thermal Engineering, 61, Yulong Ji, Gongwei Liu, Hongbin Ma, Gen Li, Yuqing Sun, An experimental investigation of heat transfer performance in apolydimethylsiloxane (PDMS) oscillating heat pipe, Pages No.690-697, Copyright (2013), with permission from Elsevier

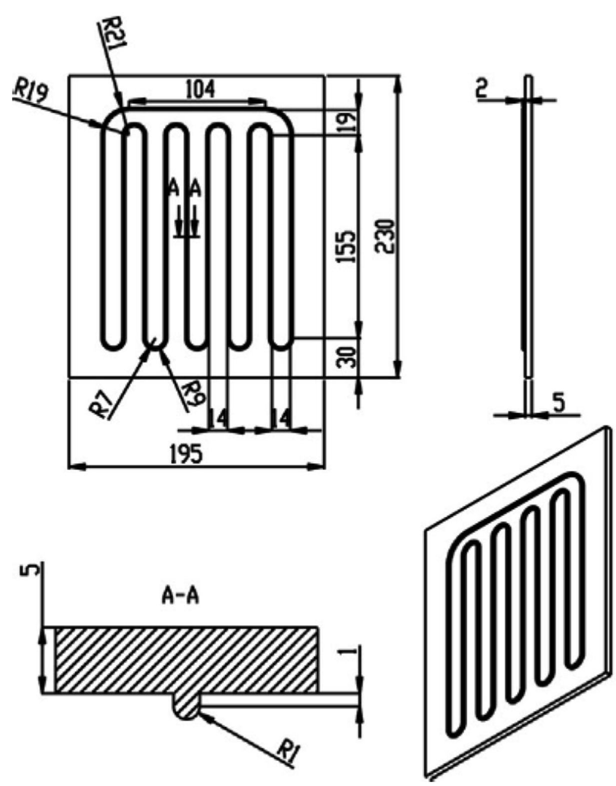


Fig. 16. Dimensions of OHP (Ji et al. [74]).
Reprinted from Applied Thermal Engineering, 61, Yulong Ji, Gongwei Liu, Hongbin Ma, Gen Li, Yuqing Sun, An experimental investigation of heat transfer performance in apolydimethylsiloxane (PDMS) oscillating heat pipe, Pages No.690–697, Copyright (2013), with permission from Elsevier

transfer rate was increased by increasing temperature difference, volume fraction and radius of solid surface. Cu–water nanofluid had maximum heat transfer compared with CuO–water and Al_2O_3–water nanofluids.

2.2. Critique of review work

2.2.1. Construction of heat pipe

Apart from few, major investigators have used copper tube as heat pipe materials for cylindrical heat pipe container. Kang et al. [77], Liou et al. [81] and Liu et al. [33] have used glass tube for heat pipe manufacturing. Ji et al. [74] have used PDMS (polydimethylsiloxane) one type of transparent tube for heat pipe. Kim et al. [53], Kim et al. [58] and Parametthanuwat et al. [30] have used steel based heat pipe materials. There are 11 articles in which investigator had used heat pipe with more than 1000 mm length, 04 had used 800–999 mm length, 06 had used 600–799 mm length, 07 had used 400–599 mm length 28 had used 200–300 mm length and 08 had used length with less than 100 mm as per their requirement. Heat pipe with length in between 200-300 mm is most popular among the researchers as it had more industrial applications. Similarly heat pipe container with less than 10 mm diameter is most common and large numbers of investigators have used it. This small diameter makes thermal management system more complex which the key need of current cooling system in electronic components. Due to ease of manufacturing and assembling, screen mesh wick with 2 nos of layer is most favorable in investigators. Except, Putra et al. [71], other researchers have used copper or steel material for wick structure.

Nazari et al. [79], Kang et al. [77], Xing et al. [78] and Goshayeshi et al. [76] used pulsating heat pipe. Ji et al. [74], Ji et al. [73] and Su et al. [75] used oscillating type heat pipe for their investigation. Putra et al. [71] and Tharayil et al. [72] used loop heat pipe. Alizad et al. [70] investigated transient behavior, performance and operational characteristics of flat shaped heat pipe. Hassan et al. [80] used rotating heat pipe.

2.2.2. Working medium

Large number of investigators has used water as a base fluid for nanofluids preparation due to easy of availability, low cost, high specific heat, low viscosity and low pumping power need in water based working medium. Saleh et al. [50], Toghrale et al. [82] and Vafaei et al. [83] have used Ethylene glycol as base liquid for nanofluids. Ji et al. [74] and Grissa et al. [84] used ethanol for nanofluids preparation. Su et al. [75] used self rewetting material, Yang et al. [85] used ammonia, Alijani et al. [86] used IPA (Isopropyl Alchohole), Goshayeshi et al. [76], used kerosene, Hormozi et al. [87] used SDS (Sodium Dodecyl Sulfate) as base fluid for nanofluids preparation. Oxides are hydrophilic in nature which can be easily disperse in polar basefluid like water. The used of nanoparticles made from aluminum oxide and copper oxide in nanofluids is maximum due to large thermal conductivity of both metals.

2.2.3. Operating variables

Investigator had mentioned concentration of nanoparticles in base fluid via two technique (1) mass concentration and (2) volume concentration. Both this techniques are interchangeable, i.e. By using simple one calculation anyone can change mass concentration to volume concentration and vice a versa. Mass concentration in between 0.5-3.0 wt% and volume concentration in between 1-5 v% is commonly used by large number of researchers. Major researchers have found that 1.0 wt% have optimum thermal performance of nanofluids in heat pipe. Less concentration of nanoparticles have poor heat transfer property of working medium and more concentration of nanoparticles leads to increase the viscosity of working medium.

Filling ratio is percentage of working fluid filled inside the heat pipe. In few papers, filling ratio was mentioned with reference to evaporator volume and few were mentioned it with heat pipe volume. Ji et al. [74] and Kang et al. [77] used filling ratio as 70 %, Liu et al. [33], Wang et al. [56] and Liu et al. [42] used 60 %, Ji et al. [73], Liu et al. [36], Wang et al. [37], Wang et al. [46], Xing et al. [78], Su et al. [75] and Goshayeshi et al. [76] used 50%, Chavda [59] used 40 % of evaporator volume. Kumaresa et al. [65] investigated heat pipe with filling ratio of 34%, Menlik et al. [34] with 33.3%, Subramaniyan et al. [88] and Li et al. [89] and Tharayil et al. [72] with 30 %, Parametthanuwat et al. [30] with 30, 40, 80%, Chen et al. [90] and Senthil et al. [61] with 25%, Hung et al. [91] and Teng et al. [92] with 20, 40, 60, 80, Mousa [1] with 20, 40, 45, 50, 55, 60, 70, 80, 100%, Chiang et al. [93] with 20, 30, 40, Mahdavi et al. [63] and Khalili et al. [66] with 10, 20, 30, 45% of heat pipe volume. Heat pipe with low filling ratio have dry out condition whereas higher filling ratio leads to over feeding and presence of unwanted working medium inside the heat pipe.

There are only limited numbers of research article in which investigators have mentioned working medium pressure inside the heat pipe. Latibari et al. [39] worked with 1 kPa, Kim et al. [53] have 12.5 kPa, Kumaresa et al. [65] used 13.46 kPa, Putra et al. [43] kept137.8 kPa, Kim et al. [58] worked with14.5 kPa, Liu et al. [42] maintained 19.97, 12.38, 7.45 kPa, Wang et al. [56] worked with 26–30 kPa, Chen et al. [90] used 7.38, 15.75, 31.18 kPa, Venkatachalapathy et al. [55] have 7.45 kPa, Wang et al. [46], Liu et al. [36] and Liu et al. [40] worked with 7.45, 12.38, 19.97 kPa, Shafahi et al. [94] worked with -1200-0 pa, Kamyar et al. [32] used -0.9 bar, Mousa [1] have 0.01 bar, Wang et al. [37] with 0.086 Pa, Goshayeshi et al. [76] maintained 0.1 Pa, Kang et al. [77] have 0.35 torr, Hajian et al. [3] used 10-2 torr, Mahdavi et al. [63] worked on10-3 torrChavda [59] kept 10-3 torr and Ramachandran et al. [60] worked with 10–4 torr. Selection of pressure is based on saturation limit of working medium but for same working fluid the thermal performance was enhanced by increasing pressure.

There are so many other applications, apart from heat pipe were experimental and numerical investigation had been carried using nanofluids. Few of them, which are related with to thermal systems like Computer Processor [95], car radiator [96,97], Heat sinks [98, 99, 100], minichannel [101], microprocessor [102,103], Brayton cycle [104], circular concentric pipes [105], channel [106], solar collector [107] etc are investigated using different types of nanofluids.

2.3. Statistical analysis

Nanofluid and hybrid nanofluid based heat pipe analysis are considered in this review work. The research work carried out in last decade are identified in various aspects, which includes, performance characteristics, experimental analysis, nanofluid preparation method and

Table 7
Heat pipe with nanofluid in previous articles.

Author	Title	Journal	Year
Sureshkumar et al. [108]	Heat transfer characteristics of nanofluids in heat pipes: A review	Renewable and Sustainable Energy Reviews	2013
Alawi et al. [109]	Fluid flow and heat transfer characteristics of nanofluids in heat pipes: A review	International communications in Heat and Mass Transfer	2014
Chan et al. [110]	Heat utilization technologies: A critical review of heat pipes	Renewable and Sustainable Enegry Reviews	2015
Sonawana et al. [111]	Effect of Nanofluids on Heat Pipe Thermal Performance: A Review of the Recent Literature	International Journal of Engineering and Applied Sciences	2016
Mohamed et al. [112]	A Review: On the Heat Pipe and its Applications	Proceedings of 4th International Conference on Energy Engineering	2017
Gupta et al. [113]	Heat transfer mechanisms in heat pipes using nanofluids-A review	Experimental Thermal and Fluid Science	2017

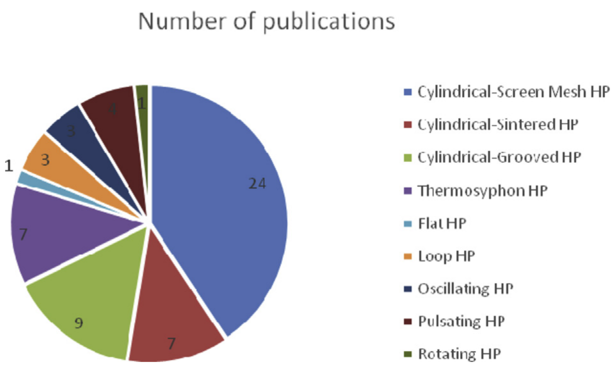


Fig. 17. Articles published on various types of heat pipes.

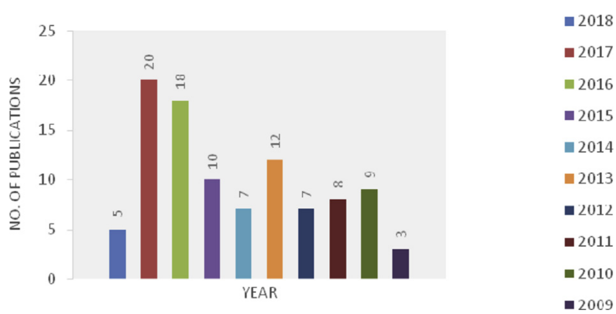


Fig. 18. Number of paper's published between 2009 and 2018.

characterization technique. The publications referred to this article are mainly from Elsevier, Taylor & Francis, Springer publication and a conference proceeding which have significant nature.

There are few review articles [108–113] related to heat pipe with nanofluid since 2010 as shown in Table 7. It was observed that the published review articles focused on a nanofluid only in one aspect as on 2018. There has been no comprehensive review on use of hybrid nanofluid in heat pipe technology since 2018.

The number of total papers published under different heat pipe and wick structure is shown in Fig. 17. It was observed that more research papers have been published in the field of nanofluid as working medium in heat pipe for the past 10 years. The number of papers published between 2009 and 2018 is shown in Fig. 18. It was found that more number of papers was published in 2017.

The comprehensive review of researches available in open literature related to use of various types of nanofluids in various types of heat pipes have been carried out and presented in Table 8.

The number of research articles published using particular types of heat pipe charged with particular types of nanofluids is shown in Table 4. As per Table 4, the researches published using cylindrical (particularly Screen mesh) heat pipe are in maximum number. Similarly, the maximum numbers of studies of various types of heat pipe charged with Al_2O_3 and CuO based nanofluids are reported. This lead to primary finding that, most common configurations of heat pipe is cylindrical heat pipe with screen mesh wick structure and most common nanofluids employed to enhance the thermal performance are Al_2O_3 and CuO. This might be due to fact that cylindrical configuration can be adjusted at most of all types of applications where as other types of configuration require proper space and orientation. Yet performance of heat pipe charged with water based nanoparticles such as Gold, Ti, ZnO, MgO, TiC, AlN, SiN, diamond, MWCNT and hybrid nanoparticles are needed to be evaluated. Similarly the performances of other types of heat pipe are to be evaluated using various nanofluids.

The number of research articles published using particular types nanofluid prepared with particular types of preparation method are as shown in Fig. 19.

As shown in Figure, the maximum number of researchers had used two step methods to prepare the nanofluids. It may be due to easy availability of oxide based nanoparticles and simple physical process of two step method. Whereas one step method required complex mechanical, thermal and chemical processes which leads to consumption of large amount of money and time. Preparation of metal oxides based nanofluids using two step method is recent trend.

The number of research articles published related to characterization of nanofluids using particular types nanofluids with particular types of

Table 8
Analysis of various nanofluids with various types of heat pipes.

Thermal System		Sintered wick type HP	Grooved type HP	Screen Mesh type HP	Thermosyphon	Flat HP	Loop HP	Oscillating HP	Pulsating HP	Rotating HP	Total
Pure Metals as Nanoparticles	Silver	1 [64]	-	6 [3], [41], [43], [47], [59], [62]	1 [30]	-	-	-	-	-	**8**
	Cu	-	1 [40]	4 [41], [44], [45], [48]	-	-	-	-	-	1 [80]	**6**
	Ti	-	-	-	1 [32]	-	-	-	-	-	**1**
	Gold	-	-	-	-	-	-	-	-	-	**0**
Metal Oxides as Nanoparticles	Al_2O_3	2 [68], [69]	1 [35]	4 [1], [54], [61], [62]	2 [28], [32]	1 [70]	1 [71]	2 [73], [74]	-	1 [80]	**14**
	CuO	3 [65], [68], [69]	3 [36], [37], [40]	4 [12], [42], [55], [62], [90]	1 [33]	1 [70]	-	-	-	1 [80]	**13**
	TiO_2	-	-	2 [49], [51]	-	1 [70]	-	-	-	-	**3**
	ZnO	-	-	1 [50]	-	-	-	-	-	-	**1**
	MgO	-	-	-	1 [34]	-	-	-	-	-	**1**
	Fe_2O_3/ Fe_3O_4	-	-	-	2 [29], [31]	-	-	-	2 [76], [77]	-	**4**
	SiO_2	-	1 [40]	1 [56]	2 [32], [90]	-	-	-	-	-	**4**
Carbide	TiC	-	-	-	-	-	-	-	-	-	**0**
	SiC	-	-	2 [52], [53]	-	-	-	-	-	-	**2**
Nitrides	AIN	-	-	-	-	-	-	-	-	-	**0**
	SiN	-	-	-	-	-	-	-	-	-	**0**
Carbon	Diamond	-	-	-	-	-	-	-	-	-	**0**
	Graphite	1 [67]	1 [39]	1 [58]	-	-	1 [72]	1 [73]	1 [79]	-	**6**
	MWCNT	-	-	-	-	-	-	-	1 [78]	-	**1**
Hybrid Nanofluids		-	1 [38]	1 [60]	-	-	-	-	-	-	**2**
Total		**7**	**8**	**26**	**10**	**3**	**2**	**3**	**4**	**3**	**66**

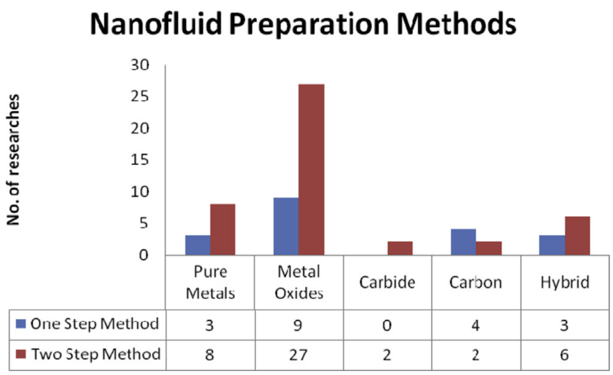


Fig. 19. No. of researches along with types of nanofluids and preparation method.

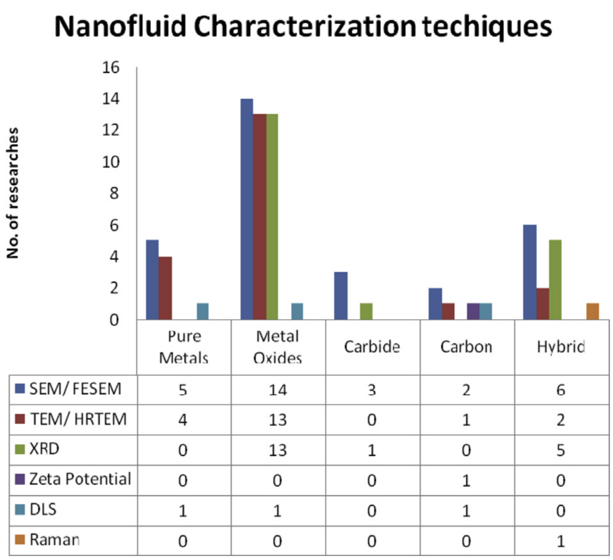


Fig. 20. No. of researches along with types of nanofluids and characterization techniques.

characterization technique are shown in Fig. 20.

As per Figure, the maximum number of researchers used SEM, TEM and XRD technique to characterize the nanofluids. Characterization nanofluids using SEM, TEM and XRD techniques are recent trend. XRD technique is use for the study of crystalline structure of nanoparticles. TEM has much higher resolution than SEM. This analysis, suggest to used TEM technique for the analysis of micro structure and surface morphology of nanofluids.

2.4. Future trends

The previous section may help to predict the current research status of nanofluid based heat pipe technology. The possible research direction of different heat pipes using mono and hybrid nanofluid are discussed in this section.

Major investigations had been carried out on cylindrical shaped heat pipe which is most commonly used heat pipe in industrial applications due to simple in construction, handling, filling and refilling of working fluid. Future research direction can focus on the study on variation of heat pipe performance with respect to heat load fluctuation, optimum orientation and material of heat pipe.

A considerable amount of research work has been carried out using mono nanofluid as working medium. The published research works are related to types of nanofluid, types of wick structure, concentration of nanoparticles, filling ratio, orientation and heat load and so on limited amount of research works has been conducted in the field of use of hybrid nanofluid and comparison of hybrid nanofluid with nanofluid in which individual nanoparticles were suspended. Considerable research work might be carried out using hybrid nanofluids to investigate the effect of various suspended nanoparticles, proportion of suspended particles, its concentration, filling ratio and surface morphology and its preparation method on thermal performance of heat pipe. Preparation of nanofluid and hybrid nanofluid is also challenging task.

Heat pipe with enhanced thermal performance has major applications in the field of electronic component cooling, automobile radiator, satellite equipment cooling, refrigeration and air conditioning system, high power LEDs cooling, phase change materials (PCM), micro reactors etc.

3. Conclusion

This paper presents an overview of thermal performance of heat pipe using mono and hybrid nanofluids as working medium. Open literature shows great potential of mono and hybrid nanofluids for the enhancement of heat transfer in heat pipe. Following conclusions can be drawn from study:

1. Performance enhancement of heat pipe using oxide based nanofluids especially aluminum and copper have higher potential to enhance the thermal performance by considering cost effectiveness.
2. Mass concentration of nanoparticles inside the base fluid plays important role in heat pipe performance. 1.0 wt% is optimum concentration for better performance. Enhanced concentration have presence of excess amount working medium and less concentration leads to dry out condition in heat pipe.
3. Heat pipe with 50% filling ratio with respect to evaporator section volume have optimum thermal performance.
4. Enhancement of heat pipe using nanofluids might be due to (1) bombards of suspended nanoparticles leads to more number of vapour bubbles which reduce the size and numbers of bubbles i.e. enhancement in heat transfer at evaporator section, (2) enhancement in thermophysical properties of working medium like thermal conductivities etc., (3) artificial layer of nanoparticles on wall surface enhance heat transfer coefficient and heat flux. It also increases heat transfer area by creating porous structure due to deposition of nanoparticles on surface.
5. Augmentation thermal conductivity is possible only by using hybrid nanofluid in place of mono nanofluid.
6. The main approach for the use of hydrid nanoparticle based working medium is to get benefit of increased heat transfer rate and stability while lowered viscosity due to synergetic effect.

Furthermore theoretical and experimental investigations are needed to understand thermal performance of heat pipe using % concentration, types of heat pipe, types of working medium, proportion of suspended nanoparticles in hybrid fluid, inclination angle, filling ratio, heat input, temperature range etc.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] M.G. Mousa, Effect of nanofluid concentration on the performance of circular heat pipe, Ain Shams Eng. J. 2 (1) (2011) 63–69.
[2] N.K. Chvda, Review of modeling the performance of heat pipes using artificial neural network, Int. J. Artif. Intell. Knowl. Discov. 7 (3) (2017) 7–12.
[3] R. Hajian, M. Layeghi, K. Abbaspour Sani, Experimental study of nanofluid effects on the thermal performance with response time of heat pipe, Energy Convers. Manag. 56 (2012) 63–68.
[4] Y. Li, J. Zhou, S. Tung, E. Schneider, S. Xi, A review on development of nanofluid preparation and characterization, Powder Technol. 196 (2) (2009) 89–101.
[5] Z. Haddad, C. Abid, H.F. Oztop, A. Mataoui, A review on how the researchers prepare their nanofluids, Int. J. Therm. Sci. 76 (2014) 168–189.
[6] N.A.C. Sidik, H.A. Mohammed, O.A. Alawi, S. Samion, A review on preparation methods and challenges of nanofluids, Int. Commun. Heat Mass Transf. 54 (2014) 115–125.
[7] S. K. Sharma Babita, S.M. Gupta, Preparation and evaluation of stable nanofluids for heat transfer application: a review, Exp. Therm. Fluid Sci. 79 (2016) 202–212.
[8] D.K. Devendiran, V.A. Amirtham, A review on preparation, characterization, properties and applications of nanofluids, Renew. Sustain. Energy Rev. 60 (2016) 21–40.
[9] H.M. Ali, H.B. Id, T.R. Shah, M.U. Sajid, Applied Sciences Preparation Techniques of TiO 2 Nanofluids and Challenges : A Review, 2018.
[10] M.U. Sajid, H.M. Ali, Recent advances in application of nanofluids in heat transfer devices : a critical review, Renew. Sustain. Energy Rev. 103 (December 2018) (2019) 556–592.
[11] S. Akilu, A. Tesfamichael, M. Azman, M. Said, A. Adriana, Solar Energy Materials and Solar Cells Properties of glycerol and ethylene glycol mixture based SiO 2 -CuO/C hybrid nano fl uid for enhanced solar energy transport, Sol. Energy Mater. Sol. Cells (2017) 1–11, no. June.
[12] S. Suresh, K.P. Venkitaraj, P. Selvakumar, M. Chandrasekar, Synthesis of Al2O3-Cu/water hybrid nanofluids using two step method and its thermo physical properties, Colloids Surfaces A Physicochem. Eng. Asp. 388 (1–3) (2011) 41–48.
[13] D. Madhesh, R. Parameshwaran, S. Kalaiselvam, Experimental investigation on convective heat transfer and rheological characteristics of Cu-TiO2hybrid nanofluids, Exp. Therm. Fluid Sci. 52 (2014) 104–115.
[14] T.-P.T. Yi-Hsuan Hung, Wei-Ping Wang, Yu-Chun Hsu, Performance evaluation of an air-cooled heat exchange system for hybrid nanofluids, Exp. Therm. Fluid Sci. (2016).
[15] L.S. Sundar, M.K. Singh, A.C.M. Sousa, Enhanced heat transfer and friction factor of MWCNT-Fe3O4/water hybrid nanofluids, Int. Commun. Heat Mass Transf. 52 (2014) 73–83.
[16] H. Yarmand, et al., Graphene nanoplatelets-silver hybrid nanofluids for enhanced heat transfer, Energy Convers. Manag. 100 (2015) 419–428.
[17] M. Hemmat Esfe, et al., Thermal conductivity of Cu/TiO_2-water/EG hybrid nanofluid: experimental data and modeling using artificial neural network and correlation, Int. Commun. Heat Mass Transf. 66 (2015) 100–104.
[18] S. Suresh, K.P. Venkitaraj, P. Selvakumar, M. Chandrasekar, Effect of Al2O3-Cu/water hybrid nanofluid in heat transfer, Exp. Therm. Fluid Sci. 38 (2012) 54–60.
[19] J. Sarkar, P. Ghosh, A. Adil, A review on hybrid nanofluids: recent research, development and applications, Renew. Sustain. Energy Rev. 43 (2015) 164–177.
[20] N.A.C. Sidik, I.M. Adamu, M.M. Jamil, G.H.R. Kefayati, R. Mamat, G. Najafi, Recent progress on hybrid nanofluids in heat transfer applications: a comprehensive review, Int. Commun. Heat Mass Transf. 78 (2016) 68–79.
[21] J.A. Ranga Babu, K.K. Kumar, S. Srinivasa Rao, State-of-art review on hybrid nanofluids, Renew. Sustain. Energy Rev. 77 (September 2016) (2017) 551–565.
[22] A.A. Minea, W.M. El-Maghlany, Influence of hybrid nanofluids on the performance of parabolic trough collectors in solar thermal systems: recent findings and numerical comparison, Renew. Energy 120 (2018) 350–364.
[23] N.A. Che Sidik, M. Mahmud Jamil, W.M.A. Aziz Japar, I. Muhammad Adamu, A review on preparation methods, stability and applications of hybrid nanofluids, Renew. Sustain. Energy Rev. 80 (January 2016) (2017) 1112–1122.
[24] L.S. Sundar, K.V. Sharma, M.K. Singh, A.C.M. Sousa, Hybrid nanofluids preparation, thermal properties, heat transfer and friction factor – a review, Renew. Sustain. Energy Rev. 68 (August 2016) (2017) 185–198.
[25] M.U. Sajid, H.M. Ali, Thermal conductivity of hybrid nanofluids : a critical review, Int. J. Heat Mass Transf. 126 (2018) 211–234.
[26] H. Babar, M. U. Sajid, and H. M. Ali, "Viscosity of Hybrid Nanofluids : a Critical Review," pp. 1–49.
[27] B. Zohuri, Heat Pipe Design and Technology Modern Applications for Practical Thermal Management, 2016.
[28] S.H. Noie, S.Z. Heris, M. Kahani, S.M. Nowee, Heat transfer enhancement using Al2O3/water nanofluid in a two-phase closed thermosyphon, Int. J. Heat Fluid Flow 30 (4) (2009) 700–705.
[29] G. Huminic, A. Huminic, I. Morjan, F. Dumitrache, Experimental study of the thermal performance of thermosyphon heat pipe using iron oxide nanoparticles, Int. J. Heat Mass Transf. 54 (1–3) (2011) 656–661.
[30] T. Parametthanuwat, S. Rittidech, A. Pattiya, Y. Ding, S. Witharana, Application of silver nanofluid containing oleic acid surfactant in a thermosyphon economizer, Nanoscale Res. Lett. 6 (1) (2011) 1–10.
[31] G. Huminic, A. Huminic, Numerical study on heat transfer characteristics of thermosyphon heat pipes using nanofluids, Energy Convers. Manag. 76 (2013) 393–399.
[32] A. Kamyar, K.S. Ong, R. Saidur, Effects of nanofluids on heat transfer characteristics of a two-phase closed thermosyphon, Int. J. Heat Mass Transf. 65 (2013) 610–618.
[33] Z.H. Liu, R.L. Hu, L. Lu, F. Zhao, H.S. Xiao, Thermal performance of an open thermosyphon using nanofluid for evacuated tubular high temperature air solar collector, Energy Convers. Manag. 73 (2013) 135–143.
[34] T. Menlik, A. Sözen, M. Gürü, S. Öztas, Heat transfer enhancement using MgO/water nanofluid in heat pipe, J. Energy Inst. 88 (3) (2015) 247–257.
[35] K.H. Do, S.P. Jang, Effect of nanofluids on the thermal performance of a flat micro heat pipe with a rectangular grooved wick, Int. J. Heat Mass Transf. 53 (9–10) (2010) 2183–2192.
[36] Z.H. Liu, Y.Y. Li, R. Bao, Thermal performance of inclined grooved heat pipes using nanofluids, Int. J. Therm. Sci. 49 (9) (2010) 1680–1687.
[37] G.S. Wang, B. Song, Z.H. Liu, Operation characteristics of cylindrical miniature grooved heat pipe using aqueous CuO nanofluids, Exp. Therm. Fluid Sci. 34 (8) (2010) 1415–1421.
[38] T. Science, Thermal characteristics of grooved heat pipe 15 (1) (2011) 195–206.
[39] M. Mehrali, et al., Effect of nitrogen-doped graphene nanofluid on the thermal performance of the grooved copper heat pipe, Energy Convers. Manag. 118 (2016) 459–473.
[40] Z.H. Liu, Y.Y. Li, R. Bao, Compositive effect of nanoparticle parameter on thermal performance of cylindrical micro-grooved heat pipe using nanofluids, Int. J. Therm. Sci. 50 (4) (2011) 558–568.
[41] K.N. Shukla, Thermal performance of cylindrical heat pipe using nano fl uids, J. Thermophys. Heat Transf. 24 (4) (2010).
[42] Z. Liu, Q. Zhu, Application of aqueous nanofluids in a horizontal mesh heat pipe, Energy Convers. Manag. 52 (1) (2011) 292–300.
[43] R.I. Nandy Putra, Wayan Nata Septiadi, Haolia Rahman, Thermal performance of screen mesh wick heat pipes with nanofluids, Exp. Therm. Fluid Sci. 40 (2012) 10–17.
[44] R. Senthilkumar, S. Vaidyanathan, B. Sivaraman, Effect of inclination angle in heat pipe performance using copper nanofluid, Procedia Eng. 38 (2012) 3715–3721.
[45] A.B. Solomon, K. Ramachandran, B.C. Pillai, Thermal performance of a heat pipe with nanoparticles coated wick, Appl. Therm. Eng. 36 (1) (2012) 106–112.
[46] P.Y. Wang, X.J. Chen, Z.H. Liu, Y.P. Liu, Application of nanofluid in an inclined mesh wicked heat pipes, Thermochim. Acta 539 (2012) 100–108.
[47] L.G. Asirvatham, R. Nimmagadda, S. Wongwises, Heat transfer performance of screen mesh wick heat pipes using silver-water nanofluid, Int. J. Heat Mass Transf. 60 (1) (2013) 201–209.
[48] M. Kole, T.K. Dey, Thermal performance of screen mesh wick heat pipes using water-based copper nanofluids, Appl. Therm. Eng. 50 (1) (2013) 763–770.
[49] R.R. Kumar, M. Narasimha, K. Sridhar, Heat transfer enhancement in heat pipe using TiO 2 nanofluid with N-butanol, Sci. Technol. 3 (4) (2013) 105–111.
[50] R. Saleh, N. Putra, S.P. Prakoso, W.N. Septiadi, Experimental investigation of thermal conductivity and heat pipe thermal performance of ZnO nanofluids, Int. J. Therm. Sci. 63 (2013) 125–132.
[51] R. Saleh, N. Putra, R.E. Wibowo, W.N. Septiadi, S.P. Prakoso, Titanium dioxide nanofluids for heat transfer applications, Exp. Therm. Fluid Sci. 52 (2014) 19–29.
[52] M. Ghanbarpour, N. Nikkam, R. Khodabandeh, M.S. Toprak, Improvement of heat transfer characteristics of cylindrical heat pipe by using SiC nanofluids, Appl. Therm. Eng. 90 (2015) 127–135.
[53] K.M. Kim, Y.S. Jeong, I.G. Kim, I.C. Bang, Comparison of thermal performances of water-filled, SiC nanofluid-filled and SiC nanoparticles-coated heat pipes, Int. J. Heat Mass Transf. 88 (2015) 862–871.
[54] N. Morteza, G. Nader, Thermal performance of screen mesh heat pipe with Al2O3 nanofluid, Exp. Therm. Fluid Sci. 66 (2015) 1112–1122.
[55] S. Venkatachalapathy, G. Kumaresan, S. Suresh, Performance analysis of cylindrical heat pipe using nanofluids - an experimental study, Int. J. Multiph. Flow 72 (2015) 188–197.
[56] Y. Wang, J. Zhang, J. Cen, F. Jiang, A feasibility study about using SiO2Nanofluid screen mesh wick heat pipe for cooling of high-power LEDs, Heat Transf. Eng. 37 (9) (2016) 741–750.
[57] M. Ghanbarpour, N. Nikkam, R. Khodabandeh, M.S. Toprak, M. Muhammed, Citation for the Original Published Paper (Version of Record): Permanent Link to this Version : thermal Performance of Screen Mesh Heat Pipe with Al 2 O 3 Nanofluid, 2015, pp. 213–220.
[58] K.M. Kim, I.C. Bang, Effects of graphene oxide nanofluids on heat pipe performance and capillary limits, Int. J. Therm. Sci. 100 (2016) 346–356.
[59] N.K. Chavda, Investigation of thermal performance of cylindrical heat pipe using silver Nanofluid : Part-I : experimental evaluation, J. Inst. Eng. Ser. C. (2019).
[60] R. Ramachandran, K. Ganesan, M.R. Rajkumar, L.G. Asirvatham, S. Wongwises, Comparative study of the effect of hybrid nanoparticle on the thermal performance of cylindrical screen mesh heat pipe, Int. Commun. Heat Mass Transf. 76 (2016) 294–300.
[61] R. Senthil, D. Ratchagaraja, R. Silambarasan, R. Manikandan, Contemplation of thermal characteristics by filling ratio of Al2O3nanofluid in wire mesh heat pipe, Alexandria Eng. J. 55 (2) (2016) 1063–1068.
[62] H. Kavusi, D. Toghraie, A comprehensive study of the performance of a heat pipe by using of various nanofluids, Adv. Powder Technol. 28 (11) (2017) 3074–3084.
[63] M. Mahdavi, S. Tiari, S. De Schampheleire, S. Qiu, Experimental study of the thermal characteristics of a heat pipe, Exp. Therm. Fluid Sci. 93 (November 2017) (2018).

[64] S.W. Kang, W.C. Wei, S.H. Tsai, C.C. Huang, Experimental investigation of nanofluids on sintered heat pipe thermal performance, Appl. Therm. Eng. 29 (5–6) (2009) 973–979.
[65] G. Kumaresan, S. Venkatachalapathy, L.G. Asirvatham, Experimental investigation on enhancement in thermal characteristics of sintered wick heat pipe using CuO nanofluids, Int. J. Heat Mass Transf. 72 (2014) 507–516.
[66] M. Khalili, M.B. Shafii, Experimental and numerical investigation of the thermal performance of a novel sintered-wick heat pipe, Appl. Therm. Eng. 94 (2016) 59–75.
[67] E. Sadeghinezhad, et al., Experimental investigation of the effect of graphene nanofluids on heat pipe thermal performance, Appl. Therm. Eng. 100 (2016) 775–787.
[68] M. Vijayakumar, P. Navaneethakrishnan, G. Kumaresan, Thermal characteristics studies on sintered wick heat pipe using CuO and Al2O3 nanofluids, Exp. Therm. Fluid Sci. (2016).
[69] M. Vijayakumar, P. Navaneethakrishnan, G. Kumaresan, R. Kamatchi, A study on heat transfer characteristics of inclined copper sintered wick heat pipe using surfactant free CuO and Al2O3nanofluids, J. Taiwan Inst. Chem. Eng. 81 (2017) 190–198.
[70] K. Alizad, K. Vafai, M. Shafahi, Thermal performance and operational attributes of the startup characteristics of flat-shaped heat pipes using nanofluids, Int. J. Heat Mass Transf. 55 (1–3) (2012) 140–155.
[71] N. Putra, R. Saleh, W.N. Septiadi, A. Okta, Z. Hamid, Thermal performance of biomaterial wick loop heat pipes with water-base Al2O3 nanofluids, Int. J. Therm. Sci. 76 (2014) 128–136.
[72] T. Tharayil, L.G. Asirvatham, V. Ravindran, S. Wongwises, Thermal performance of miniature loop heat pipe with graphene-water nanofluid, Int. J. Heat Mass Transf. 93 (2016) 957–968.
[73] Y. Ji, H. Ma, F. Su, G. Wang, Particle size effect on heat transfer performance in an oscillating heat pipe, Exp. Therm. Fluid Sci. 35 (4) (2011) 724–727.
[74] Y.S. Yulong Ji, Gongwei Liu, Hongbin Ma, Gen Li, An experimental investigation of heat transfer performance in a polydimethylsiloxane (PDMS) oscillating heat pipe, Appl. Therm. Eng. 61 (2013) 69–697.
[75] X. Su, M. Zhang, W. Han, X. Guo, Experimental study on the heat transfer performance of an oscillating heat pipe with self-rewetting nanofluid, Int. J. Heat Mass Transf. 100 (2016) 378–385.
[76] H. Reza, M. Reza, M. Goodarzi, M. Dahari, Particle size and type effects on heat transfer enhancement of Ferro-nano fl uids in a pulsating heat pipe, Powder Technol. 301 (2016) 1218–1226.
[77] S.W. Kang, Y.C. Wang, Y.C. Liu, H.M. Lo, Visualization and thermal resistance measurements for a magnetic nanofluid pulsating heat pipe, Appl. Therm. Eng. 126 (2017) 1044–1050.
[78] M. Xing, J. Yu, R. Wang, Performance of a vertical closed pulsating heat pipe with hydroxylated MWNTs nanofluid, Int. J. Heat Mass Transf. 112 (2017) 81–88.
[79] M.A. Nazari, R. Ghasempour, M.H. Ahmadi, G. Heydarian, M.B. Shafii, Experimental investigation of graphene oxide nanofluid on heat transfer enhancement of pulsating heat pipe, Int. Commun. Heat Mass Transf. 91 (2018) 90–94.
[80] H. Hassan, S. Harmand, Effect of using nanofluids on the performance of rotating heat pipe, Appl. Math. Model. 39 (15) (2015) 4445–4462.
[81] J.H. Liou, C.W. Chang, C. Chao, S.C. Wong, Visualization and thermal resistance measurement for the sintered mesh-wick evaporator in operating flat-plate heat pipes, Int. J. Heat Mass Transf. 53 (7–8) (2010) 1498–1506.
[82] D. Toghraie, V.A. Chaharsoghi, M. Afrand, Measurement of thermal conductivity of ZnO–TiO2/EG hybrid nanofluid, J. Therm. Anal. Calorim. 125 (1) (2016) 527–535.
[83] M. Vafaei, M. Afrand, N. Sina, R. Kalbasi, F. Sourani, H. Teimouri, Author ' s Accepted Manuscript neural networks Evaluation of thermal conductivity of MgO-MWCNTs/EG hybrid nanofluids based on experimental data by selecting optimal artificial neural networks, Phys. E Low-Dimens. Syst. Nanostructures (2016).
[84] K. Grissa, A.M. Benselama, Z. Lataoui, Y. Bertin, A. Jemni, Investigations of the thermal performance of a cylindrical wicked heat pipe, Int. J. Energy Res. 42 (9) (2018) 3048–3058.
[85] K. Yang, Y. Mao, Z. Cong, X. Zhang, Experimental research of novel aluminium-ammonia heat pipes, Procedia Eng. 205 (2017) 3923–3930.
[86] H. Alijani, B. Çetin, Y. Akkuş, Z. Dursunkaya, Effect of design and operating parameters on the thermal performance of aluminum flat grooved heat pipes, Appl. Therm. Eng. 132 (2018) 174–187.
[87] F. Hormozi, B. ZareNezhad, H.R. Allahyar, An experimental investigation on the effects of surfactants on the thermal performance of hybrid nanofluids in helical coil heat exchangers, Int. Commun. Heat Mass Transf. 78 (2016) 271–276.
[88] N. Deihl, Investigation of Thermal Performance of a Copper Heat Pipe with Ti02 Nanoparticles, 2013, pp. 634–638.
[89] Z.W. Li, L.C. Lv, J. Li, Combination of heat storage and thermal spreading for high power portable electronics cooling, Int. J. Heat Mass Transf. 98 (2016) 550–557.
[90] Y.J. Chen, P.Y. Wang, Z.H. Liu, Application of water-based SiO2functionalized nanofluid in a loop thermosyphon, Int. J. Heat Mass Transf. 56 (1–2) (2013) 59–68.
[91] Y.H. Hung, T.P. Teng, B.G. Lin, Evaluation of the thermal performance of a heat pipe using alumina nanofluids, Exp. Therm. Fluid Sci. 44 (2013) 504–511.
[92] T.P. Teng, H.G. Hsu, H.E. Mo, C.C. Chen, Thermal efficiency of heat pipe with alumina nanofluid, J. Alloy. Comp. 504 (SUPPL. 1) (2010) S380–S384.
[93] Y.C. Chiang, W.C. Kuo, C.C. Ho, J.J. Chieh, Experimental study on thermal performances of heat pipes for air-conditioning systems influenced by magnetic nanofluids, external fields, and micro wicks, Int. J. Refrig. 43 (2014) 62–70.
[94] M. Shafahi, V. Bianco, K. Vafai, O. Manca, An investigation of the thermal performance of cylindrical heat pipes using nanofluids, Int. J. Heat Mass Transf. 53 (1–3) (2010) 376–383.
[95] S.A. Jajja, W. Ali, H.M. Ali, Multiwalled carbon nanotube nanofluid for thermal management of high heat generating computer processor, Heat Transf. Asian Res. 43 (7) (2014) 653–666.
[96] H.M. Ali, M.D. Azhar, M. Saleem, Q.S. Saeed, A. Saieed, Heat transfer enhancement of car radiator using aqua based magnesium oxide nanofluids, Therm. Sci. 19 (6) (2015) 2039–2048.
[97] H. Ali, H. Liaquat, B. Maqsood, Experimental investigation of convective heat transfer augmentation for car radiator using ZnO e water nano fluids, Energy 84 (2015) 317–324.
[98] H. Muhammad, W. Arshad, Thermal performance investigation of staggered and inline pin fin heat sinks using water based rutile and anatase TiO 2 nanofluids, Energy Convers. Manag. 106 (2015) 793–803.
[99] H.M. Ali, W. Arshad, Effect of channel angle of pin-fin heat sink on heat transfer performance using water based graphene nanoplatelets nanofluids, Int. J. Heat Mass Transf. (2016).
[100] W. Arshad, H.M. Ali, Graphene nanoplatelets nanofluids thermal and hydrodynamic performance on integral fin heat sink, Int. J. Heat Mass Transf. (2016) 1–7.
[101] W. Arshad, H. Muhammad, Experimental investigation of heat transfer and pressure drop in a straight minichannel heat sink using TiO 2 nanofluid, Int. J. Heat Mass Transf. 110 (2017) 248–256.
[102] S. Ayub, W. Ali, A. Maryam, Water cooled minichannel heat sinks for microprocessor cooling : effect of fin spacing, Appl. Therm. Eng. 64 (2014) 76–82.
[103] A.M. Siddiqui, W. Arshad, H.M. Ali, M. Ali, M.A. Nasir, Evaluation of nanofluids performance for simulated Microprocessor, Therm. Sci. 21 (2017) 2227–2236.
[104] M.S. Khan, M. Abid, H.M. Ali, P. Amber, M.A. Bashir, S. Javed, Comparative performance assessment of solar dish assisted s-CO2 Brayton cycle using nanofluids, Appl. Therm. Eng. (2018).
[105] M. Turkyilmazoglu, Anomalous heat transfer enhancement by slip due to nanofluids in circular concentric pipes, Int. J. Heat Mass Transf. 85 (2015) 609–614.
[106] M. Turkyilmazoglu, Buongiorno model in a nanofluid filled asymmetric channel fulfilling zero net particle flux at the walls, Int. J. Heat Mass Transf. 126 (2018) 974–979.
[107] M. Turkyilmazoglu, Performance of direct absorption solar collector with nanofluid mixture, Energy Convers. Manag. 114 (2016) 1–10.
[108] R. Sureshkumar, S.T. Mohideen, N. Nethaji, Heat transfer characteristics of nanofluids in heat pipes: a review, Renew. Sustain. Energy Rev. 20 (2013) 397–410.
[109] O.A. Alawi, N. Azwadi, C. Sidik, H.A. Mohammed, S. Syahrullail, Fluid flow and heat transfer characteristics of nano fluids in heat pipes : a review, Int. Commun. Heat Mass Transf. 56 (2014) 50–62.
[110] C.W. Chan, E. Siqueiros, M. Royapoor, A.P. Roskilly, Heat utilisation technologies : a critical review of heat pipes, Renew. Sustain. Energy Rev. (2015) 1–23.
[111] Y. Hung, et al., Effect of nanofluid on heat transfer characteristics of double pipe heat Exchanger : Part-I : effect of aluminum oxide nanofluid, Exp. Therm. Fluid Sci. 52 (1) (2016) 42–52.
[112] M. Salem, A Review : on the Heat Pipe and its a Review : on the Heat Pipe and its Applications, no. December, 2017.
[113] N.K. Gupta, A.K. Tiwari, S.K. Ghosh, Heat Transfer Mechanisms in Heat Pipes Using Nanofluids – A Review, vol. 90, Elsevier Inc., 2018.