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Developments in Heat Pipe: A Comprehensive Review

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Abstract

Heat Pipe is a device for efficient heat transfer. Since its discovery in mid 1800's there have been rapid developments in heat pipes with regard to their shape, size, working fluids, wick structures, materials. Heat Pipes have been employed in large number of applications, some of which are heat recovery from waste exhaust gases, space applications, nuclear applications, temperature and humidity control devices, heat rejection from leading edge of hypersonic aircraft, light emitting diodes, heat rejection from laser diodes, cooling of large diesel pistons, solar heaters/collectors, cooling of mechanical seals in process industries etc. Researchers all over the world are engaged in research leading to more efficient heat pipes for better efficiency and newer applications.

This paper presents an account of developments in heat pipes from the inception till date. A detailed review of literature is presented covering research undertaken by various researchers. The literature has been categorized into broad categories of research and types of heat pipes. Within each category, an account of initiation, developments and present state of work are given. Scope of future work and the expected directions of work are given towards the end of the paper.

Introduction

Heat Pipe is a heat transfer device efficient enough to transfer heat even around 500 times higher than the best metal conductor available on earth[1]. The heat is transferred over long distances with very small temperature difference. A conventional heat pipe consists of a sealed, hollow, cylindrical structure having wick material all round the inner periphery of the container and working fluid sufficient enough to saturate the wick. The container material can be metal e.g. copper, stainless steel, aluminum, nickel, monel metal, molybdenum etc., ceramics, glass or composite materials[2]. It is evacuated and then filled with the working fluid. The range of the operating temperature of the working fluid is from its triple point to the critical point. Chemical compatibility of the working fluid with the container and wick material is very important. The working fluids commonly used are nitrogen, helium etc. for cryogenic purposes, methanol, freons, water, ammonia, ethylene glycol etc. for low to medium temperature range and liquid metals like sodium, potassium, lithium etc. for very high temperature range. The wick can be made up of metals, porous materials, glass fiber, woven cloth, composite materials etc. The wick is usually of a wire mesh, screened, grooved or sintered mesh type of a structure. Wicking material was used by Gaugler[3] as a heat transfer device capable of transporting large amount of heat with small temperature difference. Trefethen[4] further used this, for space applications and registered a patent for the same. Perkins and King[5,6] in late 1800's registered a patent thus becoming the pioneers to use this concept. The device was named as Perkins Tube and used either single or multi-phase processes for heat transfer from furnace to boiler. The entire concept of heat pipe lies in mainly three regions. One end of the heat pipe is the evaporator region where the heat is supplied, the other end is the condenser region for heat rejection and in between the two, is the adiabatic region. Due to continuous sensible and further latent heat addition, the working fluid gets converted to vapor and flows through the adiabatic section towards the condenser end. Here, the latent heat of condensation is rejected and the phase of working fluid changes back to liquid. This cycle is repeated till the application of heat.[7] A heat pipe can operate in any orientation from 0˚ to 90˚, although its performance depends on the inclination angle. Gay[8] modified Perkin's Tube and registered a patent for a similar device using number of vertical tubes in which the condenser was located above the evaporator. These devices were known as 'Thermosyphons'. Here, gravitational forces aid the return of the working fluid back to the evaporator, to continue the cycle and hence the wick is omitted. In later stages, Grover et al.[9] coined the term heat pipe for the first time and published the conclusions drawn out of an independent investigation. Since then, innumerable applications in the area of heat transfer are using the concept of heat pipe. As Heat Pipe functions on closed, two phase cycle hence thermal response time is very less in comparison to mainly solid conductors and various other heat transfer devices. It works nearly as an isothermal device due to very low thermal resistance and so the temperature difference between the evaporator and the condenser region is very small. Heat Pipe therefore is a self contained, highly efficient cooling device due to very high heat transfer ability, simplicity of structure, no moving parts and not requiring any external energy. Any heat pipe is rated by its energy moving axially through the heat pipe known as APR(Axial Power Rating).[10] It is used extensively in electronic cooling devices, computer applications, temperature and humidity control in air–conditioning, waste heat recovery in heat pipe heat exchangers, solar energy utilization, space applications, nuclear applications, internal combustion engines, manufacturing systems, food industry, heat rejection from leading edge of hypersonic aircraft, light emitting diodes, heat rejection from laser diodes, cooling of large diesel pistons, injection moulding dies, cooling of mechanical seals in process industries etc. Miniature heat pipes of 3-6 mm diameter and less than 400m length are used in

CPU's of PCs and electronic cooling. Almost 80% of notebook PCs use micro heat pipe for cooling. Although, the practical application of heat pipe started with use of Thermosyphons, but with further developments it continued as heat pipes with wicks for numerous heat transfer applications. To further increase the heat transfer rate the methods employed were by surface enhancement, by decreasing the thermal resistance or by addition of the additives in the working fluid. Thus, heat pipes with surface enhancement, with self rewetting fluids as working fluids and non conventional heat pipes e.g. loop heat pipes, oscillating heat pipes, sorption heat pipes, pulsating heat pipes, concentric annular heat pipes, rectangular heat pipes etc. came into existence. Some inorganic or organic salts having low melting temperature, high heat of fusion and high thermal conductivity known as Phase Change Materials (PCM), have also been tested by researchers for enhancing the heat transfer rates in heat pipes. To understand the complex mechanism of the vapor flow, liquid flow and vapor liquid interface, researchers have worked on visualization, analysis and temperature distribution using mathematical modeling, statistical methods, Numerical analysis using Volume of Fluid method(VOF), Finite element analysis, Electrical Capacitance Tomography (ECT), Computational Fluid Dynamics (CFD) as different methods and modes of analyses.

The review of literature has been categorized under the following heads:

1. Heat pipes without wick OR Thermosyphons
2. Applications of Conventional Heat Pipes
3. Heat Pipes with different working fluids
4. Heat Pipes with surface enhancement
5. Non Conventional Heat Pipes
6. Analysis of Heat Pipes

Heat Pipes without Wick or Thermosyphons

Thermosyphon

Nguyen and Abhat[11]and Anchos and Florschetze[12]studied the behavior of flow in evaporator and adiabatic sections in vertical and inclined thermosyphons. All these researchers concluded that at higher flux, a disturbance wave was created due to the counter flowing vapor, affecting the condensate return which was responsible for entrainment or flooding limit. De Vries et al.[13] studied the effect of the pump control unit on the efficiency of the conventional flat plate solar collector and the diode resistance of thermosyphon solar collector during transient insolation and found the performance of both to be comparable with fluid circulation control. Bilegan and Fetcu[14] worked on aluminum extruded thermosyphon, to study the effect of variation in operating temperature, tilt angle and length of heat pipe on the performance and found high heat transfer rates to be achievable. Akyurt[15] investigated number of thermosyphon flat plate solar collectors of different materials with different working fluids and found the performance to be satisfactory with no start up or non condensable gas generation problems. Ramos and Dobran [16]analyzed the stability of closed thermosyphon as a function of heat input, fill ratio, viscosity, density, capillary number and two phase flow Grashof Number. They developed one steady state solution for one specific heat input for low fill ratio where as for high fill ratio, for each heat input, two possible steady state solutions were obtained. Maximum heat input was found to be a function of fill ratio, total length of thermosyphon, viscosity ratio, density ratio, capillary number and two phase Grashof Number. It was a monotonically increasing function of two phase Grashof's Number where as thermosyphon length and viscosity ratio did not affect the steady state solution to a larger extent but larger density ratios or lower capillary number resulted in increased heat inputs. It was difficult to predict accurately the transient behavior of thermosyphon by linear equations as the growth of the instabilities was unpredicted. Henyue[17] performed certain experiments to analyze heat transfer and concluded the instantaneous efficiency of thermosyphon flat plate solar water heater to increase with increase in the condenser heat transfer surface. Hull[18] concluded that freezing of the working fluid by any chance is not destructive and Two Phase Closed Thermosyphon(TPCT) behaves as a thermal diode thereby preventing the reverse circulation problem in conventional solar collectors. All the previous work, of theoretical and experimental study of performance of two phase thermosyphon, and its comparison with conventional solar collector did not consider the method of heat transfer from the thermosyhpon tube to the cooling water in heat exchanger. Widely used methodology was circulation of water from the heater's tank to a header, distributing the water to all the tubes of the condenser jacket (annulus) and later collecting it again in an outlet header to return to the tank again. Hence, Terpstra and Van [19] described a different method, in which vapor and the liquid were brought at the collector outlet and the mixture was condensed in auxiliary, tube in tube heat exchanger in the upper part of the system. Radhwan et. al.[20] investigated two R-11 filled integrated solar water heaters for natural and forced convection with horizontal and inclined condenser positions. They observed that for natural convection, inclination of the condenser integrated with the collector frame had a significant effect on the overall efficiency where as not much effect was recorded for forced convection. Heat transfer rate of copper thermosyphon in relation to diameter, working fluid, fill ratio and inclination angle was found by Payakaruk et al.[21]. Although fill ratio had no effect with variation in inclination angle but between 20°-70° angle, working fluid had a significant effect on the heat transfer rate. Hasan et al.[22] studied the performance of a thermosyphon using water as working fluid, by varying the inclination angle and heat input and concluded the wall temperature of the evaporator to be the least for vertical position of thermosyphon and maximum for horizontal position for a specific heat input. With increase in inclination angle, the thermal resistance increase was very slow for an angle of 20˚ from vertical but increased sharply for inclination angle in the range of 20˚ to 30˚ and again increased at an angle of 45˚. With an increase in inclination angle from vertical, the overall heat transfer coefficient (htc) decreased. Nada et al.[23] worked on TPCT flat plate solar collector with shell and tube heat exchanger integrated with the collector frame at the top. The effect on the collector efficiency due to mass flow rate of cooling water, inlet cooling water temperature in transient conditions and the number of thermosyphon tubes as variables was investigated. It was found that the collector efficiency varied significantly and the maximum efficiency of the collector was achieved for an optimum cooling water mass flow rate with optimum number of thermosyphon tubes and was in good agreement with ASHRAE standards. For the same solar intensity, decrease of cooling water mass flow rate, increased the cooling water temperature. The efficiency curve of the tested thermosyphon solar collector with shell and tube heat exchanger had better slope than the thermosyphon solar collector with tube in tube annular heat exchanger for optimum number of thermosyphon tubes. The solar collector under experimentation was simplest in fabrication with less material cost. Further studies and more experiments were required to optimize the solar collector parameters. Experiments were performed by Noie-Baghban[24] for various aspect ratios, heat input and fill ratio. They reported heat transfer rate to be higher at 60% fill ratio than at 90%. A correlation coefficient between the predicted values and the experimental results was also introduced to determine the htc at all fill ratios. Premlatha et al.[25] studied the effect of acetone, methanol and water at different inclination angles on the thermal performance of wickless copper solar heat pipe with no start up problem. For highest solar thermal energy collection, the best working fluid was found to be water among the tested ones. Critical heat transfer rates increased and thermal resistance decreased for various inclination angles. Highest heat transport rate resulted at 45˚ inclination angle. It was advised to prevent high temperature drop in the condenser region by either disturbing or avoiding the formulation of laminar film or by making it as thin as possible by using internal fins or grooves. These results may be useful in design and fabrication of compact solar collector with efficient heat transfer and for proper selection of working fluid. Further, effect on performance due to number of thermosyphon tubes on rise in water temperature, different geometry, fill ratio and optimization of these parameters could be studied. Budihardjo and Morrison[26] experimented with water in glass evacuated solar water heater using optical and heat loss characteristics. The efficiency was reported to be lower than a similar sized flat plate solar water heater to be used for supply of domestic water. Amatachaya and Srimuang[27] studied the effect of aspect ratio on heat transfer rate and concluded that high aspect ratio was responsible for increase in heat transfer due to pool boiling phenomenon. Subramaniam et al.[28] compared the performance of a conventional flat plate solar collector with a zig-zag pattern copper tube header riser system using various geometries and found the performance of the zig-zag system thermosyphon to be better than the conventional type. Redpath[29] and Redpath et al.[30] worked to experimentally investigate the thermosyphon evacuated solar water heater for northern maritime climate and found it to be more effective than other conventional type solar water heaters. Thermosyphon fluid flow and reflective concentrator method was considered by them and an increase of 43% in Nusselt number and 55% in velocity was found due to 100% increase in condenser spacing but heat transfer efficiency was decreased by 9% of the model manifold at the same time. Huge savings in annual energy consumption was proposed provided proper and successful fabrication of such systems could be taken up. Harde et al.[31] studied the effect of coolant rate, inclination angle and nano particle concentration using CuO/water nanofluid as the working fluid on the performance of thermosyphon solar collector. Increase in inclination angle of the solar collector, concentration of nano particles and coolant rate increased the thermal performance. The performance was better with the use of nanofluid instead of water alone as the working fluid.

Closed Loop Thermosyphon (CLT)

Stauder and McDonald[32]experimented to see the boiling phenomenon on two phase thermosyphon loop containing a separator which permitted the liquid to return to the evaporator's bottom such that only steam was condensed in the higher positioned condenser of the loop. Nucleate boiling started due to high degree of superheat (> 13˚C) but after start, the superheat of the wall decreased to approximately 4˚C due to high value of htc of nucleate boiling. Koizumi and Ueda[33] worked on natural circulation, two phase loop to study the dry–out phenomenon and found the circulation flow rate to be mainly responsible for dry out and annular flow space to be the main region of its occurrence. Hirashima et al.[34] studied evaporator flow in a different type of thermosyphon and found heater type, pipe diameter, heat flux and liquid level to be the main parameters affecting the flow. Jiang et al.[35]used a test loop with 3 m riser to simulate the system design and geometry of the primary loop of a 5MW nuclear reactor by studying the thermo hydraulic features of natural circulation considering geysering, flashing and low steam quality density wave oscillations. Geysering and flashing instabilities occurred at start up from atmospheric condition and flashing took place at low operating pressure in long, non heated riser. Control of system pressure and heat flux could have been a possible method to bypass all instability. Wu et al.[36] investigated chaotic oscillations in two phase natural circulation loop and found oscillating behavior of the loop to be affected prominently by power input and inlet sub– cooling. Wang and Pan[37] found the effect of flow restrictions and compressible volume on stability using Taguchi Methods. In the light water reactor hot leg U bend, the natural circulation and flow termination during a small break loss of a coolant accident was considered by Hsu et al.[38] to study the sealing effects of nitrogen–water, two phase system and two phase flow oscillations. Experiments concluded that insufficient hydrostatic head of the down comer side was responsible for natural circulation flow termination. The carry over flow could have been re-established till the two phase level of the hot leg could be increased to the top of the loop. Ohashi et al.[39] studied High Temperature Reactor to reject decay heat by using two phase natural circulation loop. Variation in temperature along the length for water as working fluid for a particular heat input was only 2˚–3˚C but with nitrogen gas this changed to approximately 60˚C. Passive temperature control could have been achieved by properly selecting non condensable gas (NCG) with initial pressure and amount. This heat pipe was termed as "Variable Conductance Heat Pipe" (VCHP) by the researchers. Liu et al.[40] performed experiments on copper pipe, two phase loop of finned tube evaporator of the containment cooling system. To simulate the effect of NCG on the condensation htc between the steam generated in the reactor containment structure and the evaporator, surrounding air/ helium could be inducted into the vessel, during post accidental conditions. Safety reasons and high reliability were the major factors for CLTs to be very useful in cooling of nuclear reactors. CLT was also found to have better heat transfer rate and more uniform wall temperature by

Fumito et al.[41]than single loop thermosyphon. A toroidal thermosyphon was investigated experimentally for heated cooled length ratios, diameter ratio of torus tube, inclination angle and heater length tube diameter ratio by El-Din[42]and concluded reduction in heat transfer rate with increase in heated cooled length ratio and heated length tube diameter ratio whereas increase in torus tube diameter ratio increased the heat transfer rate. Inclination angle between 30°-45° resulted in best performance in terms of heat transfer rate. For Pebble Bed Modular Reactor (PBMR) experiments, reactor cavity cooling system (RCCS) was proposed by Dobson[43]using many numbers of axially symmetrical elements. The heat pipe contained fins, inside the cavity to protect the concrete structure from heat transfer by convection from the reactor vessel through the gap between the pipes, by radiation and also by the heat to be conducted to the pipe. Dobson and Ruppersberg[44] developed a theoretical simulation of a CLT and the experimental work was carried out by Ruppersberg and Dobson[45]for its validation. Start up and transient behavior was studied, for cavity cooling system of PBMR. Although, the experimental results of the temperature were in good agreement with the theoretical model, but the time predicted to achieve the temperature was 50% shorter than for the experimental value which could be due to the theory not being able to determine the rate of heat absorbed by the insulated shrouds and further release to the surroundings. They further concluded the experimental loop to prove the occurrence of oscillating flow. For simulation of the experimental loop, it was found that substantially higher value of correlating htcs were required to be considered than the existing values. Accurate simulation of heating plate, insulating materials and supporting structures were needed for the accurate prediction of heating response time by the theoretical model. Values of surface and material heat transfer properties e.g. emissivity and thermal conductivity were required to be measured accurately. The other objective was to identify shortcomings of experimental model of PBMR concept based reactor cavity cooling system for the proposed physical layout. The measurement of accurate temperature distribution of water, in natural circulation stratifying tank was found to be very difficult. Same difficulty was faced during measurement of heat transfer rate between the heating plate and the fins due to radiation and convection in the space. Liquid carryover measurement during two phase flow from the heated to the cooled legs of the loop was also not possible. Leakage should be avoided due to breakage of seals and due to differential expansion of the pipe and supporting structure. Experimental value of flow rate was considerably different than the theoretical value hence more sensitive transducers should have been used. Theoretical htc correlations were based on natural convection in the air space between the heating plate and the fins, but actually complex convection phenomenon took place due to occurrence of stratification due to higher temperature difference between the top and the bottom ends of the air space and hence large temperature difference along the fins. Loop thermosyphon with a vapor chamber was designed by Jengsooksawat et al.[46] to overcome the limitations of the heat received in the evaporator section due to separated tube construction and heat rejection limitation of the condenser region. A comparison between the conventional absorber and an accelerated absorber of the solar collector was done by Amori and Jabouri[47]under identical conditions at 33°

inclination angle. They found an increase of about 60% in the thermal performance of accelerated absorber system. The temperature of the storage tank was found to be 13°C higher than the traditional absorber. A numerical study with number of connecting pipes, heat flux, inclination angle and length to diameter ratio of the riser as the variable parameters was taken up by Freegah et al.[48].The temperature of the working fluid was found to rise with increase in number of connecting pipes. Although inclination angle did not have much effect but heat flux and length to diameter ratio had significant effect on the performance of the thermosyphon. They further worked[49] to analyze the natural convection phenomenon using CFD on steel thermosyphon with straight and helical tubes for uniform solar heat flux. Helical tube system's working fluid temperature was found to rise more than straight pipe thermosyphon under identical conditions. The increase in number of helical pipes had negligible effect on the temperature of the fluid inside the condenser. For electrical component cooling, CLT was constructed to investigate the cooling efficiency for different volumes of working fluid and condenser ambient temperature at different heat inputs by Nemec et al.[50]and found an increase in the condenser temperature with decrease in the cooling efficiency due to rise in the outlet temperature.

Applications of Conventional Heat Pipes

Heat Pipe Heat Exchangers (HPHE)

In tropical hot and humid environment, the dehumidification capacity of an air conditioner can be increased by the application of heat pipe. The relative humidity decreases by almost 10% due to improvement in indoor air quality and reduced power requirement. Saman[51]experimented with thermosyphons to achieve better heat recovery and indirect evaporative cooling. Spraying was used to achieve evaporator cooling on the condenser section of the thermosyphon array. Inclination angle, initial temperature of the primary stream, flow ratio of the two streams and wetting arrangement of the condenser were the control parameters. The results confirmed the effectiveness of the use of thermosyphons as the fresh air temperature was reduced by many degrees than using dry air alone. The modeling of warm and cold gas streams of moist air of the evaporator and condenser section of the thermosyphon HPHE (THPHE) was done by Wu et al.[52] and latent heat factor was found to be an important parameter and if included, could increase the accuracy substantially. Than et al.[53] and Than and Ong[54] compared the results of water based HPHE using ε-NTU method and concluded the effectiveness to increase by 30% with increase in number of rows. It also increased by 10–20% with number of rows changing from 4 to 6. 2*2 row arrays had increased effectiveness over 4 rows HPHE at flow rate ratio more than unity. Zhang and Niu[55] studied the annual performance of membrane based energy recovery ventilator(MERV) in terms of power consumption. It was found that with use of MERV, annual energy saved was almost 58% of the energy that was required for cooling and heating fresh air, while SERV(sensible only energy recovery ventilator) saved only 10% of it. Niu et al.[56] studied the use of HVAC system by combining chilled ceiling with desiccant cooling for comfort indoor air humidity. It was concluded that only 44% of the primary energy was used in comparison to the energy previously required for conventional constant volume air system. Balanced and unbalanced types of thermosyphon heat exchangers(THEs) with water and R123 as the working fluids were investigated by Wangnipparnto et al.[57] for the analysis with and without electro hydrodynamics phenomenon. Heat transfer rate prediction using numerical analysis was in good agreement with the experimental values for balanced HPHE. For unbalanced THE the performance increased with increase in the ratio of mass flow rates of evaporator and condenser with application of electro hydrodynamics. Zhang et al.[58]experimented with an air moisture removal system using membrane based total heat exchanger for annual energy estimate and found 33% of energy savings by independent air moisture removal. To reduce the risk of water condensation on chilled panels, performance testing was done by Zhao et al.[59] with a new design of heat pipe humidifier. Decrease in energy saving ratio was concluded with increase in relative humidity (RH), dew point temperature (dpt) and air quantity. Energy saving ratio ranged from 11.81% to 30.34% in comparison to normal dehumidifier. An increase in surface cooling power and dehumidification capacity was also registered. Noie[60] worked on 6 rows of 90 thermosyphons to investigate the performance considering air velocity and inlet temperature as the variables. ε–NTU method was used and a computer code was developed to analyze THE for variables as evaporator temperature, forced convection and heat input. The overall effectiveness varied between 37% and 65% and it was also concluded that equal air face velocities of the evaporator and condenser should be avoided. To find the effect of dpt, RH and air velocity for tropical building HVAC systems, Yau[61]studied 8 row thermosyphon HPHE in which the evaporator functioned as pre cooler and the condenser as reheating coils. It was concluded that for dehumidification enhancement HPHE should be used to improve the latent cooling ability of conventional cooling coil. Effectiveness and heat transfer rate were found to increase considerably by various researchers with increase in fresh air inlet temperature for horizontal and vertical HPHE for recommended energy savings in AC systems even for high air change requirement. Recovery of heat energy has become synonymous with energy conservation in today's world for sustainable development. The significant ways of reduction of CO_2 generation, primary energy requirement and cost are by utilizing the heat of exhaust of any process. Dobson and Pakkies[62]used R134a in a TPCT with fins as a heat recovery medium in air to air heat exchanger for a milk spray drier, to reduce the total energy requirement and hence the cost of the unit. Preheating of the incoming air stream was done by the heat recovered from the hot exhaust air and a mathematical model was developed. They concluded that total energy requirement of the milk spray drier could be recovered by 26.5%. Correlations for htc, maximum heat transfer rate, optimum evaporator and condenser length ratio, airside pressure drop and mass transfer were developed. Proper insulation could have further reduced the heat loss to the surroundings. Imperfection in design of filters could have resulted in milk particles to be present in the waste air stream. Fouling of air side fins was possible due to high dpt of the moist waste stream of air and its condensation. Accurate design of heat exchanger was desirable with periodic maintenance procedures. To ensure the feasibility of HPHE in real condition, it was recommended to design and fabricate a test heat exchanger. Noie et al.[63] worked on simulation of Cu-H_2O, finned THE for recovery of heat from the exhaust of a boiler by utilizing it to preheat the inlet air to the boiler. They found substantial savings of fuel with around 3% increase in boiler efficiency and reduction in annual CO_2 production with a payback period of 1.6 yrs. Energy recovery of 100kW was also achieved. Simulation proved that the system worked very well with an average thermal effectiveness of about 40%. Further research was still required on simulation and performance of THEs. Heat from the moist waste air stream of the mini drier was recovered to preheat the fresh air by Meyer and Dobson[64] by designing and fabricating a THPHE with R134a as the working fluid to achieve substantial energy savings and reasonable return on investment(ROI). Ong [65] conducted experiments on R 134a filled copper THPHE and water filled Loop HPHE(LHPHE). In THPHE, the temperature of the hot air duct was varied where as condenser air temperature was maintained. Individual thermosyphons were connected at the top and bottom separately by common headers. Evaporator was situated at the bottom than the condenser. In LHPHE, square wavy aluminum fins on both the evaporator and condenser sections were used. Condenser and evaporator velocities and inlet temperature of evaporator were varied considering the ambient temperature as the condenser temperature. Heat transfer rate was found to increase with increase in flow velocity and evaporator inlet temperature. Higher evaporator inlet temperature achieved higher overall effectiveness. Range of overall effectiveness of THPHE was from 0.8 to 0.5 where as for LHPHE it was from 0.9 to 0.3. Number of tube rows was needed to be decided according to evaporator inlet temperature for effective utilization of all tubes. For same air velocity, at the condenser and evaporator sections, overall effectiveness was found to be the least. Mozumder et.al.[66] conducted experiments on characteristics of heat transfer and its correlation, for finned, forced convection, different fill ratios and acetone, methanol and water as working fluids in miniature heat pipe in PCs and electronic devices. For the given heat input, axial temperature gradient was found to be the least for acetone as the working fluid. For higher fill ratios, heat transfer also increased and the optimum fill ratio proved to be 85% for maximum heat flux. Rate of increase of htc with evaporator and condenser temperature was maximum for acetone and for dry run condition.($htc_{acetone} > htc_{methanol} > htc_{water}$). A correlation for htc was proposed with evaporator temperature, saturation temperature, latent heat and fill ratio as the variables. Modeling of thermal performance of air to air THE was done by solving simultaneous principles equations and effect of number of rows of THE was also investigated theoretically by Emami[67]. Hughes et al.[68] worked using CFD, to numerically investigate the achievable heat transfer rates in HPHE used for energy recovery from ventilation air streams in building sectors. Optimum column pitch and its effect on overall heat transfer rate were also found by working on different sizes of vertical heights of heat pipe. Considerable reduction in energy consumption in HVAC sector for pre cooling and heat recovery was also reported. For transporting low potential heat, design, size of condenser section and amount of working fluid were concluded to be significant parameters of ammonia gravitational HPHE by Vantuch and Malcho.[69]

Miniature Heat Pipe (mHP)

Miniature heat pipes came into existence in Soviet Union with the design and manufacturing in Belarus and became very effective for electronic cooling and for refrigerating machines. Ma and Peterson[70] derived an equation for the minimum meniscus radius and maximum capillary heat transport limit for micro heat pipe using momentum conservation and Laplace Young equations considering contact angle effects, vapor pressure drop, tilt angle, groove dimension, channel angle effects and shear stresses at liquid solid and liquid vapor interface as the variable parameters. Peterson and Ma[71] also developed a mathematical model for prediction of heat transport and temperature gradients contributing to the overall axial temperature drop as function of heat transfer in micro heat pipe. Cilt and Say[72] found heat pipe with fins to be a very good proposition by achieving a temperature of 35˚C in the cooling region which was around 90˚C without cooling and also due to being self reliable with no moving parts, no mechanical problems and with a very high performance for cooling of PC's CPU. Prototype using fan was developed and cost analysis was also done. Cylindrical and flat copper heat pipes characteristics were predicted and software was developed by Maziuk et al.[73] for water, methanol and propane working fluids. Experiments were done by Vasilev et al.[74] using copper sintered powder wick for maximum heat transfer rate of 50 W. The capillary limit and the boiling limit were decided by axial temperature distribution with maximum heat transfer rate plot with respect to (w.r.t.) working fluid temperature. Results were verified with the predicted numerical values with +- 10% accuracy. In NASA Glen Research centre, micro loop heat pipe with silicon as container material and wick structure was developed using silicon evaporator to permit less thermal interface resistance between the heat generated source, the working fluid and the computer chip junction. This heat pipe was used for electronic cooling at the chip level. Sreenivasa et al.[75] concluded the performance of mHP to be the same at half fill ratio of the evaporator as that of the full fill ratio. Mahmood[76] experimented with water filled mHP with 5 different cross sections and 3 inclination angles but for same hydraulic diameter and concluded the best performance for htc to be at 90º inclination. Empirical correlation was also developed and the calculated values were found to be in good agreement with the experimental values. Sintered wick with copper powder of 140-170µm was found to have low manufacturing cost and high thermal performance at 900°C-950ºC and at 30-60 minute sintering time by Li et al.[77,78] in mHP. Capillary wicks with 90% Ni and 10% Cu were fabricated by Xin et al.[79] by cold pressing sintering method for mHP to analyse the performance. Hossain et al.[80] studied the heat transfer characteristics of copper micro heat pipe for heat input, inclination angle and coolant flow rate as variables. They found the coolant flow rate to have very insignificant effect on wall temperature and thermal resistance. Optimum values of htc were achieved for an inclination of 70º. Nemec et al.[81] worked with heat pipes with wick to determine the thermal performance of heat pipes for different wick structures, with various mesh sizes and various inclination angles. The first active nucleation sites were predicted to be larger than the consecutive ones by Lorenz et al.[82] while studying the effect of surface conditions on boiling characteristics in mHP. Iqbal and Akhanda[83] compared two metal mHP(TMMHP) of square cross section of copper and silver using different working fluids and at different inclination angles with identical single metal mHP(SMMHP) of copper only and found the performance of TMMHP to be multiple times higher than that of SMMHP in terms of heat transfer capacity. Design and fabrication of copper powder sintered wick was taken up by Jiang et al.[84]for cylindrical mHP. Optimization of structure parameters and its sintering process was done to enhance the thermal performance. Four step sintering procedure was also proposed for fabrication of mHP. A numerical model to perform the transient analysis for fluid flow and heat transfer on a micro flat heat pipe using hybrid wick was introduced by Famouri et al.[85] in which they implied finite volume method, implicit approach, under relaxation approach, delay method and kinetic theory to address 2D, unsteady N-S equations, time gradient terms, convergence, density of vapor core and condensation/evaporation at the interface respectively. To track the end of evaporation and beginning of condensation, transformation point and transformation line procedure was also introduced for the first time ever.

Heat Pipes with Different Working Fluids:

Different Working Fluids

Kenney and Feldman[86] performed life tests on thermosyphons with SS, carbon steel and black iron as container materials and Dowtherm A as the working fluid and found that at temperatures less than 300˚C, it worked for indefinite life time, whereas at 400˚C, the performance was satisfactory for about 1200 hours. However, thermal performance data was not reported. Most of the researchers, worked with large diameter of heat pipe due to applications in large heat exchangers in heat recovery systems. Compact heat exchangers were required in automotive heat recovery and hence small thermosyphons with small diameter were also the requirement. As the availability, environmentally neutral properties, cost, non toxicity and Figure of Merit (FOM) of water are high, in comparison to other engineering fluids hence it is considered to be a preferable working fluid for thermosyphons and heat pipes. Due to toxic and non – eco friendly behavior, freons like R-11, R-12, R-22, R-113 have been replaced by R -134a and 3M Flourinert liquids. Abou Ziyan et al.[87] and Ong and Haider-E-Alahi[88] investigated the use of R134a in thermosyphon and FC-72 was studied by Park et al.[89] for high power semiconductors. Ristoiu et al.[90] worked for different fill ratio and inclination angle on water, acetone and ethanol working fluids to find heat transfer and fluid flow characteristics of a thermosyphon and concluded critical heat transfer rate to be higher and thermal resistance to be lower for a range of inclination angles in comparison to vertical position. FCs for small thermosyphons were not studied earlier till it was considered by Jouhara and Robinson.[91] Overfill evaporator with Flourinert liquids had been in their study to ensure pool boiling conditions. The results concluded that for evaporator section, available correlations of htcs for pool boiling and combined pool boiling thin film evaporation were in good agreement with the experimental values. For condenser region, the Nusselt theory of film wise condensation over predicted the measured data at low heat input, which improved with increase in heat input. Hashimoto and Kaminaga correlation was in very good agreement for condenser section at low heat input. For very low heat input, FC-84 was the only working fluid to outperform water. Above 40W, water proved to be the best working fluid of all, due to entrainment limit of FC fluids. FC-84 and FC-77 had satisfactory performance below 40W in spite of being dielectric. They[92] further analyzed the performance of High Grade SS thermosyphons in the medium temperature range of 200˚C–450˚C for Therminol VP1 and Dowtherm A working fluids. The findings revealed that in the operating temperature range, both the working fluids had significantly low vapor pressure than water. Till 420˚C, thermal resistance of less than 0.4 K/W was achieved with effective thermal conductivity of 20 kW/mK. Rohsenow's pool boiling correlation was in good agreement even for the small diameter thermosyphon. Boiling htc in the evaporator section was mainly responsible for the increasing values of total thermal resistance with decreased power ratings. Still, in heat recovery applications, for medium temperature range of 200˚C–450˚C, no working fluid with good toxicity and environmental properties are available. So, heat pipes (with and without wick) are still under developed in this temperature range. Continuing their studies, they further[93]experimented with dielectric heat transfer liquids such as FC-84, FC-77, FC-3283 with boiling point in the range of 80˚C–120˚C and water as the working fluids in water cooled copper thermosyphon to confirm only pool boiling and combined pool and thin film boiling conditions. For predicting htc of evaporator section, liquid pool boiling correlations by Rohsenow[94], Kutateledze[95] and Shiraishi et al.[96] were used with fair degree of accuracy. For high heat fluxes, El–Gank and Saber's[97] correlation provided satisfactory results where as for low heat fluxes Nusselt's falling film theory worked well. For low Reynold's Number in condenser section, Nusselt's correlation for film wise condensation was used to predict htc. For variable fill ratio and inclination angle, the performance of the thermosyphon was observed by Ong[98] for R134a and R410a working fluids. The overall thermal resistance was found to be of the same order ($0.06 W/m^2K$) for both the working fluids. Such experiments were continued further by Ong et al.[99] for R410a and water for various heat inputs, inclination angles and fill ratios and it was found that at high inclinations, low fill ratio and high heat input, the evaporator temperature was not uniform. Kannan et al. [100,101] worked to investigate the thermal performance and maximum heat transport capacity of two phase thermosyphon using water, methanol, acetone and ethanol as the working fluids by varying fill ratio, inner diameter, heat input and operating temperature. The maximum heat transport capacity of water was found to be the best in all the cases. Increase in operating temperature increased the heat transport capacity.

Binary Fluids

The transport properties of working fluid put a limit on the heat transport capacity of any heat pipe. The addition of additives in working fluid, change the flow features and increase the heat transport properties. The performance can further be increased by use of rewetting fluids. In conventional heat pipes, the surface tension gradient is negative w.r.t. temperature which reduces the heat transport from the evaporator to the condenser region. Self rewetting fluids(SRWF) are fluids of dilute aqueous solutions having a small amount of long chain alcohols ~ 10^{-3} mole/lit, having carbon atoms more than four to change the surface tension properties of water without any other property variation. Surface tension is a major factor for capillary limit along with boiling, condenser, sonic, entrainment and viscous limits. With increase in temperature, the surface tension usually decreases with the liquid moving towards cooler condenser region. This effect is known as "Marangoni Effect" which can have a negative impact on heat transfer capacity. The wetting of surface of heated wall of the heat pipe, by the working fluid is the most important aspect for high heating loads without reaching the boiling limit of the evaporator or else evaporator priming may happen. In axially grooved gas loaded VCHP this phenomenon was observed by Eninger and Marcus[102] where large surface tension gradients induced a surface flow towards condenser region accompanied by a sub surface flow of equal magnitude but in opposite direction in the groove. Marangoni Effect is the negative surface gradient that reduces the critical temperature difference between the condenser and the evaporator and increases the evaporator temperature. Heat pipe geometry and percentage composition of any two working fluids e.g. ethanol and water in binary fluid form greatly affected the performance, as was investigated by Tien[103] and Tien and Rohani[104]. Startup characteristics of heat pipe using binary fluids were analyzed by Brommer[105]. He lowered the freezing point of pure fluid by adding appropriate liquid such as methanol in water for low temperature range of boiling point. Kuramae and Suzuki[106], Kuramae[107,108] was the first researcher to take into account the benefit of Marangoni Effect. They studied the rewetting problem of the evaporator using ethanol – water binary fluid in thermosyphons, where ethanol induced a Marangoni flow being more volatile than water, for the evaporator liquid supply. Kiatsiriroat et al.[109] worked on SS304 thermosyphon with 50% fill ratio and used binary fluids i.e. ethanol–water and Tri Ethelene Glycol(TEG)–water to investigate the thermal performance due to varying mixture ratio, pipe diameter and working temperature. For low working temperature i.e. less than 80˚C, ethanol–water mixture was used, where as for temperature more than 200˚C, water-TEG mixture was proposed, presuming that addition of TEG will probably increase the safe working limiting temperature of dry out limit. The conclusions were that for ethanol–water, flooding resulted at high temperature due to interaction between the counter current liquid and the vapor flow at vapor liquid interface. More amount of water in the mixture of ethanol–water resulted in more latent heat of vaporization, which was the reason of flooding limit at high temperature. At low working temperatures, thermal resistance was high for ethanol–water mixture due to low vapor generation of water. Binary fluids improved the performance of thermosyphons. Lesser amount of TEG in TEG-water mixture resulted in increase in heat transfer rate but with 25% TEG, the heat transfer rate was slightly reduced. Htcs were predicted using Rohsenow's and Nusselt's correlation for evaporator and condenser respectively for pure fluids. For mixtures, the weighted average of heat transfer of each component was used for total htc prediction. Faghri's equation to calculate the critical heat flux (CHF) due to flooding limit was used for pure fluids and for mixture of ethanol–water. Zhang[110] used very dilute long chain alcohol aqueous solutions of ethanol to find a non linear relationship of surface tension with temperature and positive gradient with rise in temperature for different concentrations and different temperatures. For controlling the temperature of electric device, binary fluid was more advantageous than loaded VCHP, as examined by Kadoguchi et al.[111]. Yoshoyuki[112] analyzed the heat transfer characteristics of SRWF and found that during boiling, Marangoni Effect resulted in strong inflow at the nucleation sites. For terrestrial applications and space heat pipes for normal and under gravity conditions Savino et al.[113] proposed SRWF for thin flat heat pipe and tubular heat pipe. Senthilkumar[114,115] used water cooled copper heat pipe with wrapped screen SS wick and n-butanol, n-pentanol aqueous solutions and water as the working fluids, to investigate the performance of heat pipe for variable heat input, inclination angle and flow rate. The findings were that thermal efficiency increased till a certain temperature due to improvement in surface tension of the working fluid. This temperature was dependent on surface tension, temperature gradient, type and concentration of long chain alcohol in water. SRWF were found to have higher thermal efficiency, lower thermal resistance and higher stability than pure water as the working fluid. n-pentanol had better performance due to better surface tension characteristics than n-butanol. Experiments were performed using SRWF of heptanol aqueous solution and DI water as working fluids in copper micro oscillating heat pipes(MOHPs) in horizontal and vertical positions by Yanxin et al.[116] to understand the heat transfer enhancement mechanism. The heat transfer process was found to be better to prevent the dry out with rise in temperature due to increase in surface tension. Circulation efficiency of SRWF was better than that of DI water due to lower capillary resistance. Better thermal performance of SRWF was achieved due to lower thermal resistance than DI water in horizontal position than the vertical one. Heat transfer enhancement effect was obvious in vertical orientation only with small inner diameter MOHPs.

Nanofluids

Nanoparticles are extremely fine particles of less than 50 nm size. Presence of these particles in the base fluid in dispersed mixture form constitutes a nanofluid. This term was first used by Choi et al.[117]. Usually, metals like Ag, Au, Ti, Si, Cu, Ni, Al, Diamond etc., oxides of these metals and some compounds like SiC,$CaCO_3$, graphene etc. are the nanoparticles and water, ethylene glycol, propylene glycol, engine oil etc. are the base fluids. The heat transfer characteristics were improved due to change in thermal properties behavior in comparison to the base fluid. The effective thermal conductivity increased by almost 20% or more even with a low concentration of less than 1% by volume, than the base fluid. This was mainly due to variation in particle shape, size, concentration and thermal properties of base fluid. Xuan and Li[118] discussed nanofluids to have thermal conductivity, convective heat transfer characteristics, homogeneity and long term stability far better than the base fluids. High thermal conductivity of nanofluids is of high importance for various heat transfer applications. Das et al.[119] reported behavior of heat transfer deterioration and surface fouling with Al_2O_3 nanofluids. Tsai et al.[120] worked with Au nanofluid and found significant decrease in thermal resistance with same volume concentration as compared to distilled water. Bang and Chang[121] found a decrease in pool boiling heat transfer for Al_2O_3 nanofluids for up to 4% volume concentration. Jackson and Bryan[122] worked with Au nanofluids on a copper block and Kim et al.[123] studied the behavior of ZrO_2, SiO_2 along with Al_2O_3 nanofluids. All the researchers found decrease in heat transfer due to substantial amount of nanoparticle deposition on the heating surface and reduction of bubble contact angle in specific range of experimental conditions. ZrO_2 nanofluid on copper block was tested by Chopkar et al.[124] with nucleate pool boiling and findings suggested that heat transfer was better at low volume and deteriorated with improvement in volume concentration. Surfactant addition resulted in enormous decrease in nucleate pool boiling heat transfer. Nano particle deposition was also found on heating surface. For various surface finishes of a vertical tube Narayan et al.[125] experimented with Al_2O_3 nanofluids and defined a "surface interaction parameter" for surface roughness. Boiling heat transfer was found to decrease with interaction parameter less than or near to unity and increased for a value greater than 1. It was also concluded that particles of size, same as that of nucleation sites could block the nucleation cavities and these were the cause of decrease in heat transfer. Moreover, surface conditions could control either improvement or degradation in heat transfer. To predict and analyze the flow behavior in thermosyphons using nano fluids, numerical and experimental analysis were done by Naphon et al.[126] to find the effect of variation in inclination angle, nano particle volume concentration and fill ratio on the thermal efficiency of the thermosyphon. Kang et al.[127] worked with Ag and Au nano particles and reported improvement in heat transfer due to change in thermal resistance in grooved heat pipe. To find the effect of variables such as inner diameter, fill ratio, working temperature and aspect ratio on heat transfer characteristics, Paramatthanuwat et al.[128] used silver nano fluid and pure water in a TPCT of copper with water jacketing in vertical orientation. They concluded heat transfer rate to be affected by working temperature and also found heat transfer rate of silver nano fluids to be better than that of pure water for all fill ratios. The heat capacity of working fluid could be increased by the suspension of nano particles. Shafahi et al.[129,130] worked with Al_2O_3, CuO and TiO_2 nanofluids for flat and cylindrical heat pipe with thermal conductivity, viscosity and density as the variable parameters but could not compare the results of analytical and experimental values of thermal enhancement. Han and Rhi[131] studied pure water, acetone and Ag, Al_2O_3 aqueous solutions, Ag+Al_2O_3 hybrid nanofluids, acetone and pure water for grooved wick structure SS heat pipe for various volume concentrations, orientations and fill ratios and concluded that with increase in nano particle concentration, the thermal resistance also increased. Hybrid nanoparticles worsened the performance of the system in terms of thermal resistance. At lower inclination angle the performance was better than that at the vertical position. The thermal resistance of pure water was lower than the nanofluid and hybrid fluid system. Post nanofluid performance of grooved heat pipe, was similar to that of the nanofluid system. Hybrid nanofluids were less effective than pure nanoparticles. Surface deposition shapes of the inside surface of evaporator section, adiabatic section and condenser section were responsible for different working phenomenon in nanofluids. All the above results concluded that nanofluids might not always be helpful for effective heat transfer for high energy density devices.

Sato et al.[132] investigated thermal performance of aqueous 1 butanol solution with chemically synthesized PVP capped silver nanofluids and found the dry out limit to be larger than water due to accelerated positive surface tension dependencies of nanofluid. Most of the work in nanofluids was carried out mainly on measurement, estimation, enhancement and improvement of thermal conductivity where as very few researchers have worked on viscosity which is a very important parameter in thermal applications. Viscosity of Al_2O_3, SiO_2 and TiO_2 was measured by Masuda et al.[133]. Pak & Cho[134] established the effect of temperature, volume concentration, particle shape and size on viscosity. Effect of volume fraction for Al_2O_3 and TiO_2 with deionized water was studied by Murshed et al.[135] and increase in viscosity with volume concentration was found. Effect of different volume fractions and different particle size on viscosity for TiO_2 with distilled water nanofluid was investigated by He et al.[136] and increase in viscosity with increase in particle size was reported. However, some other researchers have found contradictory results i.e. decrease in viscosity with increase in particle size in nanofluid heat pipes. The thermal characteristics of Al_2O_3/ water nanofluids were enhanced by addition of small amount of ground MWCNT (multi walled carbon nano tubes) without deteriorating the stability of nano particles. This was the outcome of the experiments conducted by Nine et al.[137] for a stable hybrid nanofluid. They further worked[138] on ultrasonic action effect on Al_2O_3/water dispersion and found particles to be agglomerated and dispersed. Quick sedimentation also occurred due to insufficient ultrasonication. Evaporator temperature is one of the main factors for pressure fluctuations and heat transfer is dependent on pressure disturbances in OHP as was found by Tanshen et al.[139] while investigating MWCNTs/water nanofluids pressure characteristics. In continuation to this, they further worked[140] to determine the effective thermal performance of OHP charged with aqueous Al_2O_3 solution and MWCNT/Al_2O_3. Thermal characteristics were highly dependent on pressure fluctuations per unit time. Highest fluctuation frequency, lowest thermal resistance and pressure distribution was achieved at 60% fill ratio for a small inclination of MWCNT in aqueous Al_2O_3. Heat input was also one of the deciding factors of pressure frequency.

Phase Change Materials (PCM)

PCM are substances having low melting temperature and solidification apart from having high heat of fusion and high thermal conductivity. These can be inorganic or organic salts such as zinc nitrate hexa hydrate, lithium nitrate hexa hydrate etc. Inorganic materials are salt hydrates with non flammability and high latent heat but corrosiveness, improper solidification, instability and super cooling tendency are some of its drawbacks. Organic PCM e.g. paraffin, propyl palmitate, butyl stearate etc. melt congruently and are more stable chemically with super cooling and do not pose a very high problem than inorganic PCM but high initial cost, flammability and more air pollution during combustion are some of the disadvantages. Free cooling can replace air conditioning. Farid et al.[141] studied the effect on reduction in hydration due to cooling of inorganic PCM and found a decrease in the storage density. Some PCM salts were studied and were found to be effective as thermal energy storage substances. The crystallization temperature of these salts is between 30˚C to 50˚C.

Thermal properties of manganese nitrate hexa hydrate was analyzed by Nagano et al.[142] using Differential Scanning Calorimeter(DSC) and it was concluded that this PCM due to its high density, non flammability and non toxic characteristics can be a suitable substance for thermal energy storage of cooling system. Arkar and Medved[143] found that mass of PCM, air volume flow rate and aspect ratio influence the latent heat thermal energy storage where as melting point of the PCM affects the thermal response and efficiency of the free cooling system. Effect of thermal cycling and reliability on melting temperature and latent heat of fusion of calcium chloride hexa hydrate was studied by Tyagi and Buddhi[144] using DSC. During thermal cycling, slight variations in latent heat of fusion were noted but melting point was stable and so it could be used as PCM for heating/cooling applications. Futane et al.[145] worked on copper methanol heat pipe with SS mesh wick structure and the PCM selected were zinc nitrate hexa hydrate, sodium sulphate deca hydrate and sodium carbonate deca hydrate with low melting points due to its high heat of fusion, high thermal conductivity, high density and stability. In the experiment, a fan was used for forced convection of air over the exposed end of heat pipe where as the other end was connected to PCM storage module. Warm air of the room was cooled by PCM during the day where as the cold air of the outside flew over the heat pipes to extract heat from the PCM during the night time. The cycle repeated on daily basis. PCM was blended with refrigerant and was used as a working fluid in a thermosyphon in an automotive evaporator designed by Delphi Thermal Systems to achieve the optimized temperature of the vehicle cabin best for the human comfort during the stop/idle position of the engine. Use and performance of PCM (paraffin) evaporator of mobile A/C and design aspects of thermosyphon based PCM cold storage evaporator were explained in detail by Kowsky et al.[146]. Paraffin, due to its compatibility with evaporator material, high heat of fusion, chemical stability and recyclable property, was chosen as the best PCM. PCM in the evaporator of automotive A/C maintains the temperature of the cabin even when the engine is idle and thus adds to the decrease in emission and increase in fuel economy which is a unique feature of Delphi design.

Heat Pipes with Surface Enhancement

Nowel et al.[147] studied micro configured heat sink etched in silicon with vertical orientation. Webb et al.[148] used surface enhancement structures on the evaporator and condenser both, for cooling hot side of thermoelectric coolers. Heat flux dissipation of around180 kW/cm^2 for R134a as the working fluid, was obtained for bent fin structure. Katoo et al.[149] used saturated distilled water as the working fluid and determined the effect of use of a plate parallel to the boiling surface at a very small gap. Degradation in heat transfer performance was noted with reduction in vapor space. The effect of working fluids and evaporator geometry using plain surface, integrated rectangular finned surface and integrated cross finned surfaces was studied by Ahmed[150] to study the boiling heat transfer. Zhang et al.[151] investigated the thermal performance of flat TPCT to observe boiling and condensation heat transfer in transparent thermosyphon using grooved surface on the evaporator. A very good performance regarding temperature leveling on the condensation surface was noted by them. Non uniformity of the temperature distribution on condenser surface was observed with decrease in air velocity. Water as a working fluid reflected better performance than ethanol for same testing range of heat flux. Grooved evaporator surface had much better performance than the plane surface and boiling heat transfer was increased. It was important to ensure the working fluid to be in the completely boiling state at the evaporator surface thereby increasing the boiling heat transfer which proved to be the most efficient way of improving the performance. It was also concluded that two phase thermosyphon should be applied for high heating powers and large base sections of heat rejection. Small plate thickness resulted in better performance. Chang et al.[152] studied the effect of type of evaporator surface, fill ratio and heat input on the thermal performance of TPCLT for electronic cooling using a rising tube, falling tube, an evaporator and a condenser in its loop with water as the working fluid. Thermal resistance was found to be decreased significantly with increase in heat input and decrease in fill ratio. Grooved surface reduced the thermal resistance of the evaporator by 15.5% in comparison to the smooth surface. Rohsenow's correlation and analysis model of Nusselt was in good agreement with the experimental results with a deviation of 12%. Influence of working fluid Vs evaporator surface for pool boiling C_{sf} was found to be lowest for grooved surface reflecting that pool boiling effect was at its best for reducing the thermal resistance of the evaporator. The performance of TPCLT was dominated by unsteady state condition due to intermittent boiling at high fill ratio. New correlations were developed for evaporator and condenser thermal resistance and were in good agreement with previous ones. Temperature oscillations were observed for smooth surface of evaporator for heat input of 60-80W and for 47% fill ratio. To study the effect of surface enhancement of evaporator on the performance Akhanda and Mahmood[153] designed, manufactured and tested a TPCLT consisting of an evaporator with enhancement structure, vapor rising tube, condenser and condensate return tube. Acetone, ethanol and methanol working fluids with surface enhancement structures of smooth surface (SS), semicircular ribbed surface (SCRS), triangular ribbed surface (TRS) and saw tooth ribbed surface(STRS) were used. Tsai et al.[154] investigated the performance of Cu-H_2O TPCT combined with vapor chamber formed evaporator for different fill ratio, heat input and for grooved, etched and sintered surfaces as evaporator surface enhancement structure for electronic cooling. Balayanan et al.[155] worked on seamless pure copper - glycol heat pipes with 60% fill ratio, to determine the performance using "Response Surface Methodology" of water - air THPHE theoretically and experimentally by variation in heat input, water temperature and air velocity and developed a correlation based on these parameters. Three factor, five level, central composite rotatable design with full replication technique was used for experimentation. SYSTAT software was used to optimize the operating parameters. For desired effectiveness, second order quadratic model was suggested by them and was used to predict the process parameters for optimal range. The main effects and interaction effects of the various combinations of the parameters/variables involved in the process could be predicted by Central Composite Design. Theoretically predicted effectiveness was in good agreement with the experimental one, within 95% confidence level limits. Maximum effectiveness was achieved as 0.98 for constant air velocity and water temperatures and variable heat input. Solomon[156] could increase heat rejection by achieving gradient wettability by internal coating of TPCT with nanoparticles. The contact angle was changed from low to high, from evaporator to condenser section due to gradient wettability and this resulted in increase in the maximum heat supplied to the thermosyphon. Solomon et al.[157] further continued their experimentation on TPCT of an aluminum pipe and modified the inner surface of the pipe to a porous structure by anodization which reduced the thermal resistance of the evaporator section to a great extent. Hsu et al.[158] coated the evaporator section of a copper TPCT with silica nanoparticles to achieve the superhydrophilic effect and the condenser region with trichloro silane to get the superhydrophobic effect to vary the wettability of the surface. This kind of arrangement resulted in the surface enhancement of the TPCT to perform at its best. It was also observed that the thermal efficiency of the evaporator region increased due to increase in the wettability of the surface where as thermal efficiency decreased due to increase in wettable surface of the condenser region.

Non Conventional Heat Pipes:

Loop Heat Pipe (LHP)

Loop heat pipe consists of capillary evaporator region, condenser region, compensation chamber also known as two phase reservoir and liquid and vapor lines. Two phase reservoir is an additional part to maintain the saturation temperature and pressure and also the accurate amount of working fluid in the device. Loop Heat Pipes are mainly used in thermal control of spacecrafts, satellites etc. Garcia et al.[159] developed a mathematical model for laminar, 2-phase, 1D flow for vapor and quasi 1D flow for liquid under steady state condition in the capillary structure. The longitudinal distribution of mass flow rate, liquid vapor interface curvature radius, maximum heat transfer capacity and capillary pressure relationship were analyzed. The experimental results were compared with the developed model. Coiled LHP of glass and stainless steel with small diameter were used to study the heat transfer characteristics and flow patterns by Jie et al.[160] for different fill ratio and heat flux. The results indicated that thin liquid film of the evaporator, secondary flow, and the disturbance due to pulsation increased heat transfer rate and CHF to a significant amount. Riehl et.al.[161] proposed a LHP experiment for testing for space application purposes at the international space station (ISS) as a part of Brazilian space program in microgravity atmosphere. For experiments, SS316 container material with anhydrous ammonia working fluid was proposed. Readings were observed in a period of 9 months aboard ISS and on Earth stations, with and without controlling two phase reservoir’s temperature on heat load profile cycles. Start up and steady state tests were also conducted. For further experimentations, three proposals were made which were, to develop and construct a device for stable power supply for the specific control algorithms and computer code for interaction between the ISS and the ground for satisfactory operation of LHP, a heat flux sensing device for determination of radiant heat flux, reaching on the radiator from Sun and Earth and a device for the documentation of all the results. It was also proposed to develop 3 LHP's – one for the ground test and two identical for undergoing tests at ISS and for ground flight test model. In continuation with the above work Riehl[162] worked to decide the various parameters that were required to be considered for the performance and acceptance tests of HPs and LHPs. Although the tests were specific for specific applications, but for the same application, sample testing was done. The performance tests were carried out for a particular inclination angle. For Acceptance test, heat supply, heat rejection, temperature and inclination angle were taken as variables. Visual inspection was done to check for any cracks less than 0.5 mm. and mass conservation was also checked and verified for leakages. Heat Pipe was accepted, only if the consecutive thermocouple of condenser region depicted any variation less than 1˚C and entire temperature variation was of the order of 5˚ C from the evaporator to the condenser region. After passing the acceptance test, it was further put in the honeycomb panel and tested for no effect of gravity forces by placing it in horizontal position. Chen et al.[163] experimented on miniature LHP for different heat rejection temperatures. The steady state conditions were similar for all the positions except for the position where the evaporator was above the condenser. Transient behavior was also studied in detail by them. Bai et al.[164] developed a mathematical model under steady state condition for LHP to predict the effect of decrease in length of two phase condenser region under the constant conductance mode due to the expansion of liquid in compensation chamber and it was found to be in good agreement with the experimental results. Tang et al.[165] worked on a different structure of mini LHP to analyze the performance containing four different parts as evaporator, condenser, vapor line and liquid line. The boiling and suction chambers, which drove the vapor to one way flow of vapor line, of the evaporator were bifurcated by a vapor separator and the evaporator's bottom was connected as the cycle channel of the refrigerant. Li et al.[166] worked on copper-water LHP with a flat, square evaporator to study and analyze the effect of variable heat input on the startup process of LHP. Wong and Chen[167] worked on evaporator dynamics to calculate the evaporator resistance in a flat plate LHP although no boiling phenomenon was observed in the evaporator. Basha et al. [168] conducted number of experiments at various heat inputs to visualize the bubbles in the compensation chamber (CC) of the evaporator to study the bubble formation dynamics in LHP in regard to solar applications. The results conclude that at high heat input, convective and nucleate boiling were distinct there by explaining the existence of critical heat input at which nucleate boiling commences. For better performance, LHP should be operated at heat input higher than critical heat load. With increase in heat input, bubble size and velocity also increase. Mathematical correlations were needed to be developed considering bubble dynamics and temperature as the variables.

Oscillating Heat Pipe (OHP)

Akachi[169] invented Self Excited Mode Oscillating Flow Heat Pipe (SEMOFHP), which are also known as pulsation heat pipe or oscillating flow heat pipe (OFHP). In a drying system, for heat recovery from exhaust gas to fresh air, this process combined with ebullition, evaporation, condensation and impulse oscillation leads to a very high heat transfer efficiency and hence can be used successfully as was deduced by Xian[170]. Phase change and oscillation of plunger piston formed by the liquid and steam of the fixed amount of working fluid injected into vacuumed curving capillaries initiate the heat transfer of heat pipe. Rittidech et al.[171] worked on a closed end oscillating heat pipe (CEOHP) air preheater, with water and R123 as the working fluids. They concluded the effectiveness to increase slightly with rise in hot gas temperature and also due to change of working fluid from water to R123. Energy thrift was achieved for the designed CEOHP. Aslan and Ozdemir[172] worked to find the correlation for prediction of heat transfer in three interconnected columns OHPs named as evaporator pipes, condenser column and free column interconnected by brass tubes and fittings. The cooler and heater tubes used in the respective column consisted of copper. Uncertainty analysis was conducted by finding the main sources of error in current, voltage, pressure, temperature and height. Variation of vapor pressure with vapor velocity was determined and the results for the position time graphs of oscillating liquid column depicted harmonic functions. More accuracy was required to measure the vapor pressure and the vapor velocity, as a time delay of even _+1 sec. could make a substantial difference in the variation curve. Graphs were plotted between time average surface temperature w.r.t. column height on the heater and cooler tube for specific cooling water temperature and heat transfer rate. Overall htc was calculated and kinetic Reynolds number was defined using Buckingham Pi Theorem. Correlation equation for htc was also suggested. It was concluded that heat input and cooling water temperature could be varied but oscillation frequency, amplitude and surface temperature change automatically. Chai et al.[173] determined the effect of use of oscillating flow Cu-H_2O HPHE in self excited mode in fluidized bed dryer with parameters like hot gas inlet temperature, hot gas RH, gas flow direction, gas flow rate and position of heat source as variables. The results indicated that the efficiency of heat recovery was better and heat exchange capacity was found to be more than thrice than the common tube heat exchanger. Efficiency of heat recovery was improved slightly with rise in the inlet temperature of hot air. It could be used in vertical direction with heat source at the top. Hot gas temperature should be higher than the saturation temperature of the working fluid for achieving maximum heat transfer capacity. Shang et al.[174] used non uniform structure comparing it with uniform structure to determine the effect of variation of heat input and heating position on output power in SEMOFHP with closed loop. The heating position was varied at three places in the non uniform part. The results of output power reflected that better heat transfer rate was achieved for uniform than non uniform structure, irrespective of heating position. For medium heat loading i.e. around 80W, the results were at its best where as at high heat loads even for non uniform structure also heat transfer rate was reduced. Easy start was achieved with non uniform structure. For the best results of heat transfer rate the non uniform structure should be at the lowest part of heat pipe and above the heat source. For non micro heat pipes the heating positions matter as gravitational effects were substantial. Nuntaphan et al.[175] proposed to use closed loop OHP as a fin in the heat exchanger with which the effectiveness was increased by 10% in comparison to conventional solid wire fin due to heat transfer with both conduction and convection. Samana et al.[176] also found similar results using OHP as fins in natural convection. In forced convection OHP as fins using R123 working fluid was tested by Samana et al.[177] in a heat exchanger using hot water and air streams for heat exchange and an increase of 5% was observed over the conventional heat exchanger depending on the mass flow rate of air and surface geometry of heat exchanger. Fin efficiency model was also developed and the results were found to be in good agreement with the experimental values.

Pulsating heat pipes (PHP)

Akachi[178] invented Pulsating heat pipes which are wickless structures having meandering bends of long capillary tube, containing more working fluid than conventional heat pipes. Phase change of working fluid is associated with local axial oscillations and circulation from evaporator to condenser and back, for tube diameter less than the critical diameter by creating a pressure difference across vapor plugs and this only is responsible for high rates of heat transfer. Critical diameter is the tube's maximum inner diameter to permit the capillary flow (Charoensawan et al. and Khandekar)[179,180]. A theoretical model to find the heat transfer rate, plug location, pressure and temperature for closed and open loop PHPs was developed by Shafi et al.[181]. Sensible heat of the slug flow was found to cause majority of the heat transfer. They further[182] developed advanced heat transfer model with multiple vapor plugs and liquid slugs with film evaporation and condensation, which also presented similar results. Tong et al.[183] worked on closed loop PHP on Pyrex glass, methanol prototype for flow visualization. Ma et al.[184] developed an analytical model to investigate the oscillating motion phenomenon in miniature PHP. Factors affecting the start up characteristics were determined by a theoretical analysis conducted by Qu et al.[185] and found vapor bubble shape and size of the cavity on the capillary inner surface to be the prime factors. Analytical relations were also developed to estimate superheat and heat flow. The effect of variation in inclination angle and inner diameter was considered by Meena et al.[186] with R123 working fluid at 50% fill ratio. They found an increase in CHF with increase in orientation. For 1D flow of PHP, a mathematical model was developed and solved using Finite Difference Method by Yang et al.[187] to predict the start up characteristics. To predict the heat transfer and flow characteristics, at all inclination angles Mameli et al.[188] modified the single loop PHP's separated flow model which was originally given by Holly and Faghri, using new heat transfer correlations to predict satisfactory results at all inclination angles. Thermal performance of single turn copper PHP was investigated by Naik et al.[189] with different working fluids, heat inputs and fill ratios for horizontal and vertical orientation. The performance was found to be better in horizontal position at all fill ratios, heat input and with all working fluids. Acetone performed better in terms of htc and thermal resistance than methanol and ethanol. Significance of non dimensional numbers on the oscillating flow characteristics of a closed loop PHP was studied by Rao et al.[190]. It was concluded that Poiseuille's number assumed more significance than other non dimensional numbers due to inclusion of geometry, flow characteristics and flow properties of PHP. At low axial temperature difference between evaporator and condenser, small diameter, high fill ratio and low operating temperature, the effect of capillary forces was found to be substantial. Infrared Thermography was used by Karthikeyan et al.[191] to observe the multiple steady states at intermediate heat input in a multi turn PHP. Various flow regimes e.g. no flow, intermittent oscillatory flow and oscillatory flow with bulk circulation were also observed simultaneously.

Concentric Annular Heat Pipe (CAHP)

Vasileiv[192] introduced the concept of co axial heat pipe. Heat input and radial temperature was measured for analyzing its performance. Faghri[193] invented a non conventional heat pipe now known as Concentric Annular Heat Pipe (CAHP). CAHP has two concentric hollow pipes of different diameters sealed at their end caps thereby forming an annular region where the wick structure is placed on the outer periphery of the inner pipe and on the inner periphery of the outer pipe. This enhances the heat flux due to increase in the area of cross section of the wick and the surface area of heat addition and heat rejection from the pipe. Faghri[193] worked to analyze a 2D, incompressible and steady flow of vapor in CAHP. He used parabolic form of the governing equations of motion in the evaporator, adiabatic and condenser section of CAHP assuming zero axial velocity at the evaporator inlet, fully developed flow at adiabatic and at condenser section inlet and used the implicit marching finite difference method. Faghri and Parvani[194] continued their work to study all the features of the laminar vapor flow with the help of 2D, incompressible model in CAHP and concluded that although elliptic model was able to provide more complete simulation of vapor flow than the parabolic model but still no significant difference in the results between parabolic and elliptic model of governing equations was observed. Performance characteristics of Cu-H_2O CAHP were compared with same configuration of conventional heat pipe and an increase of 80% was registered in heat flow. Faghri and Thomas[195] conducted the experiments to find the temperature distribution for different inclination angles and heat supply on the evaporator region, adiabatic region and condenser region. Parabolic model of governing equation was used to analyze the capillary limit. Both[196] also worked to analyze the solutions for incompressible and compressible flow using equations of fluid motion and also found the solution to predict the pressure losses in all the three regions for conventional heat pipe and for CAHP. Theoretical analysis was also done to predict the sonic limit. Layeghi and Borujerdi[197] experimented on CAHP with partial heat transfers from the evaporator and condenser sections. The analysis was done for laminar, 2D, steady and incompressible vapor flow with variable heat addition. A computer program was developed to predict the pressure and velocity distribution and for the analysis of symmetric and asymmetric heat supply and heat rejection conditions. It was concluded that the end cap wicks could be of an advantage in various CAHP applications. CAHP could provide efficient heat transfer with better performance even in the objects with different diameter. With increase in the radial Reynold's Number (Re), there was an increase in the performance by increase in the heat transfer rate. To validate the proposed numerical analysis, more experiments with further investigations should be carried out. Borujerdi and Layeghi[198] also worked to analyze steady state vapor flow and heat transfer in CAHP for number of symmetric and asymmetric cases numerically. For low to moderate Re, for symmetric cases, vapor pressure, temperature distribution and also vapor reversal, transition to turbulence phenomenon were predicted and results were found to be in good agreement with the available data. They used quick differencing scheme for the discretization process with accepted accuracy and good convergence behavior was observed for low to moderate Re and also near the transition. For low to moderate Re, very small vapor temperature drop was predicted due to small pressure along the CAHP. However, more complete models and further studies were required for prediction of a real condition in CAHP. Boo and Park[199] studied the thermal characteristics in terms of thermal transient response and isothermal property of the outer surface of CAHP with uniform heating for variable diameter ratio and fill ratio. Increase in the diameter ratio resulted in better performance. The results of CAHP were compared with a copper block of same outer diameter resulting in higher temperature difference in the axial direction as was for CAHP. Copper block reported 25 min. of time lag to the heat source where as the CAHP had an immediate thermal response. A specific diameter ratio responded for least thermal resistance for same heat input flux. Effect of fill ratio on thermal resistance was more significant than the diameter ratio variation. Isothermal characteristics of CAHP were far better than the copper block. Jalilvand et al.[200] studied the performance of Roll Heat Pipe(RHP). CAHP when used as heat roll in copy machines, xerox machines or laser printers is termed as RHP. Considering actual length of heating roll in fusing unit but with different configurations of bridge wicks, three heat pipes were fabricated. Transient thermal response was observed and the results were compared with the theoretical analysis. Effect of rotation of RHP was also studied. The observed results were comparable with the existing heat roll of the fusing unit by a difference of 5% only. With increase in heat input, warm up time decreased. Thermal resistance was the least in a certain range of heat input and at an optimum value of fill ratio during warm up period. Internal temperature distribution was analyzed experimentally and theoretically and evaporator temperature was found to be lower than the predicted value. This was due to the assumption that wick was completely filled with water where as practically it was not the case at high heat input due to recession of liquid layer.

Analysis of Heat Pipes

Non Condensable Gases (NCG)

One of the prime factors of degradation in performance of heat pipe is the formation and presence of NCG inside it. Number of researchers, have worked in this direction. Nikitkin et al.[201] and Wrenn et al.[202] worked on LHPs with ammonia as a working fluid, till 80°C operating temperature and found thermal conduction degradation. Dube et al.[203] noticed higher temperature difference in evaporator and compensation chamber temperature of a LHP at low operating temperatures due to higher partial pressure of NCG in comparison to the absolute vapor pressure of ammonia, in the condenser region. Singh et al.[204] worked on copper-water LHPs and noted heat transfer degradation due to presence of NCGs. Wang[205] investigated the effects of NCG's in HP by using numerical analysis. SINDA was used to compute thermal analysis while FLUINT was used for flow resistance computation. Finite Network Method was used being a very powerful tool for complex two phase flow analysis for variable heat input with specific thermal resistance and specific amount of NCG. The htc at the evaporator section and condenser section were calculated. The validation of the results was in agreeable condition. He et al.[206] used nitrogen as a NCG simulator to investigate the effects on the performance of a loop thermosyphon. Prado-Montes et al.[207] worked with ammonia LHP at elevated temperature upto125°C to find the effects of NCG by injecting different amounts of nitrogen for various heat input and operating temperatures. The thermal conductance of the LHP was found to deteriorate at low power levels and low temperatures but the shocking revelation was that the presence of even more than twice the expected amount of NCG had negligible effect on the operation of LHP in 15 years of life span.

Computational Fluid Dynamics (CFD)

To model liquid/gas two phase flow in a pipe, FLUENT 6.0 was used by Ghorai and Nigam[208]. Gas velocity, liquid volume fraction and interface roughness were considered as the variable parameters while using the VOF technique. The results were validated by the already available data by comparing the predicted interracial roughness. A good agreement between the experimental and mathematical model was also concluded by Lu et al.[209] while using VOF method for large heat pipes. The two phase flow and the transition from stratified to slug flow were analyzed. ECT with optimal step size for number of iterations using image constructive algorithm was used to study and visualize the liquid flow in by Liu et al.[210]. To predict the two phase concurrent horizontal gas liquid and vapor liquid flow in a tube, a VOF model was developed by DeSchepper et al.[211]. The results were compared with Baker chart and it was found that using the then present CFD codes, the simulation was possible for all horizontal flow regions. They further[212] studied the VOF model for simulation of different horizontal two phase flow regions of a hydrocarbon feedstock in the convection section of a steam cracker. Hertz – Knudsen equation was used to determine the source terms explaining the heat transfer during evaporation process in the conservation equations. To investigate the effect of fill ratio and variable heat input on the performance of thermosyphon, VOF approach was used by Alizadehdakhel et al.[213] and the effect of NCG was also considered to model the condensation process completely. Mixture of air and water vapor was used as the primary phase. Proposed equations by DeSchepper et al. were used for calculations and were modified for condensation process to consider effects of NCG. The results found the performance to improve with increase in heat input. For a specific heat input, there was an optimum value of fill ratio. FLUENT 6.2 CFD code was used and UDF subroutine was developed to model the phase change phenomenon. Experimental and CFD predicted values were in good agreement. CFD could be used to model complex heat and mass transfer during phase change processes. Annamalai and Ramalingam[214] fabricated and studied experimentally the effect of variable heat input on surface and vapor temperature at steady and transient condition for copper heat pipe. The steady state was achieved after 60 minutes. Surface convective resistance of the condenser region was responsible for increase in operating temperature of the thermosyphon with increase in surface heat flux at the evaporator end. CFD analysis was also carried out using ANSYS-CFX for the simulations and the results were in good agreement with the experimental values. Water cooling or increase in heat transfer area by use of extended surfaces could have been a better choice for more efficient operation. Ahmed et al.[215] performed the simulation of flow inside a heat pipe using FLUENT 6.3 in 2D, double precision, ax symmetric condition using the symmetry for cylindrical heat pipe. The governing equations used were solved in coupled conjugate heat transfer set up, core region of vapor flow and wall and wick structure of liquid flow through porous media and heat transfer by conduction was considered separately. The investigations were done to find the effects of variation in total length, heat flux, wall thickness, wall material and porosity. A theoretical model for pressure drop in vapor region was developed and was used for simulation. Finite volume method was used as the base for the study and macroscopic properties were considered for analysis. It was found that the drop in pressure and rise in wall temperature increased the heat flux. The temperature distribution was affected by the porosity and the wall material. No significant effect was found of heat pipe length and wall thickness. Temperature, pressure and velocity distribution of flat heat pipe using water as the working fluid with wick columns were found using CFD multiphase mixture model by Somsundaram et al.[216]. Thermal resistance was decreased and vapor velocity was increased thereby increasing heat transfer with increase in number of wick columns. Chaudhari et al.[217] performed CFD analysis using ANSYS-CFX of two phased thermosyphon to predict the overall temperature distribution under steady state condition. The results were found to be in good agreement with the previously found experimental values. The overall thermal resistance decreased with increase in heat input.

Conclusions

Research on heat pipe as a device for heat dissipation from the source has attracted a great deal of effort from the researchers. Further, different types of heat pipes for different applications, namely two – phased closed thermosyphons, conventional heat pipes, non conventional heat pipes viz. loop heat pipes, oscillatory heat pipes, pulsating heat pipe, annular heat pipe, micro heat pipes to miniature heat pipes have been developed and optimization of their design, by study and analysis, both experimental and theoretical have been of interest to the researchers. Further, attempts have been made to model the phenomenon happening inside the heat pipe using two dimensional mathematical modeling for the fluid flow and heat transfer in the annular vapor space and the wicks. This has been carried out in low to moderate temperature ranges of 50°C to 200°C which can be applied in heat transfer, heat recovery and heat exchanger applications. However, heat pipes and thermosyphons in medium temperature range of 200°C- 450°C are still under developed. Understanding the complete mechanism taking place in the evaporator and the condenser section of the heat pipe is still very difficult and as such findings for mainly for the vapor flow analysis in the laminar region and turbulent region with changes in temperature is still limited. Apart from this, there is lot of work still left to be done on the different types of heat pipes that have been evolved in the recent days. Computational fluid dynamics being a newer development still has a large potential for research. Performance of non conventional heat pipes as compared with the normal thermosyphon and conventional heat pipes at varying heat input, fill ratio, aspect ratio, inclination angle and with different working fluids including binary and nanofluids need to be studied in greater details both experimentally and theoretically using appropriate modeling and analysis techniques. Further work in the direction of composite materials and also multiple materials with compatible wick and working fluid still needs attention.

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