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Titreşimli ısı boruları üzerine bir derleme: genel değerlendirmeler ve güncel uygulamalar

A review of oscillating heat pipes: general consideration and latest applications

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Abstract

Energy consumption has been one of the most important issues that researchers have been concerned about over the last decade. Number of researches about new and renewable energy sources, have been increasing day by day. Researchers are looking on logical ways to use energy in addition to new, renewable energy sources. Especially in thermal systems, most of the energy lost occurs during heat transfer. Heat pipe systems appear as important devices that provide benefits by eliminating these heat and energy losses. Heat pipes systems transfer heat energy between two points with high performance values. Types of heat pipes and their detailed descriptions were investigated in this study. Oscillating heat pipes are relatively new systems that have quickly become the focus of research. They are extremely useful devices due to their ease of construction, simple design, and adaptability to almost every area. The study included a detailed description of oscillating heat pipes, their working mechanisms, theoretical investigations, and current applications.

Keywords: Oscillating heat pipes, nanofluids, heat pipe applications

Öz

Son yıllarda enerji tüketimi konusu, araştırmacıların endişe duyduğu en önemli konulardan biri haline gelmiştir. Yeni ve yenilenebilir enerji kaynaklarının araştırılması üzerinde yürütülen çalışmaların sayısı her geçen gün artmaktadır. Bilim insanları yalnızca yeni ve yenilenebilir enerji kaynaklarını araştırmakla kalmayıp enerji kullanımının akılcı yolları üzerinde de çalışmalar yürütmektedirler. Özellikle ısıl sistemlerde enerji kayıplarının büyük bir çoğunluğu ısı transferi işlemi sırasında gerçekleşmektedir. Isı borusu sistemleri bu ısı ve enerji kayıplarının ortadan kaldırılmasında yarar sunan önemli cihazlar olarak karşımıza çıkmaktadırlar. Isı boruları ısıl enerjinin bir noktadan bir diğerine aktarımı işlemini yüksek performans değerleri ile gerçekleştiren sistemlerdir. Bu çalışmada ısı borusu türleri ve detaylı tanımlamaları gerçekleştirilmiştir. Titreşimli ısı boruları görece yakın dönemde ortaya çıkmış ve hızla araştırmaların odak noktası haline gelmiş sistemlerdir. Kolay inşa edilebilirlikleri, basit tasarımları ve hemen her alana adapte edilebilir olmaları açısından oldukça kullanışlı cihazlardır. Çalışmada titreşimli ısı borularının detaylı tanımlaması yapılmış, çalışma mekanizmaları, teorik incelemeleri ve güncel uygulamaları değerlendirilmiştir.

Anahtar kelimeler: Titreşimli ısı boruları, nanoakışkanlar, ısı borusu uygulamaları

Nomenclature

Symbols

C_p	Specific heat capacity (J/kgK)
g	Gravitational acceleration (m/s²)
h	Specific heat (kJ/kg)
k	Thermal conductivity (W/mK)
L	Length (m)
N	Number of turns
P	Pressure (kPa)
Q	Thermal power (W)
q	Heat load (W)
r	Radius (m)
R	Gas constant
R_t	Thermal resistance (K/W, °C/W)
T	Temperature (°C, K)
u	Velocity (m/s)
$\dot{q}$	Input heat flux (W/m²)
f	Frequency (Rad/s)
Ø	Filling ratio
ε	Nonadiabatic correction factor
σ	Surface tension (N/m)
γ	Specific heat ratio
τ	Shear force (N)
μ	Viscosity (N/m²)
η	Efficiency
Ku	Kutadelatze Number
Mo	Morton Number
Bo	Bond Number
Pr	Prandtl Number
Ja	Jacob Number
Ka	Karman Number

Subscripts

c	Condenser
e	Evaporator
ef	Effective
i	In
l	Liquid
o	Out
t	Total
v	Vapor
rot	Rotational

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1 Introduction

Nowadays, the world is facing a great problem. The energy demand has been increasing with the increasing human population and environmental factors [1]. Researchers also study the rational use of energy in addition to finding new and renewable energy sources. Regarding energy sustainability during energy transfer in thermal systems, the reduction of irreversibility is crucial. According to researchers, reducing energy consumption has a crucial importance [2],[3].

Heat pipes are magnificent devices that are used for heat transfer from one point to another and have interesting abilities. The working fluid flows in two phases during the heat transfer process in heat pipe devices. These devices are efficient heat transfer systems that can be used for many different applications, including solar energy systems, electronic cooling, and space heating [4]. Basically, a heat pipe is in the form of a closed tube with a wick and an amount of fluid inside. The evaporator, condenser, and adiabatic zone make up a heat pipe, which operates on the evaporation-condensation cycle principle [5],[6].

When using heat pipes, the fluid evaporates with heat from a heat source in the evaporator portion before moving to the condensation section, which raises the vapor pressure. The capillary effect provided by the wick structure allows the working fluid to heat the environment while condensing and returning to the evaporator area. The evaporation-condensation cycle continues as long as heat input and output continue. In this way, heat transfer from one point to another point is provided [7].

When heat pipes are examined, it is seen that there are different types of heat pipe applications according to their usage areas. There are detailed descriptions and application studies of these structures in the literature.

Thermosiphon systems are heat pipes that stand out as passive water heating systems with a wide usage area. These systems basically consist of solar collectors, storage tanks, and connection equipment. The tank should be positioned at a higher level in these systems [8]. The driving force for the system is produced by the density differential of the fluid, which is brought on by the heat input through the collector [9],[10].

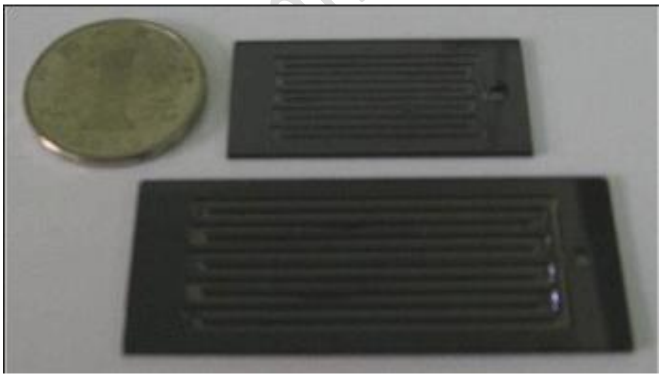

Figure 1. Micro heat pipe [11].

Micro heat pipes are small heat pipe systems often used for cooling electronic components (figure 1.). The working fluid in these devices is in both two (liquid and gas) phases at the same time. The capillary effect provides the driving force in the system [8],[11].

In variable conductance heat pipes, condensation volume is reduced by adding some incompressible gas to the condenser. The amount of incompressible gas might rise or decrease depending the temperature change. The changes in the volume of incompressible gas also affect the condensation volume and the heat pipe conductivity controlled in this way [12],[13]. In addition, rotational and loop heat pipes are also systems that have found a place in heat pipe applications [14],[15]. Schematic of a variable conductance heat pipe has shown in Figure 2.

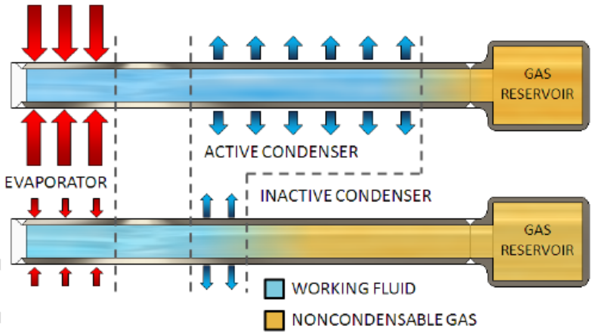

Figure 2. Schematic of a variable conductance heat pipe [12].

Oscillating heat pipes (OHP) are heat transport mechanisms in which the fluid exists in the device both as liquid and as vapor at the same time. The fluid forms a chain with an array of liquid slugs and vapor bubbles in the capillary tube. In these systems, working fluid starts to evaporate with the input heat energy, and this causes the fluid to move towards the condenser region with increasing vapor pressure in a capillary tube. In the condenser region, heat is released from the fluid to the reservoir. This causes the vapor pressure to decrease, so the fluid moves back to the evaporator region. The vapor pressure rises again as the fluid returns to the evaporator region, and this oscillatory movement continues as long as there is heat input and output to and from the system [16].

There is evaporator, condenser, and adiabatic regions in an OHP system. There are generally three types of OHPs: open ended, closed ended, and closed loop OHP's [17]. types of oscillating heat pipes have shown in Figure 3., Figure 4. and Figure 5.

Open ended OHPs operate in a way that exposes the working fluid to atmospheric pressure, and this design is less preferred since it does not allow vacuuming before filling and highly limits the working conditions. While such limitations are reduced in closed-ended OHPs, the emergence of oscillatory motion in the form of fluid flow within each channel is seen as the main feature limitations of these systems. In closed loop heat pipes, the entire system is formed in such a way that a single capillary tube. This form allows a cyclic flow through the entire channel, and it is seen that the system limitations are largely eliminated as the heat transfer rate increases [18],[19].

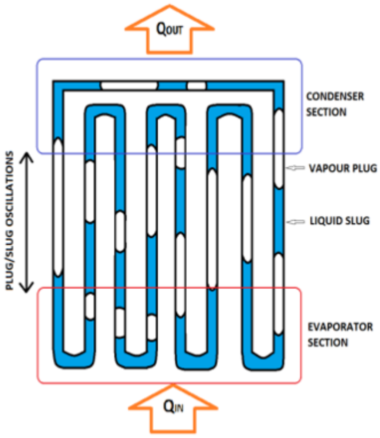

Figure 3. Closed loop oscillating heat pipe [17].

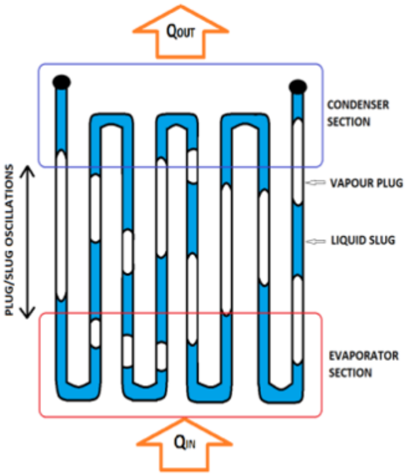

Figure 4. Closed ended oscillating heat pipe [17].

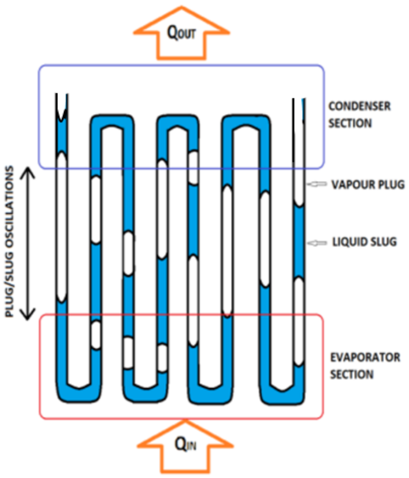

Figure 5. Open ended oscillating heat pipe [17].

2 Working fluids of oscillating heat pipes

OHPs are devices that are structurally composed of capillary pipes. As stated in the preceding section, the transfer process in these systems is carried out by two-phase flow. The driving force needed to occur in the system is provided by the vapor pressure, which acts directly proportional with the heat input and output [16].

One of the most significant elements affecting the system's ability to transmit heat is the working fluid's thermophysical characteristics, such as thermal conductivity, viscosity, etc. The compatibility of the fluid and pipe material also directly affects the system's performance. Under these conditions, it turns out that working fluids are one of the most significant elements that have a direct impact on OHP performance. The following are crucial considerations for selecting the working fluid for OHPs [20].

- ❖ Compatible operation of working fluid and pipe material,
- ❖ Stable thermal performance,
- ❖ Wettability of heat pipe wall,
- ❖ Acceptable vapor pressure across the working temperature range,
- ❖ Elevated latent heat,
- ❖ Low thermal resistance,
- ❖ Low fluid viscosity values,
- ❖ High surface tension,
- ❖ Acceptable freezing and flow temperatures.

The working fluids that are used in OHPs have a wide range. These fluids can generally be examined under two headings: conventional working fluids and nanofluids.

2.1 Conventional working fluids for oscillating heat pipes

OHPs appear as structures suitable for a variety of fluids to be used. The conventional working fluids can be defined as pure fluids and their mixtures. Different pure fluids or their mixtures can be selected as working fluids depending on the needs, for example, the required heat transfer amount, heat flux operation temperature, etc. While fluids such as water, acetone, alcohols, etc. are widely used in these systems, it is seen in the literature that materials such as refrigerants, metals, oils, etc. are also used (Table 1) [21].

Im Y. H. studied two different OHP systems that were produced from capillary copper pipes (2 mm inner diameter). One of the OHPs has 5 turns and the other has 20 turns, and the working fluid is selected as r-134a refrigerant. The system evaporator was heated with water at varying temperatures between 20-60°C and the flow rate was adjusted to 5.1 liter per minute. Water at 10 °C is selected as the condenser cooler fluid in the system. It is obtained from the results that both heat pipes exhibited thermal resistance values of around 0.1 °C/W with refrigerant R134-a [22].

Hao et al. carried out experimental studies using an OHP produced from polytetrafluoroethylene with a 2.41mm inner diameter and using water, ethanol, and acetone as fluids. As a result of experiments carried out for 50% and 70% filling ratios, an increase in the heat input for all three fluids also increased the heat transfer coefficient, and it was discovered that the thermal resistances increased, respectively, for acetone, ethanol, and water [23].

Table 1. Thermophysical properties of some common fluids [21].

Working Fluid	Freezing Point (°C)	Boiling Point (°C)	Working Range (°C)
Helium	-271	-261	(-271)-(-269)
Nitrogen	-210	-196	(-203)-(-160)
Ammonia	-78	-33	(-60)-(100)
Pentane	-130	28	(-20)-(120)
Acetone	-95	56	(0)-(120)
Methanol	-98	64	(10)-(130)
Flutec PP2	-50	76	(10)-(160)
Ethanol	-112	78	(0)-(130)
Heptane	-90	98	(0)-(150)
Water	0	100	(30)-(200)
Toluene	-95	110	(50)-(200)
Flutec PP9	-70	160	(0)-(225)
Thermex	12	257	(150)-(350)
Mercury	-39	361	(250)-(650)
Cesium	29	670	(450)-(900)
Potassium	62	774	(500)-(1000)
Sodium	98	892	(600)-(1200)
Lithium	179	1340	(1000)-(1800)
Silver	960	2212	(1800)-(2300)

Zhu et al., in their study, used fluids obtained from mixtures of water and acetone in different ratios (13/1, 4/1, 1/1, 1/4, 1/13), with filling ratios varying between 35-70%. It has been noted that the startup performance of the mixture fluids for the 10 W heat input is better than distilled water, but water and acetone pure fluids exhibit lower thermal resistance values for the 35 and 50 W heat input [24].

Tokuda and Inoue, conducted experimental studies on an OHP using molten sodium as the fluid under the conditions of a 50% filling ratio, and evaporator temperatures varying between 800-900°C and condenser temperatures ranging from 600°C to 700°C. The findings indicate that the highest heat transport rate of 477 W is obtained at 820°C evaporator and 609°C condenser temperatures, and the system thermal resistance varies between 0.3-2.8 K/W [25].

Barrak et al. provided the integration of a cooling coil and an OHP with the aim of improving the dehumidification efficiency of the cooling coil. While water, methanol, and a mixture of these two fluids are used as the fluids in the OHP heat exchanger, the filling ratio is set at 50%. The dehumidification performance of the cooling coil increased by 17% for water, 21% for fluid mixture, and 25% for methanol [26].

Ji et al. have investigated an OHP system that was produced from 310s stainless steel pipe, which has a 6 mm inner diameter for high temperature (over 500 °C) applications. The working fluid was obtained from a mixture of 78% potassium and 22% sodium. When the results of the experiments with a 45% filling ratio are examined, it is discovered that a stable oscillation motion occurs at temperatures above 500°C and that the system has the least amount of thermal resistance value of 0.08 °C/W at 3169 W heating power [27].

Li et al carried out thermal and visual experiments on an OHP system in which nitrogen was used as the working fluid. A vertical, bottom heated OHP system was tested under changing filling ratios of working fluid between 25% - 76%. According to results, the optimum filling ratio is increasing with increasing heat input, and latent heat transfer efficiency is higher than sensible heat transfer efficiency for nitrogen oscillating heat pipes [28].

2.2 Nanofluids

In the last few decades, nanofluids have become an important research subject for thermal systems. Nanofluids can be defined as fluids obtained by adding nonmetric particles to a base fluid. The aim of these processes is to improve the system performance by increasing the thermal conductivity of the fluids used in thermal systems. This situation has made the application of nanofluids in thermal systems quite widespread in recent years [29].

While it's known that some fluids commonly used in nanofluid production are water, ethylene, glycol, acetone and various oils. Carbides, nitrites, metals, metal oxides etc. are widely used as nanoparticle materials [30].

The most important point in the production of a stable nanofluid is to ensure a homogeneous distribution of nanometric particles in the fluid. In some cases, it may be necessary to use additional materials such as surfactants, binders etc. to ensure homogeneous distribution. The literature review showed that there are two basic methods for nanofluid production [30].

The one-step method is the first method of nanofluid production. In this method, nano metric particles are synthesized directly in the base fluid. Although this method allows us to skip some intermediate steps, it is rarely used due to its chemical difficulties and cost [31],[32].

Another method in nanofluid production is called as two-step method. In this method, first nano metric particles are produced, and then dispersion is formed with the base fluid. Centrifuge devices, ultrasonic mixers etc. can be used during the preparation of the dispersion. Ease of application and low cost are the factors that make this method more common [31],[33].

Zhou et al. carried out experimental studies about an OHP system with nanofluids obtained by adding carbon nanotubes to 1/1 water-ethanol mixture at rates varying from 0.05-0.5% wt. It has been observed that the fluid with 0.2% wt concentration provides the minimum thermal resistance as 0.066°C/W which is obtained at 56 W heating power and 35% filling ratio [34].

Jin et al. tested an OHP system made of copper pipe with Fe_3O_4/water nanofluid. The heat flux value increased from 1561 W/m^2 to 1602 W/m^2 as the fluid concentration increased from 1% wt to 4% wt, and the highest heat flux value, 1603 W/m^2, was obtained by applying an external magnetic field to the system, according to the results of the experiments performed for different concentration values [35].

Zhou et al. made a series of experimental studies using graphene nanofluids with different concentration values (volumetric: 1.2, 2.0, 5.7, 9.1, 13.8, and 16.7) on an OHP system. Heat inputs ranging from 10 to 100 W were used in the experiments for 45% 55% 62% 70% 90% filling ratios, and in accordance with the results, it was observed that the optimum concentration value for 55-62-70% filling ratios were 2-3.5%. According to the researchers, the thermal resistance of the system is reduced by 83.6% at 2% concentration, 62% filling ratio, and 80 W heat input conditions [36].

A general summary of nanofluid effect on heat transfer is shown in Table 2.

It is clearly seen that the working fluid selection is one of the most important factors that affect system performance for OHP systems. The effect of nanofluids on system performance cannot be ignored, but some specific fluids should be used for specific situations, such as high temperature or cryogenic applications.

Table 2. Effect of nanofluids.

Fluid	Particle Size (nm)	Heat Transfer Increase (%)	Ref.
Cu/EG	10	40	[37]
Cu/Water	75-100	23.8	[38]
Cu/Water	100	78	[39]
Fe/EG	10	18	[40]
Ag/Toluene	60-80	16.5	[41]
Cu_2O/Water	200	24	[42]
Au/Ethanol	4	1.3	[43]
Fe_3O_4/Water	10	38	[44]
TiO_2/Water	15	30-33	[45]
Al_2O_3/Water	20	20	[46]
CuO/Water	33	11.5	[47]
SiC/Water	25	15.9	[48]
NCTs/Engine Oil	20-50	30	[49]
NCTs/Poly Oil	25	160	[50]
NCTs/EG	15	19.6	[51]
Su/FC-72	9,8	52	[52]
Al_2O_3/Water	56	32.5	[53]
SiO_2/Water	10	20	[54]
Fe_2O_3/Kerosene	20	19	[55]
Diamond/Water	50	36	[56]

As it can be seen in the above section, better performance values can be obtained than conventional fluids with the use of nanofluids in OHP systems. It is quietly obvious that, by adding nanoparticles to the working fluid, the conductivity of the fluid can be raised up to 78% and the thermal resistance of the system can be reduced up to about 84%.

3 Operation mechanism and theoretical modelling

In OHPs, the heat transfer process occurs by utilizing two-phase flow. The reasons, such as the vapor pressures regional variations, the random formation of vapor-liquid chain, and the existence of phase change effects in the heat transfer during the process, make the theoretical calculations quite complex and difficult. When the studies in the literature are examined, it is seen that many studies have been carried out with the aim of creating a valid theoretical model, but much more work needs to be done in this area.

3.1 Theoretical investigations

Researchers working on OHPs have carried out many studies in recent years to develop an accurate theoretical model.

According to Yin et al. the process of heat transfer in OHPs has been theoretically shown to be considerably different from that in traditional heat pipes. In their study, they used the spring-mass model to numerically model the heat and mass transfer process and developed an equation that reveals the maximum heat transfer amount [57].

$$\int_0^{r_0} 2\pi\rho_v u_v^2 r\,dr = (-\rho_1+\rho_2)\pi r_0^2 + 2\pi r_0\sigma(cos\alpha_r + cos\alpha_a) + 2\pi r_0\left(\int_0^{L_1}\tau_d\,dx\right) \quad (1)$$

In the equation expressed by Eq. 1; ($\int_0^{r_0} 2\pi\rho_v u_v^2 r dr$): the vapor pressure created by the increase in the vapor volume, ($(-\rho_1+\rho_2)\pi r_0^2$): difference of pressure acting on a liquid plug by vapor slugs, ($2\pi r_0\sigma(cos\alpha_r + cos\alpha_a)$): surface tension of the liquid plug and ($2\pi r_0(\int_0^{L_1}\tau_d dx)$) represents the tension between the heat pipe surface and the fluid [57].

When the boundary conditions are placed into Eq. 1, the differential equations solution gives the maximum heat transfer value (Eq. 2) [57].

$$q = \frac{3\pi h_{lv}\mu_l L\emptyset}{N} \quad (2)$$

In OHP systems the heat entered the system through the evaporator section is dissipated into system by the oscillation motion. Thus, the frequency of oscillation motion becomes an important parameter to define the heat transfer process. Spinato et al. studied on a R134-a filled oscillating heat pipe theoretically and experimentally. Experimental results demonstrated that the frequency is effective on the working conditions of OHP systems. They developed a frequency equation for single turn oscillating heat pipes with a spring mass damper system. The frequency equation is given in Eq.3 [58].

$$f = \frac{1}{L_l + L_v}\sqrt{\frac{\rho_v RT}{\rho_l\emptyset(1-\emptyset)}} \quad (3)$$

Yoon et al. improved the equation for multi-turn oscillating heat pipes, which is expressed as follows [59].

$$f = \frac{1}{NL_{OHP}}\sqrt{\frac{\varepsilon\gamma P_v}{\rho_l\emptyset(1-\emptyset)}} \quad (4)$$

The artificial neural network approach (ANN) is another model used to develop a theoretical model for OHP. The algorithms created by this method aim to predict the optimum operating conditions for OHPs by revealing the relationship between the effective parameters.

Wang et al. created an ANN model to forecast an OHP's thermal resistance. using water as the fluid. In the model where the filling ratio, the ratio of the inner diameter-evaporator length, the ratio of evaporator-heat pipe lengths, heat flux, and the number of turns are used as input parameters, the number of hidden layer neurons was determined as 10 (by trial and error method). The ANN model was created with 221 data collected from literature, and It was noted that the outcomes were consistent with the experimental findings and the MSE value for the model was 0.0025 and the correction factor was 0.9961 [60].

Wang et al. developed an ANN model that was used under different working fluids and changing operating conditions. Dimensionless numbers, which are precisely defined in the sections below, and number of turns, diameter-evaporator length ratios are selected as input parameters in the model. The temperature of the cooling fluid was used as the reference temperature for the calculation of dimensionless numbers, and it was discovered that the model's results were consistent with the experimental results with 0.138 MSE and 0.9824 correction factor values [61].

Another approach to constructing theoretical models is using semi-empirical models developed using dimensionless numbers. There are very few methods used in the literature to determine the performance of OHPs. Shafii et al. have presented an equation (Eq. 5.) where the thermophysical properties of the working fluid, the inner and outer pipe diameters, and the evaporator length are used as effective parameters to determine the thermal characteristic of OHPs [62].

$$\dot{q} = \frac{Q}{2\pi r_i N L_e} \tag{5}$$

Semi empirical model approach is implemented as a combination of theoretical analysis and using a set of empirical data. In the studies carried out, equations using dimensionless numbers have been developed to calculate the Kutadelatze number (Ku), which is a performance representation for OHPs [63]. In Eq. 6, "Ku" is defined as the proportion of the heat flux into the system to the critical heat within the system.

$$Ku = \frac{\dot{q}}{h_{fg}\rho_v{}^{0,5}\{\sigma g(\rho_l - \rho_v)/(\rho_v{}^2)\}^{0,25}} \tag{6}$$

The purpose of theoretical studies is to calculate the "Ku" or maximum heat flux, with the help of dimensionless numbers obtained from experimental data such as Morton number (Mo), Bond number (Bo), Prandtl number (Pr), Jacob number (Ja), Karman number (Ka), and number of turns (N).

The Jacob number is defined by sensible heat transfer and phase change heat transfer, which are the two processes that create heat transfer in OHPs, and expressed as the ratio of sensible heat transfer to phase change heat transfer.

$$Ja = \frac{C_{p,l}\Delta T_{e-c}}{h_{lv}} \tag{7}$$

For liquids, the Prandtl number describes how single-phase convection affects heat transfer.

$$Pr = \frac{C_{p,l}\mu_l}{k_l} \tag{8}$$

Bond number is defined as the buoyancy to surface tension ratio of the working fluid and is expressed as in Eq. 9.

$$Bo = \frac{r_h^2 g(\rho_l - \rho_v)}{\sigma} \tag{9}$$

Morton number (Eq. 10.) is another dimensionless number used in the predicted OHPs performance calculation; It demonstrates the interaction of the viscosity, buoyancy, internal, and surface tension forces that take place when vapor bubbles are formed in the core boiling at the evaporator portion.

$$Mo = \frac{g\mu^4(\rho_{l-}\rho_v)}{\rho_l^2\sigma^3} \tag{10}$$

Karman's number (Eq. 11.) is generally used for closed loop OHP systems. It reveals a proper velocity scale.

$$Ka_s = fRe_l^2 = \frac{\rho_l(\Delta P)_l r_i^2}{\mu_l^2 L_{ef}} \tag{11}$$

Khandekar et al. presented a semi-empirical definition of thermal performance for water, ethanol, and R123 fluids in their work. In the study, the filling ratio of the heat pipe was assumed to be 50% constant, and the effects of the filling ratio on the system performance were ignored. As a consequence of the studies, an equation that predicts the heat flux input of the system has been revealed [63]. The heat flux equation is shown in Eq. 12.

$$\dot{q} = 0{,}54\exp(\beta)^{0,48}\mathrm{Ka}^{0,47}\mathrm{Pr}_l^{0,27}\mathrm{Ja}^{1,43}\mathrm{N}^{-0,27} \tag{12}$$

"β" is the inclination angle of the heat pipe with the horizontal axis. In the calculations, the arithmetic average of the evaporator and condenser temperatures obtained from the experimental data was used. The operating temperature is used to find the thermophysical properties of the working fluids.

Kholi et al. conducted a detailed literature review on previous studies about "Ku", and introduced a new "Ku" approach in line with the data obtained from the literature [64].

$$Ku = \left[f(\emptyset)\left(\frac{d_i}{L_e}\right)^{1,45}\left(\frac{L_e}{L_{ef}}\right)^{0,658}\left(\frac{L_e}{L_k}\right)^{-1,111}\right] * [Pr^{0,881}Ja^{1,109}Bo^{-2,259}[Mo^{-0,101}Ka^{0,018}N^{-0,09}(exp\beta)^{0,21}] \tag{13}$$

In Eq. 13 "f(ø)" is a function dependent on the filling ratio "φ"of the heat pipe. It is defined in Eq. 14.

$$f(\emptyset) = 0{,}26 - 2{,}220\emptyset + 7{,}331\emptyset^2 - 9{,}883\emptyset^3 + 4{,}615\emptyset^4 \tag{14}$$

The different studies from the literature are shown in Table 3. It is clear that the most important aspect of determining an appropriate Ku equation is the use of a large-scale data set.

As seen in literature it is very hard to modelling the two phase flow in capillary tubes. It should be noted that current studies on this subject are not sufficient. On the other hand, semi-empirical model approach is a promising method to construct an effective theoretical model.

There are also some studies done by computational fluid dynamics (CFD) method for OHP systems. CFD method is a useful and strong method for analyzing a thermal system. However, it is known that modelling and specification of complex systems such as OHPs are too hard to apply. As mentioned before, there is a two phase flow and an unpredictable structure of the liquid bubble-vapor slug chain in a capillary channel in OHP systems. On the other hand, with increasing studies, researchers are approaching better modelling methods.

Duy Tan Vo et al. conducted experimental and numerical simulation studies on OHP systems [65]. They produced an 8 turn OHP out of pyrex tubes with an inner diameter of 1.85 mm. Experimental studies were conducted with 50%, 60% filling ratios of R123 working fluid and numerical simulations done by ANSYS Fluent. Volume of fluid (VOF) approach and k-ε turbulence model are applied during analysis. It is discovered that simulation results are in a harmony with experimental results. Rudersha and Kumar tested and numerically analyzed an OHP which made out of copper tubes that have 2mm and 3mm inner and outer diameters respectively [66]. AL_2O_3-Water and SiO_2-Water nanofluids are used as working fluids with different concentration values. Experimental test and CFD analysis are conducted together during study. In the experimental studies, the lowest thermal resistance values for SiO_2 and Al_2O_3 nanofluids were measured as 1.76 and 1.68 K/W respectively, while the CFD results recorded as 2.35 and 1.82 K/W. Lin et al. generated the models of a miniature OHP mathematically and physically [67]. They conducted the CFD analysis of the system with both mixture and VOF approaches and also tested the system physically. It is noted that, mixture approach has better results than VOF but there is still %31.33

average error between experimental and analysis results. Nagwase and Pacghane investigated an OHP system in which DI water used as the working fluid [68]. During the study, experimental and numerical tests were carried out due to varying power inputs. The numerical analysis was carried out by a CFD simulation with the VOF model. As the result of examinations, it was obtained that the thermal resistance decreased with the increasing power input, and it was revealed that there was an error rate between the numerical and experimental results in the range of 5-10%. Gupta and Parwani developed a CFD simulation with the approach of VOF model for an OHP system in accordance with the bottom heating mode and performed the analysis of the system [69]. As seen in the results, the thermal resistance value of the system is recorded as 0.295 K/W for CFD analysis and 0.24K/W for the experimental tests. Suresh and Bahamara have conducted a research on an OHP system in which water-ethanol and water methanol mixtures were used as the working fluid [70]. Experimental studies and CFD analysis were carried out for 50% filling ratio and thermal power input ranging from 10-70W. When the thermal resistance values are examined, it is seen that the error between experimental and CFD studies varies between 6-30%. Rajendra et al. investigated an OHP system, in which DI water was used as the working fluid, experimentally and numerically [71]. According to the results, the thermal resistance values of the system obtained from CFD analysis approached the experimental results with an error of 8%.

The literature research shows that numerical studies carried out on OHP systems have shown an increasing trend in recent years, yet they are still insufficient for the prediction of results. In the current situation, among the estimation approaches, it is revealed that semi empirical methods (dimensionless numbers) provide more acceptable results, while ANN and CFD studies provide promising results. More studies on these issues need to be conducted.

4 Design and experimental procedures for oscillating heat pipes

As in all engineering systems, there are critical points that should be considered during the design of heat pipes.

The selection of the working fluid and the suitable pipe material for the fluid, as well as the diameter selection step, should be initiated during the heat pipe design process. The process works in the same way in OHP systems. The main parameter that affects the OHP system's efficiency is the oscillation motion of the liquid plug-vapor slug chain. It is also known that surface tension, capillary effect, and viscous forces play important roles in the formation of this oscillation motion. Pipe diameters should be determined carefully to generate an appropriate oscillation motion. Pipe diameters in OHP systems should be between 0.5 mm and 3 mm, according to the literature.

One of the major factors affecting the oscillation character is the interaction that takes place at the liquid-vapor contact. In cases where gravitational force is effective, liquid vapor interface characterization is defined according to Bond number. Interface development occurs depending on surface tension and channel diameter. The effects of surface tension on interface formation increase as the channel diameter decreases. The bond (Eq.9) number may also be defined as the ratio of surface tension to body strength.

The value of the bond number affects the oscillation character via surface tension. The effect of the surface tension on the system decreases with increasing Bond number values. For these systems a certain Bond number value limit is specified. Below this limit, the formation of the interface is leaded by surface tension. With the assumption of Bo≤1 the system could work at the area in which effects of surface tension are dominant. If the Eq.9 rearranged for OHP systems, equation of maximum inner diameter can be revealed as follows.

$$r_{i,max} \leq \sqrt{\frac{\sigma Bo}{g(\rho_l - \rho_v)}} \quad (15)$$

Table 3. Semi-empirical models for Ku.

Author	Equations	Conditions
Katpradit et al. [71]	$Ku_0=53.680(r_i/L_e)^{1.127}(C_p\Delta T/h_{lv})^{1.417}[r_i(g(\rho_l- \rho_v)/\sigma))^{0.5}]^{-1.32}$ $Ku_{90}=0.0002(r/L_e)^{0.92}(C_p\Delta T/h_{lv})^{-0.212}[r_i(g(\rho_l- \rho_v)/\sigma))^{0.5}]^{-0.59}[1+(\rho_v/\rho_l)^{0.25}]^{13.06}$	Water, R123, Ethanol, 60°C Working Temperature (WT), 50% Filling Ratio (FR), 0° Inclination angle, 90° Inclination angle
Shafii et al. [62]	$Ku_{90}= a*(c_{pl}\Delta T_{e-c}/h_{lv})^{b}*(c_{pl}\,\mu_l/k_l)^{-0.7}(r_i(g(\rho_l-\rho_v)/\sigma))^{0.85}(\mu(g\Delta\rho_{lv})^{0.25}/\rho_v^{0.5}\sigma^{0.75})^{0.8}(r_i/L_e)^{0.7}(r_o/r_i)^{2.6}$	Water, Ethanol, 30-50% FR, 90° Inclination angle
Qu and Wang [73]	$Ku_{90}= 8,3Bo^{-1.598}Mo^{0.026}Pr^{-3.458}Ja^{*-0.157}(r_i/Le)^{1.21}(Le/Lc)^{-0.232}$	Water, Ethanol, 50% FR, T = (LeTe + LcTc) / (Le + Lc), 90° Inclination angle
Rittidech et al. [74]	$Ku_0= 0.0052[(r_i^{4.3}L_t^{0.1}/Le^{4.4})N^{0.5}(\rho_v/\rho_l)^{-0.2}Pr^{-25}]^{0.116}$	Water, R123, Ethanol, 50 °C WT, 50% FR, 0° Inclination angle
Rittidech et al. [75]	$Ku_{90}= 0.0067[(r_i^{3.1}L_t^{0.1}/L_e^{3.2})^{-0.26}N^{0.9}Pr_{v-l}^{2}(\omega\mu_v^{3}/\sigma^{3}\rho_v)^{0.01}]^{0.175}$	Water, R123, Ethanol, 55°C WT, 50% FR, 90° Inclination angle
Charoansawan et al. [76]	$Ku_0= 2.13x10^{-9}Pr_l 0.75Ja^{-0.38}Bo^{-0.84}Ka^{0.58}(k_c/k_a)^{1.21}$	Water, R123, Ethanol, 50% FR, 0° Inclination angle
Dehshali et al. [77]	$Ku_{rot}=f(\emptyset)Bo^{2.259}Mo^{0.0101}Ja^{1.109}Pr^{0.881}(r_i/L_e)^{1.400}(L_e/L_{ef})^{0.658}exp(0.003Fr)$	Water, Ethanol, Rotational OHP

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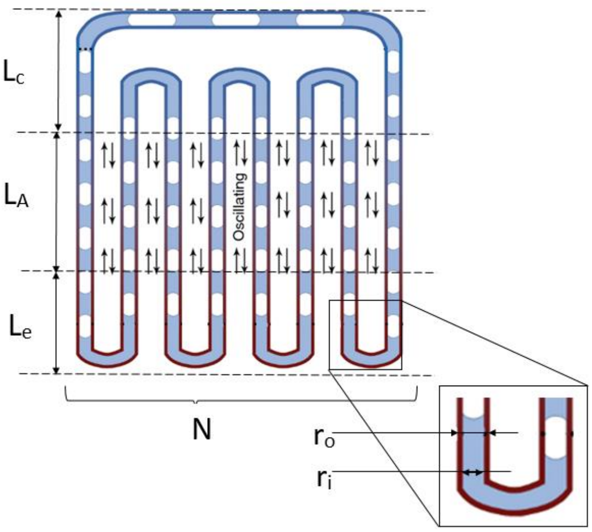

Figure 6. The calculated dimensions of an OHP system.

After determining the diameter value, the evaporator, condenser, and adiabatic zones of the system should be dimensioned. The maximum heat transfer capacity given in Eq. 5 should be considered while determining the evaporator and condenser dimensions during sizing. The size is usually determined by the requirements needed in the application. After the lengths are determined, the effective surface area can be adjusted by producing less or more number of turns. An example of calculated dimensions can be seen in Figure 6.

In the literature research, it is seen that a specific value calculation is not defined for the diameters of turns in OHP systems. This value is usually determined according to the evaporator and condenser dimensions in the application and the effective area needed. However, Belfi stated that the diameter of the turn was designed as 1.5 times the outer diameter of the pipe in the study [78].

In experimental studies, an appropriate experimental setup for the tested systems should be established in order to achieve the right output. The experimental setups used in the experimental studies on the OHP systems were also examined in the literatures. Before evaluating the experimental setup design, it is necessary to define the OHP system's performance evaluations. In OHP systems, system evaluation is carried out over performance and/or thermal resistance values. While calculating these values, the evaporator and condenser temperatures of the system and the heat transfer amounts realized in these regions are used. The first performance evaluation used in OHP systems is system efficiency. In OHP systems, the efficiency of a system is defined as the ratio of heat dissipated in the condenser to heat entering the evaporator and can be expressed as follows.

$$\eta = \frac{\dot{Q}_c}{\dot{Q}_e} = \frac{\dot{Q}_o}{\dot{Q}_i} \qquad (16)$$

Here, the heat entering the system in the evaporator zone is also considered as the power input of the system. Thermal resistance is another term used in system evaluation. The thermal resistance is expressed as the following and is the temperature differential between the system's evaporator and condenser regions divided by the system's power input.

$$R_t = \frac{\Delta T}{\dot{Q}_i} \qquad (17)$$

The arithmetic averages of the temperatures measured from the channel surfaces for each of the evaporator and condenser regions are used to calculate the temperature difference in this case. In experimental studies, a heat source should be placed near the evaporator area and the condenser area should be exposed to a heat sink. These heating and cooling processes can be accomplished in a variety of ways. Heating methods that use electrical energy are quite common. When a suitable insulation is performed in applications such as wire winding and metal plate integration to the evaporator area, the power input of the system can be obtained directly by electrical power measurement. In addition, methods such as water flow, air flow, and solar radiation heating can also be used. Cooling with water flow is the most commonly used cooling process. The amount of heat transfer occurring on the fluid in processes involving fluids such as water and air is computed by measuring the mass flow rate, the input and outlet temperatures, and the heat transfer rate in the system.

The heating and cooling methods should be decided first when establishing a suitable experimental setup for testing an OHP system that has been designed and manufactured. Calibrated measuring instruments should be integrated into the zones described above, according to the method to be used. Excellent heat pipe insulation is critical for measurement accuracy. System analyses can be performed after the data has been transferred to the PC environment using a data logger.

5 Oscillating heat pipe applications

Detailed descriptions of OHPs are given in the previous sections. In this section examples of different application areas in the literature are given. OHPs have found their place in almost every area where heat transfer processes are used because of their simple structure and ease of application. These applications appear in different types and forms according to factors such as working conditions.

5.1 Low temperature applications

Low operating temperatures have a negative impact on most heat transfer systems. A start-up point for these systems is often established in accordance with the thermal power input. Among heat pipe systems, OHP systems also suffer from performance declines at low working temperatures. The driving force in these systems that produces the oscillation movement occurs once the steam pressure rises. When sufficient thermal power input isn't provided to the system evaporator, the required steam pressure in the system does not occur, and the oscillation movement does not start. In this case, heat transfer in the system does not occur and the system fails to function. The evaporation point of the fluid has crucial importance in determining the system's start-up point at low temperatures. The evaporation temperature of the selected fluid should be lower than the operating temperature of the system.

Liang et al. experimentally investigated a 4-turn heat pipe made of 0.9 mm diameter stainless steel pipe [79]. The heat pipe using neon as the working fluid was tested for different filling ratios, and the effective conductivity value for a 24.5% filling ratio was recorded to be between 6100 W/mK - 22.180 W/mK. Liang et al. in their study, they investigated the effect of condenser temperature and filling ratio effect on cryogenic OHPs experimentally [80]. The study revealed that the system fails when there is a dry out at low fill ratios and increases in condenser temperatures cause a decrease in thermal resistance values at constant heat input. Yong Hoon Im et al. designed an OHP-Heat Storage system for sub-zero temperatures with a 5-Turn OHP using R-134A refrigerant as the working fluid and investigated the system experimentally [81]. When the results are examined, it is seen that the lowest thermal resistance value of 1.18 K/W is obtained for -20°C outdoor and 0°C heat storage temperatures. Sagar et al. tested a 2-Turn OHP system using liquid nitrogen as the working fluid for 38%, 57%, 76%, and 95% filling ratios, with heat inputs ranging from 1 W – 80 W [82]. The results show that the ideal filling ratio for the system is 76%, and the maximum heat transfer capacity that can be achieved without dry out is 70 W.

5.2 Oscillating heat pipes in electronic cooling

The cooling processes of electronic devices have become an important issue nowadays. Most electronic devices show decreasing performance values with increasing working temperatures. Some system components could malfunction, or very high energy losses may occur as a result of these performance declines. Repairing or changing malfunctioning components may cause high costs for electronics. In addition, an effective cooling system can result in significant energy cost reductions when viewed in terms of energy management. However, the fragile structure of electronic devices complicates the heat management processes. On the other hand, the requirement for a highly compact cooling system adds to the process's complexity. OHP systems are closed systems, and it is safe to integrate them with electronics. Micro OHPs can also be used to alleviate the sizing issue. Example studies on electronic applications of OHP systems are given below.

Wang et al. investigated the phase change material-OHP battery heat management system experimentally [83]. When the results are examined, it is seen that the startup temperature of the OHP should be below the phase change temperature for an acceptable temperature distribution. The terminals that function as batteries should be located away from the adiabatic region. It has also been noted that this novel system is more efficient than the use of a lean OHP. Lv et al. used OHP system to cool a 100 W led chip [84]. It has been experimentally proven that the water fluid system cools more effectively than two other systems that use water and methanol as working fluids. Wang et al. designed a three-dimensional OHP system for use in electronic chip cooling [85]. Sintered copper particles are added to the system evaporator to improve the thermal efficiency of the OHP system. The results reveal that the addition of copper particles significantly enhances heat pipe performance. Wang et al. used the three-dimensional OHP system that they had developed in their previous work for cooling concentrated photovoltaic cells (CPV) [86]. CPV cells should be kept below 57°C. It has been observed that the system is suitable for a heat flux of 5.88W/cm^2. Ling et al. investigated various structural effects on three-dimensional OHPs to be used for cooling electronic device surfaces [87]. They have demonstrated that electronic device surfaces can be kept below 35°C with the new leaf-shaped 3-D OHP (Figure 7.) with phase changing material (PCM) system and this system works with higher performance than conventional ones. Li and Li designed and produced a novel OHP system which aimed to be used to cooling CPUs of a data center servers [88]. OHP devices were tested with acetone and R133 working fluids with different filling ratios. It is discovered that optimum filling ratio is changing between 75%- 80% and the lowest thermal resistance of the system obtained as 0.225 ^{o}C/W with acetone working fluid. It is also noted that the OHP system removes about 250 W heat from CPU.

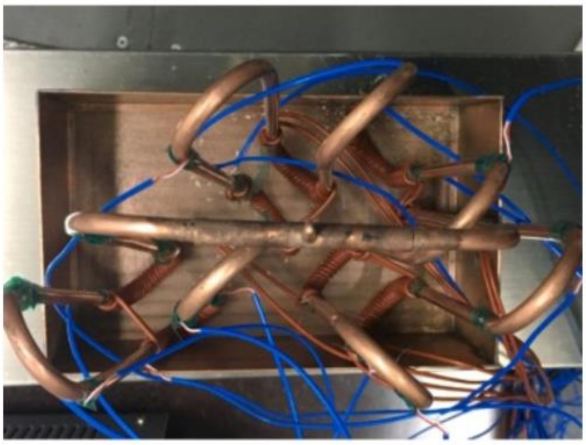

Figure7. 3D OHP system for CPV cooling [88].

5.3 Oscillating heat pipes for heat recovery

Heating, ventilating, and air conditioning (HVAC) systems have the largest share in energy consumption on a global scale. Nowadays, the majority of thermal energy management research is conducted on these systems. The use of more efficient HVAC systems, especially in temperate and hot climate regions, has been shown to significantly reduce energy costs. Heat recovery applications appear to be a viable solution for improving system performance. Heat recovery is a process that meets a portion of the air conditioning requirement by providing pre-cooling or pre-heating as needed. Aside from these, the reuse of waste heat is a required method other than air conditioning. The fact that, the energy, that has already been converted into heat is not discharged into the environment has a positive impact on environmental sustainability. Case studies on heat recovery applications of OHP systems are given in this section.

Mahajan et al. experimentally studied on an OHP – heat exchanger (OHP-HEX) system with an OHP (Figure 8.) to improve the performance of a ventilation system [89]. The system preheats the fresh air using the heat extracted from the exhaust air. When the analysis results are examined, it is seen that the system provides 40 Pa pressure drop and 8°C preheat. Wan et al. carried out experimental studies for low-grade energy recovery with the graphene oxide nanofluid OHP system [90]. It has been observed that the system performance increased by 8.55% with a working fluid with a concentration of 0.03% by mass for heat inputs ranging from 10 to 100 W. Zhao et al. designed and tested an external expansion OHP system for use in heat recovery and storage [91]. Experiments with water and self-rewetting working fluids revealed that in all cases, water has a more stable structure. Liu et al. developed a top-heating OHP system for a diesel vehicle to preheat the fuel with the heat drawn from exhaust gas [92]. With this system, a thermal conductor made of pure copper has been tested comparatively, and it has been seen that the OHP system exhibits 1.66 times higher performance values than pure copper, as well as being lighter in weight. Mahajan et al. have developed an OHP-Heat exchanger (HEX) system for preheating and precooling in building ventilation systems [93]. Experimental studies on the 1x0.5 m² OHP-HEX system have revealed that the ventilation systems energy usage is radically reduced with the OHP-HEX integration.

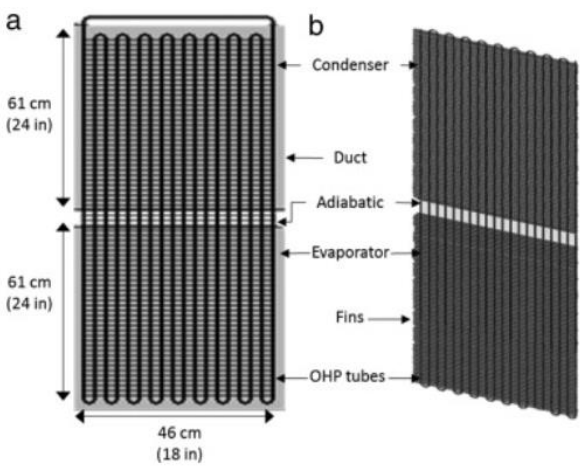

Figure 8. OHP heat exchanger [85].

5.4 Solar oscillating heat pipe applications

Solar energy, which is widely acknowledged as our planet's primary energy source, has a structure that stands out among usable resources due to its environmentally friendly structure, low operating costs, and ease of operation. Solar energy can be used in a variety of ways. While humanity's annual energy consumption is approximately 54 billion MW/h, the total energy received from the sun in a year is 28 thousand times this value, or 1.5 quadrillion MW/h. According to the report of International Energy Agency, the energy of sunlight reaching the planet in 1.5 hours is equal to the energy need for one year, and by 2050, solar energy is expected to provide 11% of our planet's energy needs [94].

Especially in thermal applications of solar energy systems, studies on efficiency increases with the development of various integrated systems, are common. In this study, OHP solar energy applications on distillation systems, water heating systems, space heating systems, and power generation systems are investigated.

Jin et al. experimentally investigated a transparent OHP system using solar absorptive nanofluid with the aim of the increase the thermal performance in solar energy systems [95]. It is noted that the system showed the lowest thermal resistance value at %83 filling ratio, and the thermal conductivity value was 6000 W/mK in the use of 3% nanofluid. The energy conversion performance of the system reached up to 92%. Xu et al. developed a novel solar collector in which they use an OHP system as a solar absorber to a parabolic solar collector [96]. With experimental studies, it was observed that the OHP thermal resistance reduced to 0.26°C/W and both the total collector and OHP efficiency increased with increasing evaporator temperature. Wang et al. aimed to develop a system with high efficiency value for solar energy harvesting by combining an OHP and a thermoelectric generator (Figure 9.) [97]. The thermoelectric generator integrated on the OHP condenser receives the heat from the system's OHP evaporator, which is directly exposed to sunlight. The findings indicate that the maximum energy conversion efficiency of the system is 1.22%. Aref et al. investigated the efficiency increase in a combined OHP system [98]. They combine a variable diameter OHP with a solar collector. The OHP condenser used in the system is created by the pipes with an inner diameter of 3 mm, and the adiabatic and evaporator parts have an inner diameter of 2 mm. Experimental investigations have shown that the developed system works with 72.4% efficiency for 60% filling ratio under 1030 W/m² thermal irradiance. Zhao et al. developed a system using OHP to perform long distance heat transfer processes in solar collectors [99]. Water and self-rewetting fluids were used as working fluids in the tests carried out with different OHPs with 3 mm and 4 mm inner diameter values. It has been observed that the 3 mm inner diameter heat pipe works more efficiently, and the startup temperature increases with the increasing filling ratio.

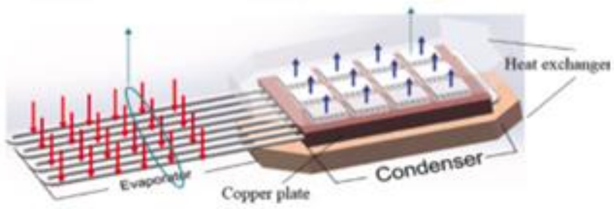

Figure 9. OHP electric generator [97]

5.5 Structural studies

Because of their working mechanisms, OHP systems are highly affected by gravitational forces. The fluid, whose vapor pressure rises as it absorbs heat in the evaporator region, moves into the condenser region by working against gravity. The fluid, whose vapor pressure rises as it absorbs heat in the evaporator area, moves into the condenser area by working against gravity. The fluid, whose vapor pressure decreases in the condenser region due to heat transfer to the environment, returns to the evaporator region due to gravity force. Furthermore, the heat transfer surface area is a constraint for OHP systems. Because these devices are made of capillary pipes (0.5 mm - 3 mm in diameter), the surface area where the heat transfer process occurs is small. There are numerous studies and similar issues in the literature that address these. Various geometric structures and configurations were used in studies aimed at system improvement.

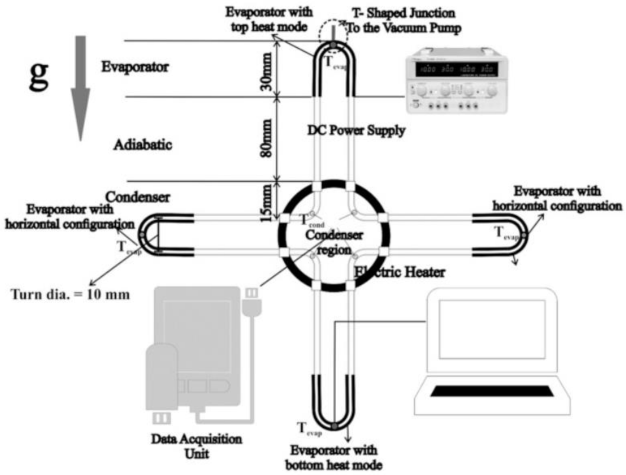

Figure 10. Rotational closed loop oscillating heat pipe system testing station [77].

The effects of axial rotation on performance on a single turn closed-loop OHP system were investigated by Qian et al. [100]. Experiments and theoretical studies were conducted. The experimental studies revealed that increasing the rotation speed and power input improved system performance. The errors in theoretical studies evaluated using the gray system approach ranged from 3.36% to 16.6%. Dehshsali et al. studied the effects of rotational speed and fill rate on system performance in closed-loop OHP systems with rotation [77]. Schematic of the rotating heat pipe system has shown in Figure 10. The fluids in the experiments were pure water and ethanol. Experiments were carried out at speeds of 200, 400, 600, and 800 rpm and filling ratios of 30%, 50%, and 70%. When the results were examined, it was discovered that 50% filling ratio produced the best results for both fluids. When 800 rpm and 200 rpm speeds were compared, it was discovered that water had a 13% lower thermal resistance and ethanol had a 5.6% lower thermal resistance at 800 rpm. Tseng et al. presented a new oscillating heat pipe design with a 3D structure [101]. Two 54*60mm copper blocks were integrated into the evaporator part of the heat pipe in the experimental setup, and the thermal power input of the system was provided through these blocks. As a result of the experimental studies, it was discovered that the thermal resistance value of the system reduced from 0.148K/W to 0.0595K/W as the thermal power input increased up to 1 kW. Qu et al. have made an experimental study on a multilayer structure [102]. In the study, heat pipes with different layers were tested for different thermal power inputs and filling ratios, as well as on a two-dimensional oscillating heat pipe of comparable dimensions for comparison. The copper heat pipes used in the experiments had an inner and outer diameter of, respectively, 2mm and 3 mm. In horizontal and vertical deployment scenarios, tests were carried out on 1, 2, 3, 4, and 5-layer three-dimensional heat pipes. As a result of the experiments, it was discovered that the initial operating temperature decreases as the number of layers increases from 1 to 4, with the 5-layer heat pipe having the highest value for this parameter. Qu et al. aimed to create a flexible oscillating heat pipe with their research [103]. The heat pipe is made from an internal micro-channel (grooved) copper tube with an outer diameter of 4 mm, fluororubber 246 with an outer diameter of 6 mm and an inner diameter of 4 mm which is used to provide adiabatic flexibility. External fin integration has been achieved in the heat pipe's condenser section. While distilled water was selected as the fluid in the experiments, the tests were repeated at 50, 60 and 70% fill rates for four different geometric configurations of the heat pipe. It has been discovered that the heat pipe performs best in the upright and flat positions. Lyu et al. experimentally investigated an OHP system with helium as the working fluid [104]. They tested the effect of inclination angle, filling ratio and heat input on the system's efficiency. It is noted that the optimum filling ratio is changing with different heat input values. The highest conductivity is obtained as 12357 W/mK at 90^{o} inclination angle and 66.1% filling ratio.

5.6 Other applications of oscillating heat pipes

This section contains examples of other OHP applications that were not covered in the previous sections.

Liu et al. have made experimental studies to reveal the thermo-hydrodynamic characteristics of micro OHP systems [105]. The channel diameter of the heat pipe used in experiments was 50 µm and the working fluid was acetone. In experiments, the effects of filling ratio, inclination angle, and heat input parameters on the system's performance were investigated, and it was noted that the optimum filling ratio was 53% for the system. Iwata et al. designed an OHP band system for use in space applications [106]. HFC-134a was selected as the fluid in the heat pipe system with a channel diameter of 0.4 mm. It has been experimentally demonstrated that the heat pipe system can work even in horizontal positioning; thermal resistance starts to increase at temperatures below 20°C and does not operate below −15 °C. Yu et al. developed an 18 channel three-dimensional OHP system for use in high power applications [107]. In the study, a novel liquid metal-ammonia hybrid mixture was used as the working fluid. In experimental studies, it has been seen that the system can operate effectively under 1000 W heat input and 111.1 W/cm^2 heat flux conditions. It was noted that the use of liquid metal fluid affected the system's performance quite well, and the thermal resistance was reduced to 0.0351°C/W. Wu et al. experimentally tested a high temperature OHP (over 500°C) with liquid metal working fluid [108]. The working fluid is prepared with 78% potassium and 22% sodium metals. They discovered that the system may work successfully between 22% - 80% filling ratio values and increasing filling ratio decreases the requirement of heat input value. It is noted that the lowest thermal resistance has obtained at 58% filling ratio and 0° inclination angle.

6 Conclusions

In this study, OHP systems have been described in detail. Theoretical studies and the latest applications in the literature about these systems have been investigated.

In conclusion;

- Modelling studies are insufficient due to the complex structure of two-phase flow that occurs in OHP during the heat transfer process. The semi-empirical model approach [72]-[77] has better solutions than others. The ANN model [60]-[62] and CFD analysis [68]-[71] have promising solutions, yet there should be more theoretical studies to reveal a consistent mathematical model.
- One of the most crucial factors that directly influences system performance is working fluid. Fluids with higher viscosities and/or corrosiveness etc. affects system performance negatively. The nanofluid OHP systems show better efficiency than conventional

fluids [25], [27], [34]. The addition of nanoparticles, the fluid conductivity can be increased up to 78% [39] and the systems thermal resistance can be decreased up to 83.6% [39]. With the use of nanofluids, nanoparticles may accumulate at the evaporator section in case of overheating, and this situation increases the thermal resistance.

- Dry out situation occurs in the system when filling ratios are insufficient or thermal power inputs are too high [80]-[82]. According to the filling ratio, dry out increases thermal resistance.
- In general, OHP systems perform better in cooling applications than in heating applications. Electronic cooling, surface cooling, and heat exchanger applications present lower thermal resistance values [84],[85],[93],[95],[103].
- The tilt angle appears to have a significant effect on system performance. OHP systems show the best performance values in vertical position with bottom heated mode [98]. Studies can be conducted to pave the way for use independent of gravity.
- Simple structure, ease of production, and a wide working temperature range make these devices useful and economical in heat transfer processes.

7 Author contribution statements

In the scope of this study, authors, in the formation of the idea, literature review, writing and editing the article, were contributed.

8 Ethics committee approval and conflict of interest statement

The prepared article does not require approval from the ethics committee.

The article was written with no conflict of interest with any individual or organization.

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