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THERMAL PERFORMANCE MEASUREMENT OF HEAT PIPE

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Abstract:
Heat pipe is device working on two phase change of working fluid inside. This phase change of working fluid lead to increasing heat transport efficiency of heat pipe. The basic heat pipe working position is vertical position, when the heat pipe can transport maximal heat flow from evaporator to condensator. This article deal about wick heat pipe construction and propose device to identify thermal performance. The result of article is comparison of thermal performance transported by heat pipe from working positions.

Key words: Heat pipe, heat transfer, thermal performance, capillary structure, experimental measurement

1. Introduction

Capillary-driven two-phase systems offer significant advantages over traditional single-phase systems. With the typically increased thermal capacity associated with the phase change of a working fluid, considerably smaller mass flow rates are required to transport equivalent amounts than in single-phase liquid or gas systems for a given temperature range. Moreover, heat transfer coefficients of two-phase systems are much greater than in single-phase flows and result in enhanced heat transfer. Lower mass flow rates and enhanced thermal characteristics provide the benefits of smaller system size (and weight) while providing increased performance. The thermal capacity of a single-phase system depends on the temperature change of the working fluid; thus, a large temperature gradient or a high mass flow rate is required to transfer a large amount of heat. However, a two-phase system can provide essentially isothermal operation regardless of variations in the heat load. Additionally, singlephase systems require the use of mechanical pumps and fans to circulate the working fluid, while capillary-driven two-phase systems have no external power requirements, which make such systems more reliable and free of vibration. The best known capillary-driven two-phase system is the heat pipe, where a schematic of a conventional heat pipe is shown in Fig. 1. The concept of the heat pipe was first presented by [1] and [2], but was not widely publicized until an independent development by [3] at the Los Alamos Scientific Laboratories. Heat pipes are passive devices that transport heat from a heat source (evaporator) to a heat sink (condenser) over relatively long distances via the latent heat of vaporization of a working fluid. As shown, a heat pipe generally has three sections: an evaporator section, an adiabatic (or transport) section, and a condenser section. [4].

With evaporator heat addition, the working fluid is evaporated as it absorbs an amount of heat equivalent to the latent heat of vaporization, while in the condenser section, the working fluid vapor is condensed. The mass addition in the vapor core of the evaporator section and mass rejection in the condenser end results in a pressure gradient along the vapor channel which drives the corresponding vapor flow. Return of the liquid to the evaporator from the condenser is provided by the wick structure. As vaporization occurs in the evaporator, the liquid meniscus recedes correspondingly into the wick structure. Similarly, as vapor condenses in the condenser region, the mass addition results in an advanced meniscus. The difference between the capillary radii in the evaporator and condenser ends of the wick structure results in a net pressure difference in the liquid-saturated wick. This pressure difference drives the liquid from the condenser through the wick structure to the evaporator region, thus allowing the overall process to be continuous [4].

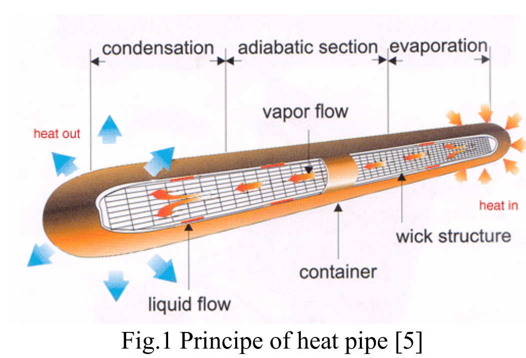

Fig.1 Principe of heat pipe [5]

Due to the two-phase characteristics, the heat pipe is ideal for transferring heat over long distances with a very small temperature drop and for creating a nearly isothermal surface for temperature stabilization. As the working fluid operates in a thermodynamic saturated state, heat is transported using the latent heat of vaporization instead of sensible heat or conduction where the heat pipe then operates in a nearly isothermal condition. This nearly isothermal condition offers benefits of transporting large amounts of heat efficiently, decreasing the overall heat transfer area and saving system weight. The amount of heat that can be transported through the use of latent heat is typically several orders of magnitude greater than transported by sensible heat for a geometrically equivalent system. Additionally, no mechanical pumping systems are required due to the capillary-driven working fluid. Given the wide range of operating temperatures for working fluids, the high efficiencies, the low relative weights, and the absence of external pumps in heat pipes, these systems are seen as attractive options in a wide range of heat transfer applications [4].

2. Heat pipe construction

The major components of a heat pipe are a sealed container, a wick structure, and a working fluid. The wick structure is placed on the inner surface of the heat pipe wall and is saturated with the liquid working and provides the structure to develop the capillary action for liquid returning from the condenser to the evaporator. Return of the liquid to the evaporator from the condenser is provided by wick structure. [6].

2.1 Heat pipe container

The container, working fluid, and wick structure of a heat pipe determine its operational characteristics. One of the most important considerations in choosing the material for the heat pipe container and wick is its compatibility with the working fluid. Degradation of the container or wick and contamination of the working fluid due to chemical reaction can seriously impair heat pipe performance. For example, noncondensable gas created during a chemical reaction eventually can accumulate near the end of the condenser, decreasing the condensation surface area. This reduces the ability of the heat pipe to transfer heat to the external heat sink. The material and geometry of the heat pipe container also must have a high burst strength, low weight, high thermal conductivity, and low porosity [7].

2.2 Working fluid

Using the proper working fluid for a given application is another critical element of proper heat pipe operation. The working fluid must have good thermal stability properties at the specified operational temperature and pressure. The operational temperature range of the working fluid has to lie between its triple point and its critical point for liquid to exist in the wicking material. The wettability of the working fluid contributes to its capillary pumping and priming capability. High-surface-tension fluids are commonly used in heat pipes because they provide the capillary pumping and wetting characteristics necessary for proper operation. Other desirable thermophysical properties include a high liquid thermal conductivity, high latent heat of vaporization, low liquid viscosity, and a low vapor viscosity [7].

2.3 Wick Structures

The wick structure and working fluid generate the capillary forces required to pump liquid from the condenser to the evaporator and keep liquid evenly distributed in the wicking material. Heat pipe wicks can be classified as either homogeneous wicks or composite wicks. Homogeneous wicks are composed of a single material and configuration. The most common types of homogeneous wicks are wrapped screen, sintered metal and axial groove. Composite wicks are composed of two or more materials and configurations. The most common types of composite wicks are variable screen mesh, screen-covered groove, screen slab with grooves, and screen tunnel with grooves. Regardless of the wick configuration, the desired material properties and structural characteristics of heat pipe wick structures are a high thermal conductivity, high wick porosity, small capillary radius, and high wick permeability [7].

3. Heat pipe classification

3.1 Heat pipe classification by wick structure

The wick provides a means for the flow of liquid from the condenser to the evaporator section of the heat pipe. It also provides surface pores that are required at the liquid–vapor interface for development of the required capillary pressure. The wick structure also has an impact on the radial temperature drop at the evaporator end between the inner heat pipe surface and the liquid–vapor surface. Thus, an effective wick requires large internal pores in a direction normal to the heat flow path. This will minimize liquid flow resistance. In addition, small surface pores are required for the development of high capillary pressure and a highly conductive heat flow path for minimization of the radial surface to liquid–vapor surface temperature drop. To satisfy these requirements, two types of wick structure have been developed. These are the homogeneous wicks made of a single material, examples of which are shown in Fig. 2, and the composite wicks containing two or more materials, with some typical examples displayed in Fig. 3.

One common wick structure is the wrapped screen wick shown in Fig. 2*a*. This type of wick structure is designated by its mesh number, which is an indication of the number of pores per unit length or unit surface area. The surface pore size is inversely proportional to the mesh number and the liquid flow resistance can be controlled by the tightness of the wrapping. This is attractive, but because of the interruptions in the wick metal by a liquid of low thermal conductivity in the moderate-range heat pipe, the radial temperature drop from the inner pipe surface to the liquid–vapor surface at the evaporator end can be quite high. This problem can be alleviated through use of the sintered metal wick structure shown in Fig. 2*b*. Notice here that the pore size is small but the small pores will make it more difficult for the liquid to flow from the condenser to the evaporator [4].

The axially grooved wick shown in Fig. 2*c* possesses highly conductive metal paths for the minimization of radial temperature drop. Axially grooved heat pipes are most commonly found in space applications. The annular and crescent wicks, shown respectively in Fig. 2*d* and *e*, have small resistance to liquid flow but are vulnerable to liquids of low thermal conductivity. The artery wick, shown in Fig. 2*f* was developed to reduce the thickness of the radial heat flow path through the structure and to provide a low-resistance path for the liquid flow from the condenser to the evaporator. However, these wicks often lead to operating problems if they are not self-priming, because the arteries must fill automatically at startup or after a dryout [4].

3. 2. Heat-pipe classification by working fluid

Theoretically, heat pipe operation is possible at any temperature between the triple state and the critical point of the working fluid utilized, albeit at significantly reduced transport capabilities near the two extremes due to the fluid property characteristics of surface tension and viscosity. Several typical heat pipe working fluids are given in Table 1, along with the corresponding triple point, critical point, and most widely utilized temperature range for each individual fluid. Classification of heat pipes may be in terms of geometry, intended applications, or the type of working fluid utilized. Each heat pipe application has a temperature range in which the heat pipe is intended to operate. Therefore, the working fluid must be chosen to take into account this operating temperature (along with the pressure condition), but also its chemical compatibility with the container and wick materials. Depending on operating temperature, four different types of heat pipes are usually described with regard to commonly used working fluids:

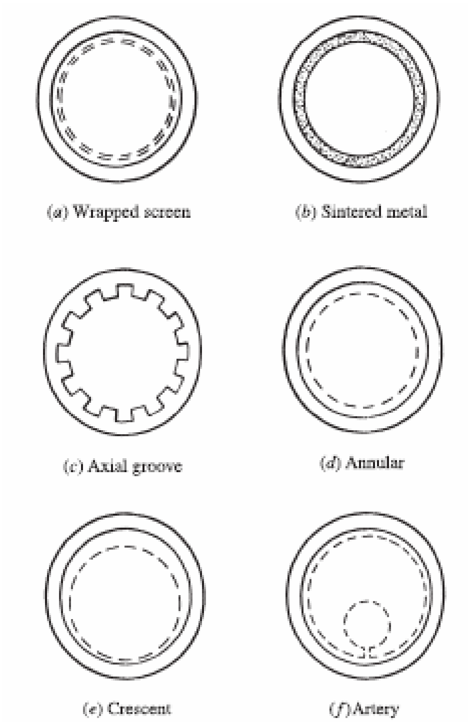

Fig. 2 Cross sections of homogenous wick structures [8]

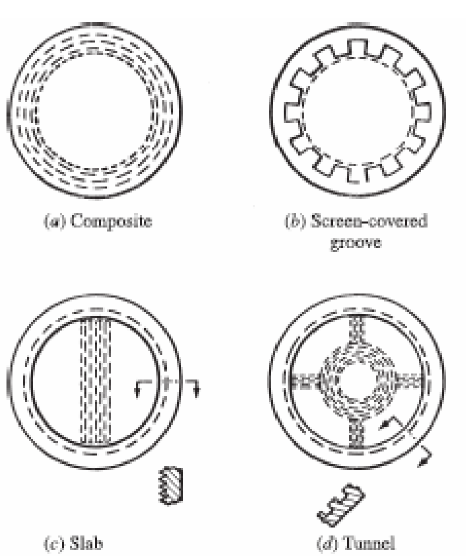

Fig. 3 Cross sections of composite wick structures [8]

All the composite wicks shown in Fig. 3 have a separate structure for development of the capillary pressure and liquid flow. Notice that in some of the structures in Fig. 3, a separation of the heat flow path from the liquid flow path can be provided. For example, the screen-covered groove wick shown in Fig. 3*b* has a fine mesh screen for high capillary pressure, axial grooves to reduce flow resistance, and a metal structure to reduce the radial temperature drop. The slab wick displayed in Fig. 3*c* is inserted into an internally threaded container. High capillary pressure is derived from a layer of fine mesh screen at the surface, and liquid flow is assured by the coarse screen inside the slab. The threaded grooves tend to provide uniform circumferential distribution of liquid and enhance radial heat transfer [4].

1. *Cryogenic heat pipes* designed to operate from 1 to 200 K, with working fluids such as helium, argon, neon, nitrogen, and oxygen. These typically have relatively low heat transfer capabilities, due to very low values of the latent heat of vaporization and low surface tensions of the working fluids. In addition, startup of the heat pipe involves transitioning from a supercritical state to an operating liquid–vapor condition.
2. *Room (low)-temperature heat pipes* with operating temperatures ranging between 200 and 550 K. Working fluids typically used in this range include methanol, ethanol, ammonia, acetone, and water.
3. *Medium-temperature heat pipes* with operating temperatures ranging from 550 to 700 K. Mercury and sulfur are typical fluids in this range, along with some organic fluids (e.g., naphthalene and biphenyl).
4. *High (liquid-metal)-temperature heat pipes* operating above 700 K. Very high heat fluxes can be obtained using liquid metals due to the characteristics of the fluid: namely, very large surface tensions and high latent heats of vaporization. Examples of liquid metals commonly used include potassium, sodium, and silver. In the case of liquid metal heat pipes, startup typically involves starting from an initially frozen working fluid [4].

Table 1 Typical heat pipe working fluids [4]

Working Fluid	Triple Point (K)	Critical Point (K)	Useful Range (K)
Oxygen	54.3	154.8	55–154
Nitrogen	63.1	126.2	65–125
Ethane	89.9	305.5	100–305
Butane	134.8	425.0	260–350
Methanol	175.2	513.2	273–503
Toluene	178.1	593.9	275–473
Acetone	180.0	508.2	250–475
Ammonia	195.5	405.6	200–405
Mercury	234.3	1763	280–1070
Water	273.2	647.3	273–643
Potassium	336.4	2250	400–1800
Sodium	371.0	2500	400–1500
Lithium	453.7	3800	500–2100
Silver	1234	7500	1600–2400

Because the amount of heat transferred by a heat pipe depends on the latent heat of vaporization, the transfer of appreciable quantities of heat is possible, even for long distances. Axial heat flows of 10^8 W/m^2 are easily reachable with sodium heat pipes. By calculating an effective thermal conductivity k_{eff}, values may reach 108 W/m.K (sodium heat pipe) [9], which is several orders of magnitude greater than the conductivity of the best conductors. One of the most common applications of a heat pipe is that of a heat flux transformer. Using a heat pipe, high heat fluxes from a heat source can be injected over a small surface area, which is then rejected over a larger condenser surface area. Thermal flux transformation ratios greater than 10 : 1 can allow systems to employ final heat rejection with low cooling capability methods, such as natural convection or single-phase cooling [4].

3.3 Heat pipe classification by type of control

In addition to classification by the temperature range of the working fluid, heat pipes may be classified by the type of control employed. Control is often necessary because a heat pipe without control will self-adjust its operating temperature in accordance with the heat source at the evaporator end and the heat sink at the condenser end. For example, it may be desirable to control the temperature in the range prescribed in the presence of a wide range of variations in heat source and heat sink temperatures. On the other hand, it may be required to permit the passage of heat under one set of conditions and block the heat flow completely under another set of conditions. This leads to a consideration of the performance of heat pipes known as thermal switches and thermal diodes. There are described four major control approaches.

1. *Gas-loaded heat pipe.* The presence of a noncondensible gas has a marked effect on the performance of a condenser. This effect can be exploited for heat pipe control. Any noncondensible gas present in the vapor space is swept to the condenser section during operation, and gas will block a portion of the condenser surface. The heat flow at the condenser can be controlled by controlling the volume of the noncondensible gas.
2. *Excess-liquid heat pipe.* Control can also be attained by condenser flooding with excess working fluid. In the excess-liquid heat pipe, excess working fluid in the liquid phase is swept into the condenser and blocks a portion of the condenser. In case of variable conductance observe that a decrease in vapor temperature will expand the control fluid in the bellows, which forces excess liquid to block a portion of the condenser.
3. *Vapor flow–modulated heat pipe.* The performance of the heat pipe can be controlled by the vapor flow through the adiabatic section. Increase in heat input or an increase in heat source temperature felt at the surface of the evaporator causes a rise in the temperature and pressure of the vapor in the evaporator section. The flow of this vapor through the throttling valve creates a temperature and pressure drop that results in a reduction in the magnitudes of these quantities in the condenser section. Thus, the condensing temperature and pressure can be held at values that yield the required condenser performance even though the temperature at the heat source has increased. In the event that the heat input increases, the condenser can keep pace with this increase and adjust its performance by means of the throttling valve.
4. *Liquid flow–modulated heat pipe.* Liquid flow control is also an effective way of maintaining control over heat pipe performance. One way of controlling liquid flow is through the use of a liquid trap. This trap is a wick-lined reservoir located in the evaporator end. The wick in the trap, referred to as the trap wick, is not connected to the operating wick in the rest of the heat pipe. In the normal mode of operation with the heat pipe operating in the standard fashion, the trap wick is dry. If the heat input increases or the attitude of the heat pipe changes, condensation may occur in the trap and the liquid trap may become an alternate condensing end of the pipe. As liquid accumulates in the trap, the main wick begins dryout which results in operational failure. An example of a heat pipe with the evaporator section below the condenser section is a type of control because the heat pipe can function as a thermal diode providing that the wick is designed appropriately. Notice that the condensed liquid is returned to the evaporator section with the assistance of the gravitational force. This type of heat pipe is commonly referred to as a thermosyphon. [4].

4. Operation of heat pipe

The overall thermal resistance of a heat pipe, defined by equation, should be low, providing that it functions correctly.

$$R = \frac{T_{hot} - T_{cold}}{\dot{Q}} \qquad (1)[10]$$

In order for the heat pipe to operate the maximum capillary pumping pressure, $\Delta P_{c,max}$ must be greater than the total pressure drop in the pipe. This pressure drop is made up of three components.

1. The pressure drop ΔP_l required to return the liquid from the condenser to the evaporator.
2. The pressure drop ΔP_v necessary to cause the vapour to flow from the evaporator to the condenser.
3. The pressure due to the gravitational head, ΔP_g which may be zero, positive or negative, depending on the inclination of the heat pipe.

For correct operation,

$$\Delta P_{c,max} \geq \Delta P_l + \Delta P_v + \Delta P_g \qquad (2)\ [10]$$

If this condition is not met, the wick will dry out in the evaporator region and the heat pipe will not operate. The maximum allowable heat flux for which equation 2 holds is referred to as the capillary limit. Typically, the capillary limit will determine the maximum heat flux over much of the operating range; however, the designer must check that a heat pipe is not required to function outside the envelope either at design conditions or at start-up. During start-up and with certain high-temperature liquid metal heat pipes, the vapour velocity may reach sonic values. The sonic velocity sets a limit on the heat pipe performance. At velocities approaching sonic, compressibility effects must be taken into account in the calculation of the vapour pressure drop. The viscous or vapour pressure limit is also generally the most important at start-up. At low temperature, the vapour pressure of the fluid in the evaporator is very low, and, since the condenser pressure cannot be less than zero, the maximum difference in vapour pressure is insufficient to overcome viscous and gravitational forces, thus preventing satisfactory operation. At high heat fluxes, the vapour velocity necessarily increases; if this velocity is sufficient to entrain liquid returning to the evaporator, then performance will decline, hence the existence of an entrainment limit. The above limits relate to axial flow through the heat pipe. The final operating limit discussed will be the boiling limit. The radial heat flux in the evaporator is accompanied by a temperature difference that is relatively small until a critical value of heat flux is reached above which vapour blankets the evaporator surface resulting in an excessive temperature difference [10].

Total heat flux may by readily be obtained if we assume:

1. the liquid properties do not vary along the pipe,
2. the wick is uniform along the pipe,
3. the pressure drop due to vapour flow can by neglected.

$$\dot{m}_{max} = \left[\frac{\rho_l.\sigma_l}{\mu_l}\right].\left[\frac{K.A}{l}\right].\left[\frac{2}{r_e} - \frac{\rho_l.g.l}{\sigma_l}.\sin\theta\right] \qquad (3)[10]$$

And the corresponding hat transport $\dot{Q} = \dot{m}_{max} .L$ is given by

$$\dot{Q} = \left[\frac{\rho_l.\sigma_l.L}{\mu_l}\right].\left[\frac{K.A}{l}\right].\left[\frac{2}{r_e} - \frac{\rho_l.g.l}{\sigma_l}.\sin\theta\right]$$

(4) [10]

5. Experiment

Heat pipe is simple but ingenious device to heat transfer. Heat transfer by heat pipe occur based on evaporation and consequential condensation of working fluid. After this meaner is possible to transfer great thermal performance by little dimensions devices, too. One from many methods how to determine performance of heat pipe is calorimetric method, which was used in experimental measurement by [11]. Calorimetric method emanating from calorimetric equation where known mass flow, specific heat capacity, input and output temperature of coolant. Total heat power of heat pipe determine from difference between input and output temperature of circumfluent coolant. For the experimental measurement was proposed measuring unit, which consist from measuring apparatus (thermostat, measuring centre, ultrasonic flowmeter, auto-transformer) necessary to measuring thermal performance of heat pipe.

Fig. 4 Experimental measurement of heat pipe performance

5.1 Measurement

Heat source for the heat pipe was controllable transformer, which was connected with resistance wire to heat pipe. Temperature of heat pipe evaporator section was measuring with NiCr-Ni thermocouple taped on heat pipe surface. Electrical isolation under resistance wire constituted mica tape. Evaporator section of heat pipe was heating by resistance wire connecting on the transformer, which regulates necessary working temperature of heat pipe. To determine of heat pipe performance was designed cooling system consisted from small copper pipe placing on condenser section of heat pipe. To better heat transfer from heat pipe to cooling system was surface of het pipe painted with heat-conductive paste. Through the cooling system flow cooling water and is regulated by thermostat. The input and output temperature flowing water through cooling system is measured by NiCr-Ni thermocouples. Adiabatic and condensate section of heat pie is isolated by polystyrene as a heat loss protection into surround. The temperature and mass flow data from measuring enter into measuring centre and by software AMR to PC. Heat performance transferred from evaporator to condensate section by heat pipe is calculated based on calorimetrical equation from measured value of input and output temperature, mass flow and special thermal capacities cooling water circulate in cooling system [12].

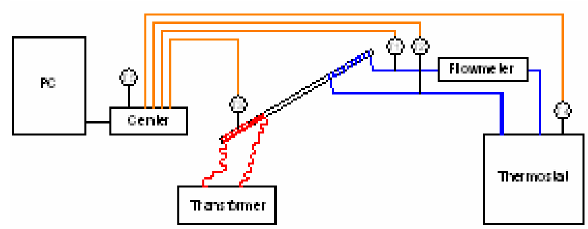

Fig. 5 Scheme of measuring unit

5.2 Results

Heat pipe, which research of ability work at various positions are wick heat pipe with screen capillary structure meshed 200, 100 and 50, total length is 50 cm made in our workplace department. Working fluid in heat pipes is ethanol. Amount of ethanol in heat pipe is 20% from overall heat pipe volume as discuses [13]. Measurement of thermal performance of heat pipe was at two positions: vertical and angel 45° and temperature of heat source were 70 °C.

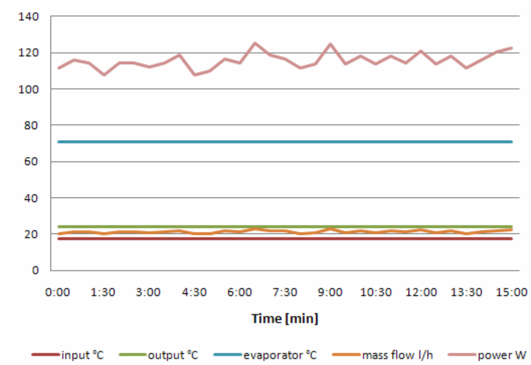

Fig. 6 Results from experimental measuring heat performance of wick heat pipe with screen mash 100 capillary structure at position angel 45°.

Heat performance solution of heat pipe is based on calorimetrical equation and values from experimental measuring. The same calculations were used at work [14].

$$Q = \dot{m}.c.\Delta t \quad (5)$$

$$\Delta t = t_2 - t_1 \quad (6)$$

Where is Δt [°C] – temperature difference, t_1 [°C] – input temperature, t_2 [°C] – output temperature, $\dot{m}$ [$J.kg^{-1}.K^{-1}$] – mass flow of liquid, c [$J.kg.s^{-1}$] – special thermal capacities of liquid.

The next measurement of ability work at various positions is wick heat pipe with sintered capillary structure thickness 1 mm from copper powder 63 μm granulate and total length 45 cm made in our workplace department. In this case was used ethanol as a working fluid, too. Measurement of thermal performance of heat pipe was at three positions: horizontal, vertical and angel 45° and temperature of heat source were 50 °C.

Table 2 Average value heat performance of wick heat pipe

Wick heat pipe Working fluid - Ethanol		Average value performance [W]
Capillary structure – mash 200	Angle 45°	131
	Vertical position	146
Capillary structure – mash 100	Angle 45°	162
	Vertical position	175
Capillary structure – mash 50	Angle 45°	173
	Vertical position	183

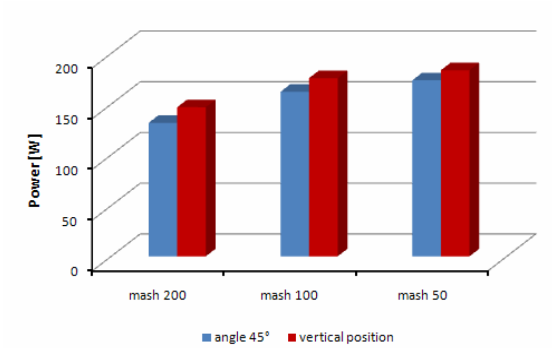

Fig. 7 Graph dependences heat performance from working position of wick heat pipe

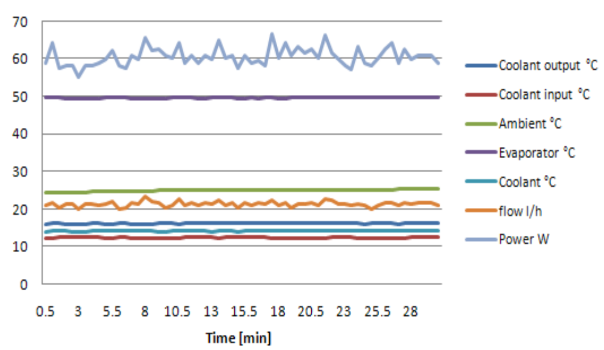

Fig. 8 Results from experimental measuring heat performance of wick heat pipe with sintered capillary structure from copper powder 63 μm granulate at horizontal position

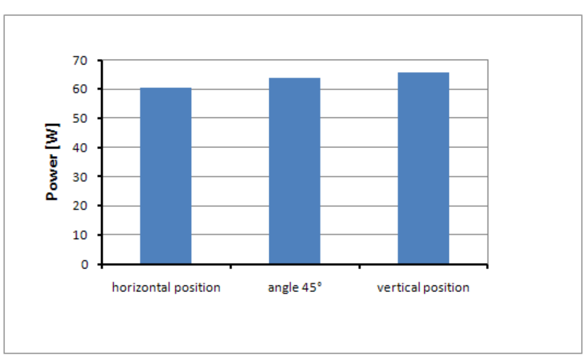

Fig. 9 Graph dependences heat performance from working position of wick heat pipe

Table 3 Average value heat performance of wick heat pipe

Wick heat pipe Working fluid - Ethanol		Average value performance [W]
Capillary structure – sintered powder 63 μm	Horizontal position	60,5
	Angle 45°	63,8
	Vertical position	65,5

Third measurement, we do again measurement of wick heat pipe with screen capillary structure, the same as at first measurement, but now at three various positions: vertical, angel 45° and horizontal and temperature of heat source was 50 °C. On figure number 10 is shown graphic dependences heat performance from working position of wick heat pipe. In table 4 are average value of heat pipe heat performance measured obtained from experimental measurement. From graphic dependences it is possible deduce effect of position and various type of mash screen capillary structure to heat pipe performance. Results from research heat performance of heat pipe with mesh screen structure show, that heat performance rise from reducing dimension of mash screen structure. Reason of that, is creating a stronger capillary pressure surface tension of working fluid inside capillary structure.

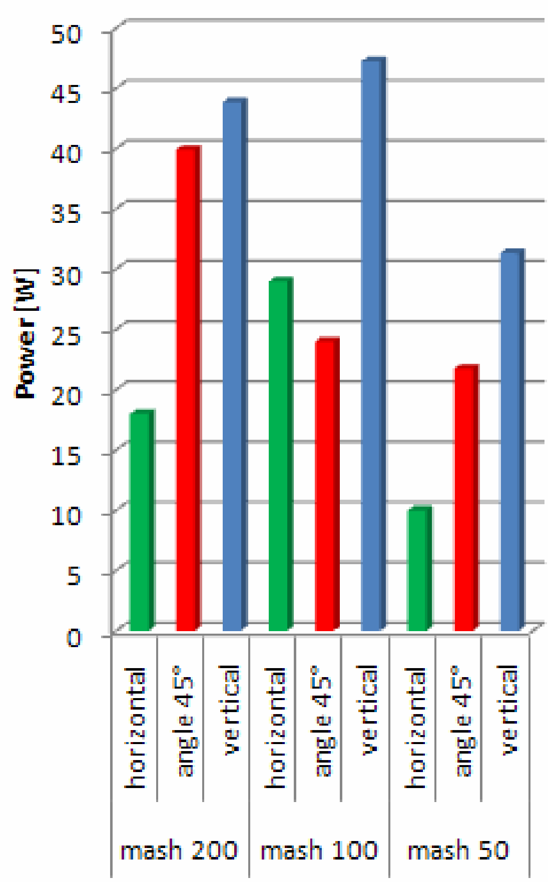

Fig. 10 Graph dependences heat performance from working position of wick heat pipe

Table 4 Average value heat performance of wick heat pipe

Wick heat pipe Working fluid - Ethanol		Average value performance [W]
Capillary structure – mash 200	Horizontal position	18
	Angle 45°	40
	Vertical position	44
Capillary structure – mash 100	Horizontal position	29
	Angle 45°	24
	Vertical position	47
Capillary structure – mash 50	Horizontal position	10
	Angle 45°	22
	Vertical position	31

6. Conclusion

From experimental measuring thermal performance of heat pipes are create graphic dependences average values of thermal performance from working position of heat pipe. Ideal working position of heat pipe is vertical position. Heat pipe operate on maximum performance and maximum mass flow transfer in this position. This experiment has testify that the wick heat pipe is able operate at any other position as vertical and even at the horizontal position. From results measured performances of heat pipes at various working position discover that the wick heat pipe is able operate at horizontal position and total heat performance transfer is not very different as at vertical position, which capillary structure cause.

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