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Gravity in Heat Pipe Technology

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Abstract

This work deal with heat pipes experiments depending on the gravity, because gravity is one of the phenomenon which affects the heat transport ability of the heat pipe. In heat pipe technology is gravity on the one side positive when ensure the circulation of the working fluid in gravity heat pipe (GHP) (thermosiphon) and on the other side negative when act opposite the capillary action in the wick heat pipe (WHP). The work describes principle, design and construction of gravity heat pipe (GHP) and wick heat pipe (WHP). Experimental determination influences gravity on the heat transport ability of gravity heat pipes by changing working position. Experimental and mathematical determination influences gravity on the heat transport ability of wick heat pipes by changing working position.

Keywords: heat pipe, wick structure, gravity, capillary action, heat transfer, thermal performance, mathematical model

1. Introduction

Heat pipe technology is one form of technology which is mostly used in technical application. It is mainly used in area of heat transfer such as electronic cooling, heat recovery from technical processes, recovery of heat from ground and sun for use in the heating system.

The principle of two-phase heat transfer with liquid phase transport due gravity first use Angier March Perkins in device known as a Perkins Tube in the middle nineteenth century. Today is Perkins invention known as a Thermosiphon. The capillary effect used in liquid phase transport in two-phase heat transfer device was first suggested by Gaugler in 1942 under the name Heat Pipe [1].

The basic heat pipe or thermosiphon consists of hermetically sealed pipe in which the working medium is at a defined pressure. Heating one end (evaporation part) of the pipe and cooling the other end (condensation part) cause the working medium to evaporate. Vapour flow

through the adiabatic part of heat pipe into the condensation part which condenses in to liquid and returns back to the evaporation part via gravitational force or other forces (e.g. capillary action, centripetal force, osmosis or electrohydrodynamics) which evaporates again. This creates the natural circulation of the working medium associated with heat transfer. In the case of heat transfer with a phase change of the working medium, the latent heat of the substance is released and hence the heat transfer efficiency through the heat pipe is very high [2].

Due to very high heat transfer coefficients for boiling and condensation, these devices are highly effective thermal conductors over many other heat-dissipation mechanisms. They contain no mechanical moving parts and typically require no maintenance. The other advantages of devices with heat pipe technology are a fast start action of the heat transfer, their geometric shape and weight [3]. In **Figure 1**, schema of heat pipe is shown.

Both thermosiphon and heat pipe are heat transfer devices which work on the same principle. The difference is only in the method of the liquid phase transport. In one device, the gravity acts positive and in other acts negative [4].

The gravitational force is an attractive force, which acts between two masses, two bodies or two particles. Gravity not acts only between objects on the Earth, but also acts between all objects, anywhere in the Universe. Sir Isaac Newton found that to change the speed or direction of movement of the object, gravity force is required. He also found that gravity force causes the apple to fall from the tree, or humans and animals live on the surface of our planet rotating around its own axis without being thrown away. He further deduced that there are gravitational forces among all objects. Newton’s gravity law is a mathematical description of how the bodies attract each other, based on experiments and observations performed by scientists. The mathematical expression of the Newton’s law is

$$F = \frac{Gm_1m_2}{r^2} \tag{1}$$

where G is the gravity constant and it value is $6.6726 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$.

It claims that the gravity is proportional to the product of two masses (m1 and m2) and is inversely proportional to the square of the distance (r) between its centres of gravity. The

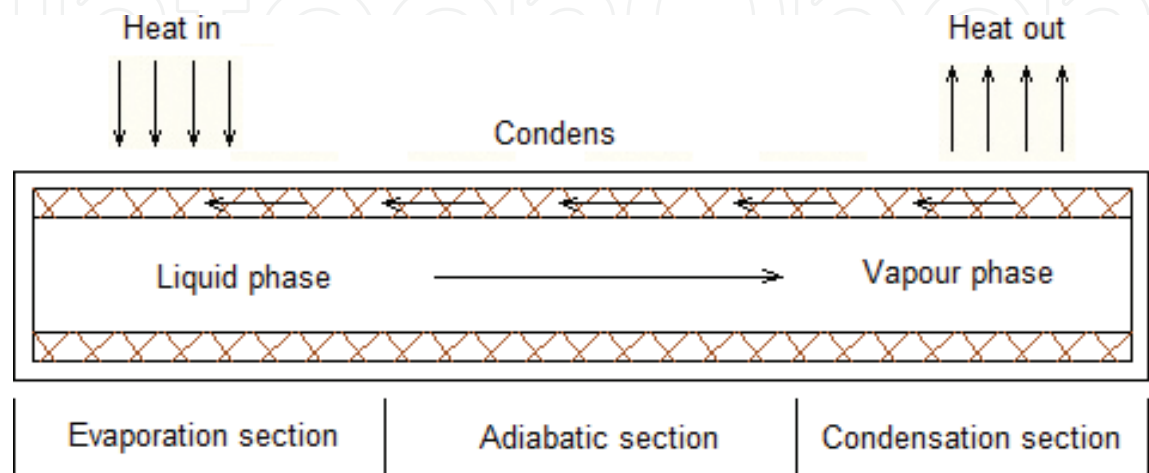


Figure 1. Principle of heat pipe.

influence of the gravitational force goes from every object into the space in all directions and at an infinite distance. However, the gravitational force rapidly decreases with a distance.

Capillary action (or capillarity) describes the ability of a liquid to flow against gravity in a narrow space such as a thin tube.

This spontaneous rising of a liquid is the outcome of two opposing forces:

Cohesion—the attractive forces between similar molecules or atoms, in our case, it is between the molecules or atoms of the liquid. Water, for example, is characterised by high cohesion since each water molecule can form four hydrogen bonds with neighbouring molecules.

Adhesion: the attractive forces between dissimilar molecules or atoms, in our case the contact area between the particles of the liquid and the particles forming the tube.

In view of molecular physics, capillarity is caused by capillary pressure. Consider the liquid with surface tension that perfectly wet the walls of the vessel. When the capillary with the internal radius is immersed into the liquid, a concave hemispherical surface of radius is formed in the capillary. The internal pressure under concave surface in capillary is less about the capillary pressure compared to the horizontal surface in the larger vessel. This results in the liquid rising in the capillary to such a height that the hydrostatic pressure corresponding to the height of the liquid column is the same as the capillary pressure. The height (h) of a liquid inside a capillary is given by the expression

$$h = \frac{2\gamma \cos\theta}{\rho g r} \quad (2)$$

where γ is the liquid air surface tension, θ is the contact angle, ρ is the density of the liquid, g is the gravitational field and r is the tube radius.

In case, if the forces of adhesion are greater than those of cohesion and gravity (when it exists), the molecules of the liquid cling to the wall of the tube. We will observe that the upper surface of the liquid becomes concave (the height of the liquid at the contact area is higher than its height at the centre of the tube). The cohesive forces between the molecules of the liquid are “attempting” to reduce the surface tension (i.e. to flatten the upper surface of the liquid and thus prevent the increased surface area in the concave state). In doing so, the molecules keep climbing up until a steady state between cohesion and adhesion is achieved (with or without the gravity component). This also explains why this phenomenon occurs exclusively in thin tubes (also in the absence of gravity). In wider vessels, only a small fraction of the liquid comes into contact with the vessel walls, and so adhesive forces are negligible and there is hardly any rising of the liquid.

2. Heat pipe construction

The heat pipe may have several basic parts depending on its type. During the heat pipe development, the main components and materials remained the same. The simplest type of heat pipe consists of two basic parts, the body (container) and the working medium. A capillary structure (wick) can be placed inside the heat pipe body to allow the condensed liquid phase of

the working fluid wicking against the vapour flow due the capillary action. Such a heat pipe is called a wick heat pipe (WHP). The heat pipe without capillary structure is called gravitational heat pipe because it returns the liquid phase from the condenser part to the evaporator part which is due to gravity [5].

2.1. Heat pipe container

The container of the heat pipe can have for different applications different shapes, but the most often is in the form of a closed pipe of a circular, flat or triangular cross-section. The main function of the heat pipe container is to isolate the working fluid from the outside environment. The container of the heat pipe should be strong enough to prevent internal dimension and internal pressure in case of compression or bending. The choice of the container material depends on many of its properties and should have the most appropriate combination (working fluid and environment compatibility, strength-to-weight ratio, thermal conductivity, porosity, wettability, machinability, formability, weldability or bondability). The container material should have a high thermal conductivity, solid and tough but easily machined, formable and easily soldered and welded. The surface of the material should be well wetted, but at least as porous as possible to avoid gas diffusion. The materials most commonly made of heat pipes are steel, copper, aluminium and their alloys. Various coatings of steel materials are also used [6].

2.2. Working fluid

Since the operation of the heat pipe is based on evaporation and condensation of the working fluid, its selection is an important factor in the design and manufacture of the heat pipe. The working fluid is chosen in particular according to the working temperature range of the heat pipe. Therefore, when selecting a working fluid, it is necessary to be careful if the operating temperature range of the working fluid lies in the operating temperature range of the heat pipe. The heat pipe can operate at any temperature that is in the range between the triple and the critical point of the working fluid. In case of several working fluids having the same working temperature is the decision criterion appropriate combination of its thermodynamics properties. The recommended features that working fluid should have are compatibility with the capillary structure material and the heat pipe container, good thermal stability, wettability of the capillary structure and heat pipe container, vapour pressure in the operating temperature range, high surface tension, low viscosity of the liquid and vapour phase, high thermal conductivity, high latent heat of vaporisation, acceptable melting point and solidification point [6].

2.2.1. Heat pipe classification by working fluid

The heat pipe is able operate at any temperature between triple state and critical point of the working fluid, but in the area near this point, heat pipe reduced its ability to transfer heat due to characteristic properties of viscosity and surface tension of the liquid phase working fluid. In **Table 1**, typical heat pipes working fluids are sorted by operating temperature range. The application of heat pipe depends mainly on operating temperature range of the working fluid. Depending on it, heat pipe is divided into four groups:

1. *Cryogenic heat pipe* has an operating temperature range of 1–200 K. The gases are used as a working fluid in cryogenic heat pipes, for example, helium, argon, oxygen, neon or nitrogen.
2. *Low-temperature heat pipe* has an operating temperature range of 200–550 K. Working substances such as methanol, ethanol, ammonia, acetone or water are used.
3. *Medium temperature heat pipe* has an operating temperature range of 550–700 K. Working fluids such as mercury, sulphur or some organic liquids (naphthalene, biphenyl) are used.
4. *High-temperature heat pipe* has an operating temperature range in the temperature range above 700 K. As a working fluids are used metals such as potassium, sodium, silver, which melt at high temperatures and are in the liquid state [5].

In practice, water is the most often used working fluid in heat pipe, because it has optimum operating temperature range, is the cheapest, available, has the best thermodynamics properties and the highest latent heat of vaporisation, which is its great advantage in heat transfer compared with the other fluids. However, due to the high pour point, it is not suitable for low-temperature operations outside and is not compatible with all materials. In low-temperature operations, the often used fluids are ethanol, ammonia and CO₂. In high-temperature operations, suitable liquid metals with a low melting point such as sodium and potassium are used. Some fluids have been stopped to use due to increased health, safety and environmental requirements. For example, the use of CFCs in European countries is forbidden, and the use of HFC halogenated hydrocarbons is gradually being phased out in favour of fluids that have a less impact on the environment.

Working fluid	Melting point at atmospheric pressure (°C)	Boiling point at atmospheric pressure (°C)	Latent heat of vaporisation (kJ.kg ⁻¹)	Useful range (°C)
Helium	–271	–269	21	–271 to –269
Nitrogen	–210	–196	198	–203 to –160
Ammonia	–78	–33	1360	–60 to 100
Acetone	–95	57	518	0–120
Methanol	–98	64	1093	10–130
Ethanol	–112	78	850	0–130
Water	0	100	2260	30–200
Mercury	–39	361	298	250–650
Caesium	29	670	490	450–900
Potassium	62	774	1938	500–1000
Sodium	98	895	3913	600–1200
Lithium	179	1340	19,700	1000–1800
Silver	960	2212	2350	1800–2300

Table 1. Typical heat pipe working fluids.

2.3. Wick structures

The wick structure is placed on the inner surface of the heat pipe so that the heat pipe can operate both in the horizontal position and in the position with the evaporator located above the condenser. The wick structure function in heat pipe is to transport the condensed liquid phase of the working fluid from the condenser part to the evaporator part of the heat pipe. Another function is to ensure a uniform temperature distribution throughout the evaporator surface. There are several types of wick structures but neither is ideal. Each wick structure has some advantages and disadvantages. Therefore, when choosing a wick structure, it is necessary to consider the conditions in which the heat pipe will operate. The choice of the wick structure of the heat pipe depends on many factors. Some of them are closely related with the properties of the working fluid, working conditions and compatibility of the heat pipe components. The most important factor is ability to create capillary pressure required to working fluid transportation from the condenser section to the evaporator section where the heat pipe receives heat. The maximum capillary pressure produced by the wick structure increases with decreasing pore size. The permeability of the wick structure increases with increasing porosity. Thickness of the wick structure is another factor to take care, because the heat transfer capacity of the heat pipe depends on the wick structure thickness. Generally, the wick structure of heat pipe should have small capillary radius, high porosity, high thermal conductivity and high permeability [6].

2.3.1. Wick structure classification

Depending on whether the wick structure of a heat pipe is made from one or more structures, it is divided into homogeneous or non-homogeneous (composite). The homogeneous wick structure is created only by one structure. In **Figure 2**, typical homogeneous wick structures are shown. The mesh screen wick structure shown in **Figure 2a** consists of metal meshes located on the inner surface of the pipe. The vapour flow resistance of the working fluid depends on the tightness of the mesh wrapping in the heat pipe. The porous wick structure shown in **Figure 2b** is created from the porous material made by sintering metal powders or ceramic and carbon foams and felt. Compared to other structures, the porous wick structure has a higher effective thermal conductivity. The grooved wick structure shown in **Figure 2c** is formed by cutting the grooves into the inner surface of the heat pipe material. It creates sufficient capillary pressure, does not impose resistance to the vapour flow and preserves the thermal conductivity of the material [5].

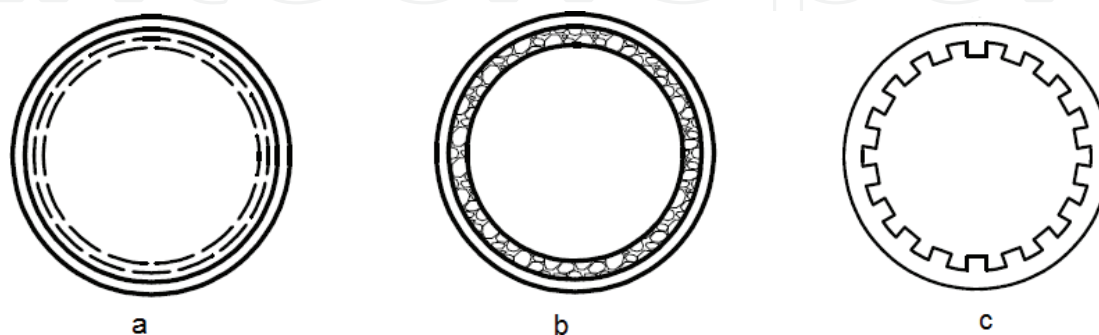


Figure 2. Cross-sections of homogenous wick structures. (a) Wrapped screen, (b) sintered metal, (c) axial groove.

The composite wick structure is made of two or more kinds wick structures. In **Figure 3**, typical composite wick structures are shown. By the composite wick structure, a separate flow of the liquid phase and vapour phase working fluid in the heat pipe is achieved. For example, if the wick structure with grooves on the inner wall are covered by a metallic mesh, high capillary pressure is created and axial grooves reduces flow resistance. Thus heat transfer capacity of the grooved wick heat pipe in antigravity position can be improved.

2.3.2. Wick structure manufacturing

The grooved wick structure is a simple wick structure in view of production. The grooved wick structure shown in **Figure 4** is most often made by longitudinally cutting grooves in the pipe material of dimensions only a few tenth millimetre. Another possibility of producing grooved structures is the production of groove moulds by casting or sintering metal powders which are then inserted into the tube. The copper tubes manufacturers already offered a wide range of copper pipes with longitudinal grooves suitable for using in heat pipe production. In applications of this wick heat pipe, it should take in account that cutting the grooves may weaken the pipe container. Since low capillary pressure is formed in the wick structure with axial grooves, it is suitable to use them in applications where the heat pipe operates in a horizontal or in a position with an evaporator position under the condenser.

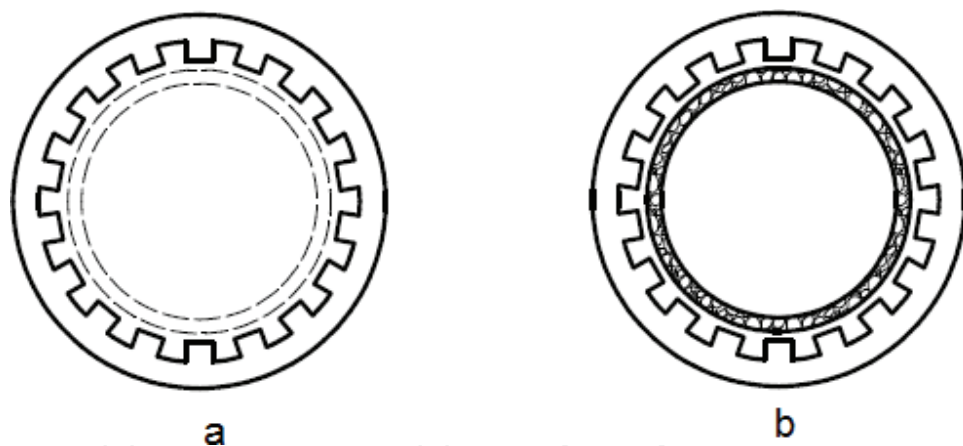


Figure 3. Cross sections of composite wick structures. (a) Axial groove – wrapped screen, (b) Axial groove – sintered metal.



Figure 4. Grooved wick structure.

The mesh screen wick structures are among the most commonly used wick structures of wick heat pipes. It is mainly for their simply production, easy availability, wide range of materials and variability to create different combinations (number of layers and number of mesh types) according to heat flux transfer and heat pipe orientation. In general, fine-meshed anti-corrosion meshes with a mesh size range of 50–250 are used to mesh screen wick structure production. Mesh size is given by the number of holes in the screen per unit length (inch = 25.4 mm). The mesh screens are coiled into several layers so that they are firmly attached to the inner surface after insertion into the pipe by their own expansive forces. In **Figure 5**, samples of fine mesh screens from which the wick structures for heat pipes have been made are shown. In **Figure 6**, samples of mesh screen wick structures inserted in the pipes are given.

Although the production of the porous wick structure is the most difficult from all types of wick structures, is one from the three most used wick structures in the heat pipe, because is able creates a large capillary pressure that allows the heat pipe to transfer a high heat flux in the antigravity position. One method of making a porous wick structure is to sinter a copper powder uniformly poured around a coaxially centred steel mandrel located inside the copper pipe at a temperature close to melting the powder material in a high-temperature electric furnace. The formation of a suitable porous structure by sintering the metallic powder depends, in addition to the sintering temperature, both from the time of sintering and the grain size of the powder. Copper powders



Figure 5. Fine mesh screens (mesh 50, 100, 200).



Figure 6. Mesh screen wick structures.

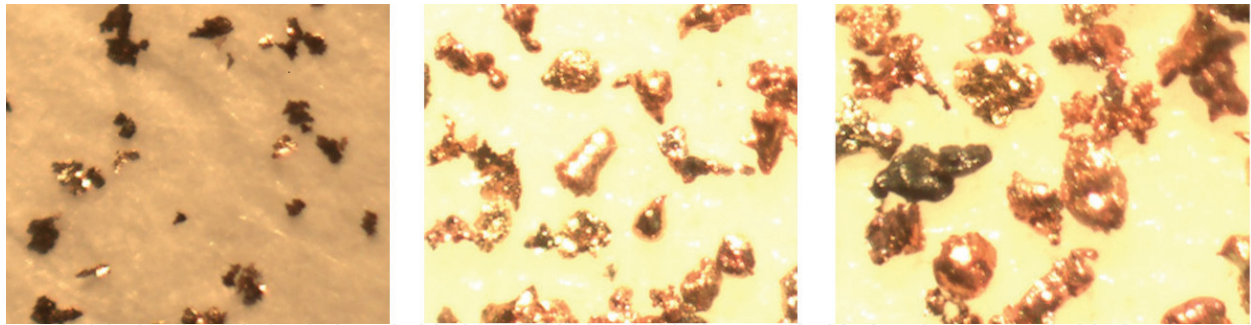


Figure 7. Granules of copper powders (35, 63, 100 μm).

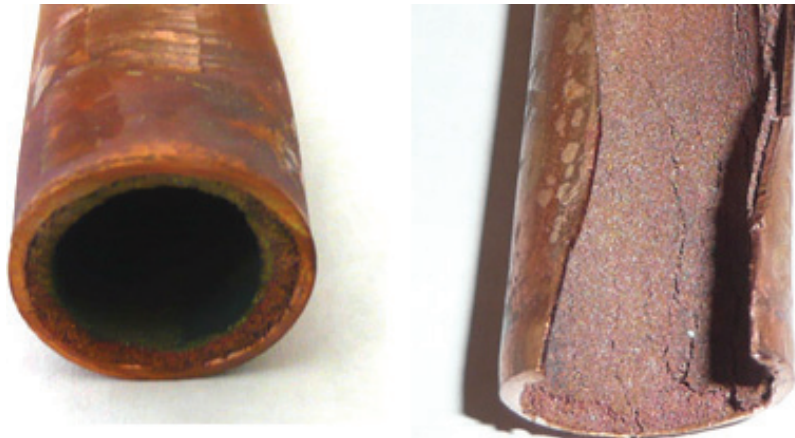


Figure 8. Sintered porous wick structure.

with a particle size of 30–100 μm or copper fibbers of 2–3 mm in length and a diameter of 20 – 100 μm are used to production porous sintering structure. In **Figure 7**, the granules of copper powders used to production sintered structure are shown. In **Figure 8**, samples of sintered wick structures made of copper powder with a grain size of 63 μm are shown.

Modern technologies allow to manufacture porous structures from metallic, ceramic or carbon materials in the form of foils or felt with different pore size ranges that are suitable for condensate transport from the condenser to the evaporator in the heat pipe. Porous structures made of ceramic materials have smaller pores, but their disadvantages are that they have little stiffness and therefore must be scaffold with a metal grid. The problem of scaffold porous structure is that while the ceramic structure itself can be chemically compatible with the working fluid, the second added material may not be compatible. Recent attention has been paid to the production of porous structures made of carbon materials. Structures of carbon materials have finer grooves on the surface, which allow to produce high capillary pressure and are chemically stable [7].

3. Heat pipe manufacturing

The main requirements on the heat pipe production are the high purity of the material of the individual parts and the working substance, as well as their mutual compatibility.

The basis of the heat pipe construction is the pipe body and the working fluid. The production of a heat pipe primarily consists in selecting a suitable material of the pipe and the working fluid. The working fluid is selected according to the temperature conditions in which the heat pipe will be used, because heat flux transferred by the heat pipe depends on the material of the pipe, the working fluid and their mutual compatibility. An important part of the wick heat pipe is the wick structure, which also has a large impact on the amount of transferred heat flux.

The main components of heat pipe are as follows:

- Pipe body (container)
- Working fluid
- Wick structure
- End caps
- Filling pipe

The heat pipe body may be of any cross-section, for example, circular or square, may include mounting flanges for ease of assembly and may be bent into various shapes. The wick structure can be formed by grooves extruded into a pipe body or fine mesh screen, porous material and artery inserted into the heat pipe body [8]. **Figure 9** shows a schema of the wick heat pipe construction.

The most common shape of the heat pipe is cylinder, because in addition of easily available product (wide assortment of material and the size of the pipe cross-sections), it provides certain advantages also in terms of strength and thermomechanical parameters. The advantage of producing a cylindrical shaped heat pipe is in the ease of handling with the cylindrical material. In practice, heat pipes with flat rectangular, triangular or other cross-sections are also used. The most common heat pipes are manufactured with an inner diameter of 8–25 mm and an internal diameter of 2–5 mm—the so-called micro-heat pipes. The production process of the heat pipe can be divided into several sub-processes involving mechanical and chemical treatment of materials.

Technological process of the heat pipe production cycle:

- Body production and end caps.
- Production of wick structure.
- Cleaning of components.
- End caps closure by impervious joints (welding, soldering).
- Mechanical verification of body strength and tightness.
- Vacuuming of inner space and filling with the working fluid.
- Sealing the filling pipe (welding, soldering).

Before heat pipe production, it is necessary to thoroughly clean all components of the heat pipe to avoid any undesirable influence, which could ultimately have an effect on the heat transfer

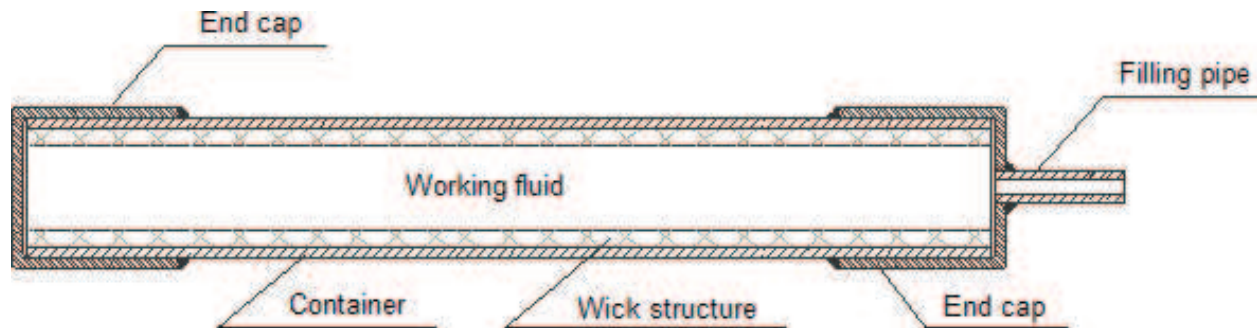


Figure 9. Schema of the wick heat pipe construction.

ability reduction. In cleaning process, first, the mechanical impurities and rust from the body of the pipe are removed manually and then chemical cleaning of the body, wick structure, end caps and filling pipe are followed [9].

3.1. Mechanical part of heat pipe production

In the mechanical part of the production, the individual components of the heat pipe are first prepared: the body, the filling pipe, the wick structure and the end caps. All components are then joined together by welding or soldering. In the case of wick heat pipe production, a wick structure is placed in the internal space of the body before heat pipe closure. The closure of the heat pipe is the connection of the body with the end caps. In **Figure 10**, the standard types of the heat pipe closure by end caps are shown. The filling pipe is connected to one of the end caps due the inner space vacuuming. After vacuuming, the heat pipe is filled with the working fluid and filling pipe is pressed, and after disconnecting from the vacuuming pump, filling pipe is sealed by soldering.

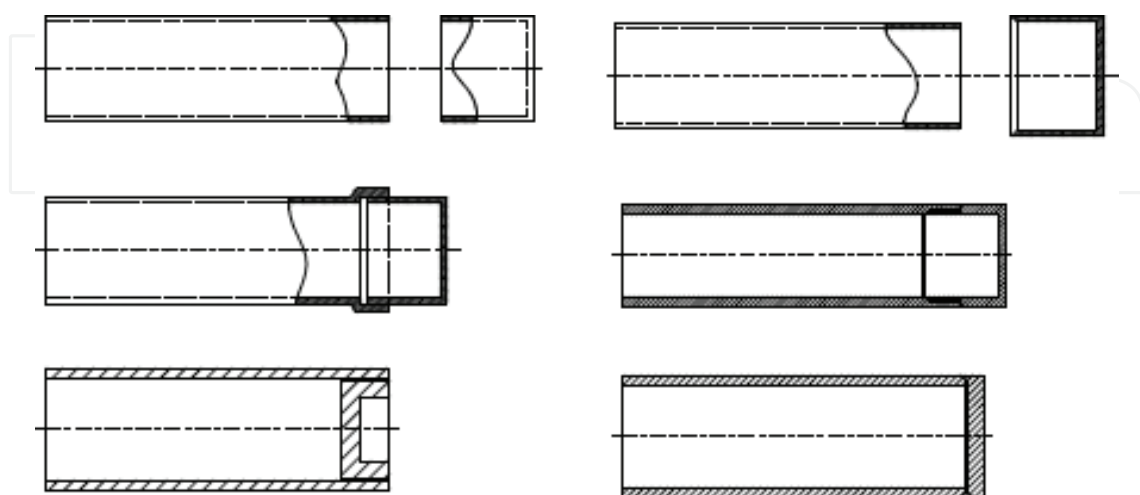


Figure 10. Types of the heat pipe closure by end caps.

3.2. Chemical part of heat pipe production

In the chemical part of the production, mechanical impurities and rust from the body of the heat pipe are first removed. This is followed by wet cleaning of the heat pipe components including cleaning with solutions, acids, basic acids which is precisely determined for each type of material. The ultrasound cleaning, vacuuming, degassing and passivation are processes that guarantee a high purity of the heat pipe material and thus contribute to long-lasting failure free operation. Generally, two important goals are achieved by cleaning. The first goal is to ensure good wetting material of the heat pipe well by working. The second goal is to remove all particles of dirt because the presence of impurities in solid, liquid or gaseous form may have an adverse effect on the heat transfer ability of heat pipe. Small particles can inhibit the formation of capillary pressure in the wick structure. Machining or human hand grease may reduce the wettability of the wick structure. Oxides formed on the walls of the wick structure may also reduce the ability of the working fluid to wet the surface. It is also highly advisable to use an ultrasonic cleaner to clean the heat pipe material, as the ultrasound breaks down, impurities are firmly absorbed on the surface of metallic particles that cannot be removed by any other way. The cleaning of the heat pipe is repeated immediately before filling with the working fluid, after connecting the body with the end caps and the filling tube. After cleaning, the tube is degassed by heating to a higher temperature and vacuuming the interior. In the case of a wick heat pipe, it is necessary to remove the oxide layers from the wick structure by chemical cleaning (e.g. solvents).

3.3. Filling the heat pipe with the working fluid

The working fluid added in to the heat pipe must be completely clean, free from all mechanical impurities and gases, as their trace residues can also react with the body material of the heat pipe and forms undesirable elements. Clean substances can be purchased without any problems at special chemical stores. However, even in pure liquids and solids, an incompressible gas may be present. These gases can be removed by repeated freezing and thawing cycles. The working fluid in the filling bottle can be frozen using liquid nitrogen or dry ice.

Filling process of each type working fluid is happening under other conditions. The characteristic of the filling process depends on the state of the working fluid at ambient temperature. If the working fluid is at the room temperature in the gaseous state (cryogenic), the filling can be carried out via a gas container of high quality. On the other hand, filling and closing of liquid-metal heat pipes is appropriate to do in the vacuum chamber [10].

The filling of low-temperature heat pipes can be carried out at room temperature without the use of any protective atmosphere. Before filling the heat pipe, it is advisable to suck the air from it to ensure removal of undesirable components contained in the materials, which could be later shown as non-condensing components. In addition, due to under pressure is the working fluid naturally enter to the heat pipe and thus the equilibrium state of the pure vapour and liquid phases at a lower pressure than atmospheric will achieve [11]. The scheme vacuuming and filling of heat pipe with the low-temperature working fluid is shown in **Figure 11**.

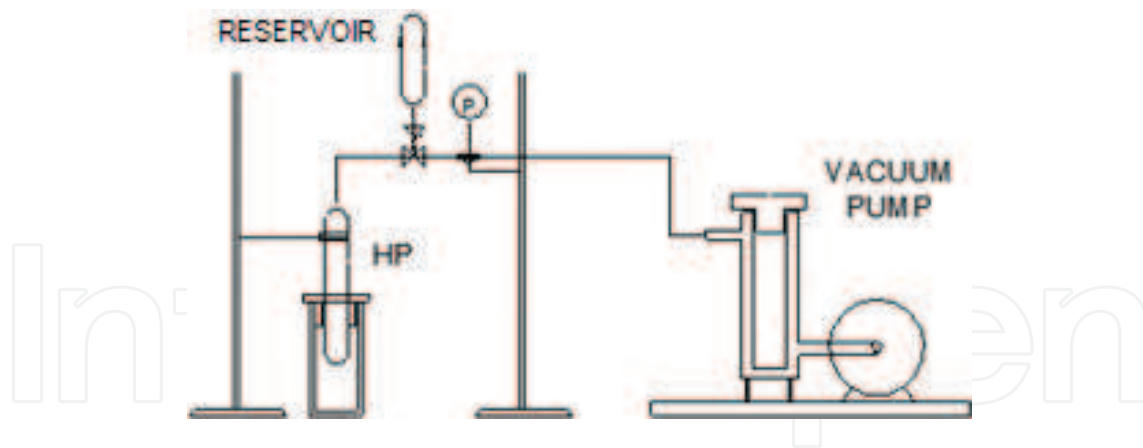


Figure 11. Schema vacuuming and filling of heat pipe.

4. Heat pipe experiments

The gravity is on the one side positive when ensure the circulation of the working fluid in gravity heat pipe (thermosiphon) and on the other side negative when act opposite the capillary action in the wick heat pipe. The gravity action in the Earth gravity field acts in one direction. If the working position of heat pipe in gravity field changed, the gravity action on the condensate flow of the working fluid also changed. Thus at the vertical position of heat pipe, gravity action can be positive or negative depending on the heat source position and at the horizontal position is the gravity action zero. Because heat transport ability of the heat pipe depends on condensate mass flow of the working fluid, the gravity is one of the main parameters which influence the heat transport ability of heat pipe. Therefore the main goal of the experiments is the determination influence of the working position (gravity) on the thermal performance amount transferred by heat pipes.

To determination thermal performance amount transferred by heat pipe was proposed measuring device consisted from measuring apparatus (rotary board, heater with heating thermostat, cooler with cooling thermostat, flowmeter, temperature sensors and data logger) shown in **Figure 12**. Thermal performance of heat pipe measurement consists of heating the evaporation section by a circulating medium at 80°C and cooling the condensation section by a circulating medium at 20°C. Rotating the rotary board is possible set up the working position of heat pipe. To determine thermal performance of heat pipe was used calorimetric method emanating from calorimetric equation where known mass flow, specific heat capacity, input and output temperature of circulating cooling medium.

$$Q = \dot{m} \cdot c \cdot \Delta t \quad (3)$$

$$\Delta t = t_2 - t_1 \quad (4)$$

where is Δt (°C) is the temperature gradient, t_1 (°C) is the input temperature, t_2 (°C) is the output temperature, \dot{m} (J.kg⁻¹.K⁻¹) is the mass flow of liquid and c (J.kg.s⁻¹) is the special thermal capacities of liquid.

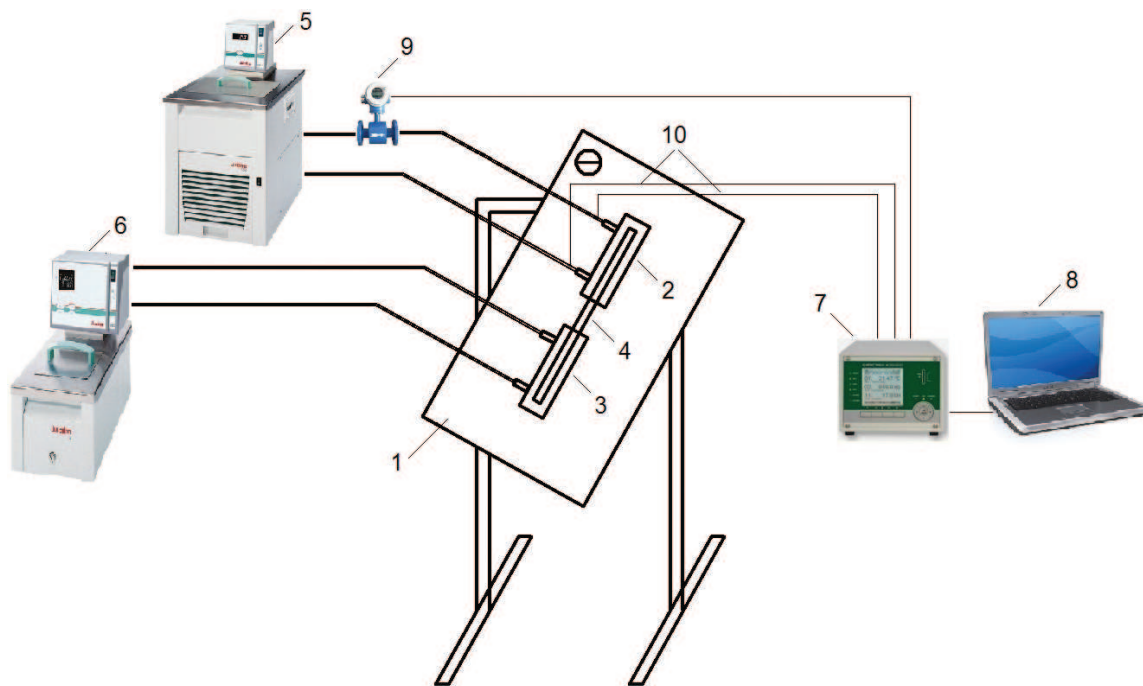


Figure 12. Scheme of measuring device: (1) rotary board, (2) cooler, (3) heater, (4) heat pipe, (5) cooling device with thermostat, (6) heating device with thermostat, (7) data logger, (8) notebook, (9) flowmeter, (10) temperature sensors.

4.1. Gravity heat pipe experiments

Gravity heat pipe experiments deal with the influence of working position, heat pipe diameter, quantity and kind of working fluid on heat transport ability gravity heat pipes. The experimental measurements were performed with heat pipe diameters (DN12, DN15, DN18, DN22 and DN28) and working fluids (distilled water, ethanol and acetone).

4.1.1. Determination of the working fluid quantity

First experiment was focused on determination optimal quantity of working fluid in heat pipe. Determination of the quantity of the working substance is governed by basic options:

- The working fluid quantity is chosen so that the heat pipe contains both vapour and liquid over the operating temperature range.
- Lack of substance (may lead to drying of evaporator part of heat pipe).
- Surplus substance (can lead to congestion of the condensation part of the heat pipe).
- It is recommended that the working fluid to fill up at least 50% of evaporator part of the heat pipe.

This experiment was realised with heat pipe of DN 15, working fluid ethanol and working fluid quantity in range 10–50%. In **Figure 13**, results influence of working fluid quantity on heat pipe thermal performance is shown. The experiment show that the ideal quantity of

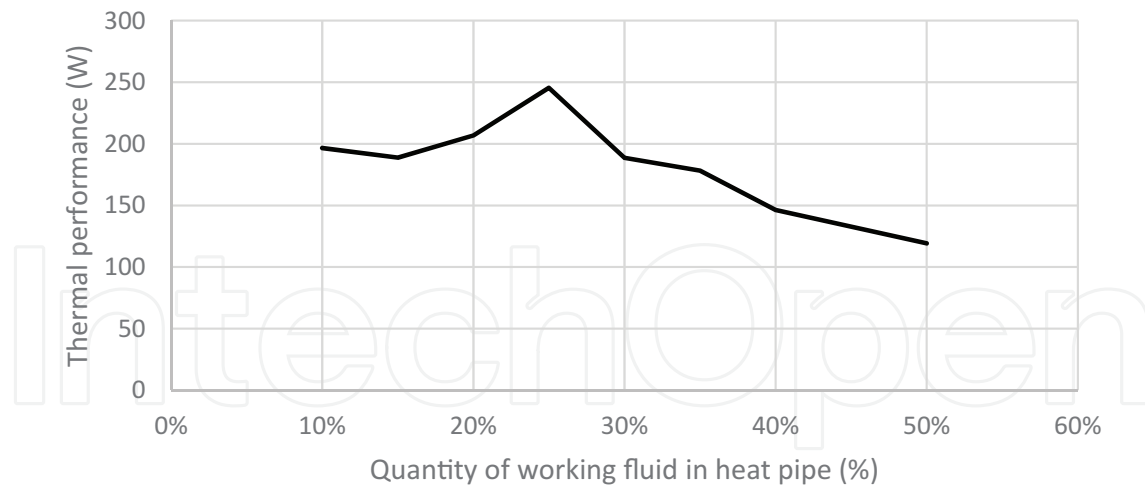


Figure 13. Influence of working fluid quantity on heat pipe thermal performance.

working fluid is in the range of 10–30% of the total heat pipe volume and the best working heat pipe was heat pipe with 25% of the total heat pipe volume from volume tube. With the increasing of working fluid quantity more than 40% the heat transfer ability rapidly decrease.

4.1.2. Influence working position on heat transfer ability of heat pipe

Second experiment was focused on the influence working position on heat transfer ability of heat pipe. This experiment was realised with heat pipes of various diameters, working fluids and working positions in range from vertical to horizontal with the sequence of the inclination angle about 15° . In **Figures 14–16**, thermal performances transferred by gravity heat pipes at working positions in range 0 – 90° from vertical position are showed. Results show that gravity heat pipes are able transfer heat at any working position beside the horizontal position. In general, with the increasing inclination angle up to 75° from the vertical position, the heat transport ability is not changed much, even it could be say that is equal in all range or a little decrease with the top at position of 60° .

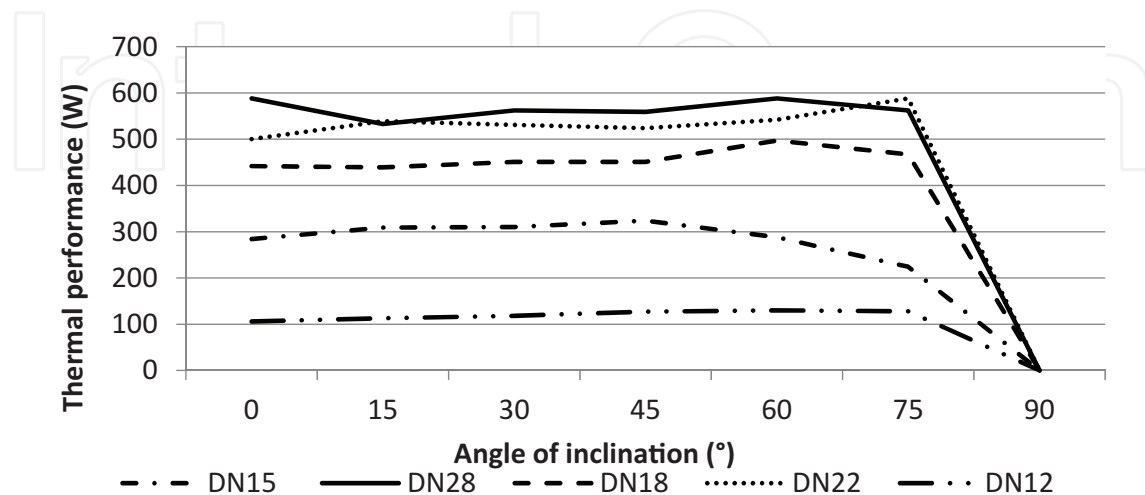


Figure 14. Influence working position on heat transfer ability of heat pipe with working fluid water.

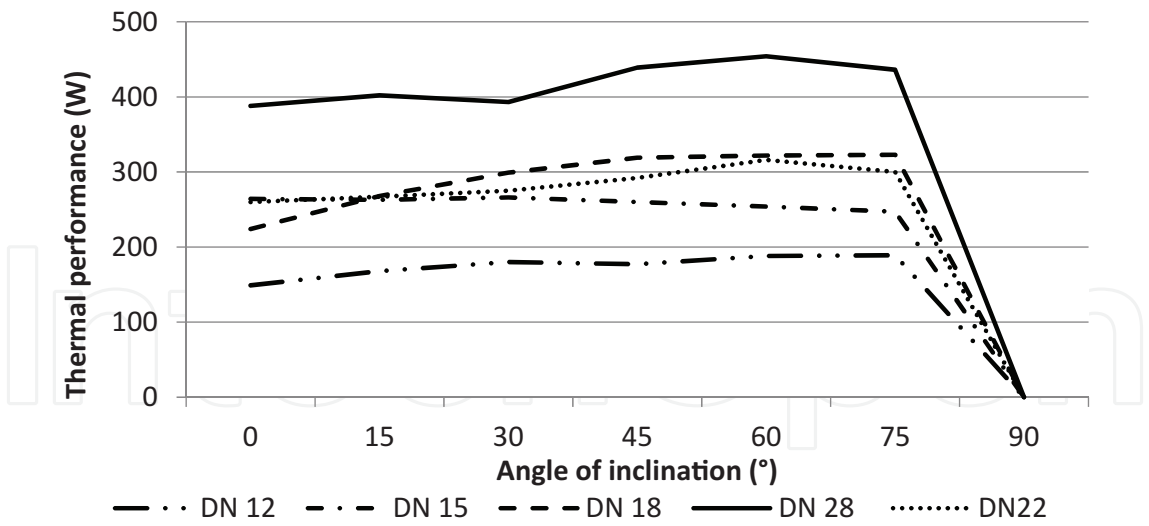


Figure 15. Influence working position on heat transfer ability of heat pipe with working fluid ethanol.

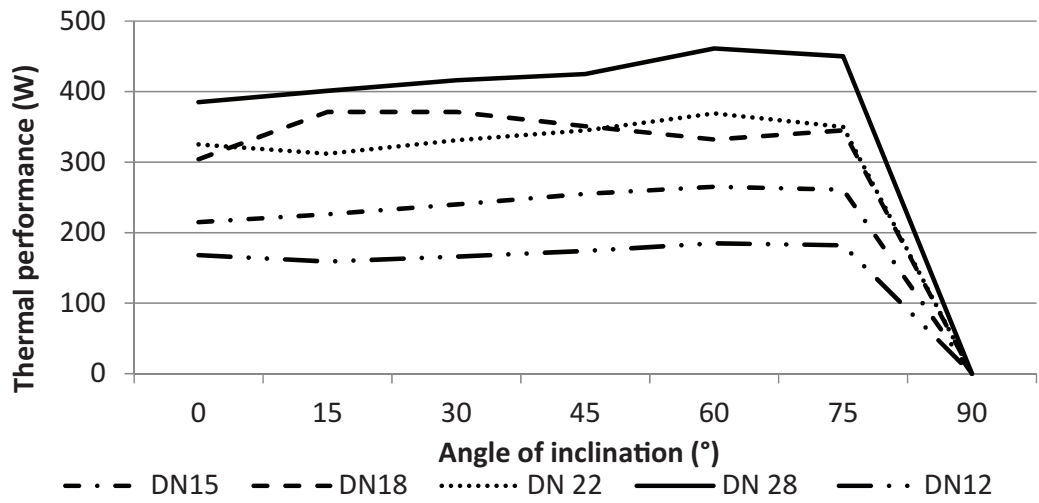


Figure 16. Influence working position on heat transfer ability of heat pipe with working fluid acetone.

4.1.3. Influence heat pipe diameter and working fluid on heat transfer ability of heat pipe

According to above experiments possible perform comparison influence heat pipe diameter and working fluid on heat transfer ability of heat pipe. In **Figure 17**, the average value of thermal performance values transferred by heat pipes with various diameter and working fluid at working position in range of 0–75° are shown. This experiment confirms assumption that with the changing heat pipe diameter and working fluid is thermal performance transferred by heat pipe changed too. With the increase of heat pipe diameter increase thermal performance.

In **Figure 18**, thermal performance transferred by heat pipe recalculated on heat flux transferred through the heat pipe cross-section. Heat flux transferred by heat pipe per cm² of heat pipe cross-section express expression

$$Q_s = \frac{Q}{S} \quad (5)$$

where Q is thermal performance transferred by heat pipe (W), S is cross-section area of heat pipe (cm^2).

The goal of this comparison was to find, if the increase of heat pipes diameters increase heat flux transferred per cm^2 . It was expect that the heat pipe with bigger diameter transferred bigger heat flux too. But this comparison show that the heat pipes with smaller diameter transferred higher heat fluxes per cm^2 of heat pipe cross-section area than heat pipes with bigger diameter.

Comparison influence of working fluid kind influence on the heat pipe heat transport ability show that the heat pipe with working fluid acetone and ethanol transfer approx. the same heat

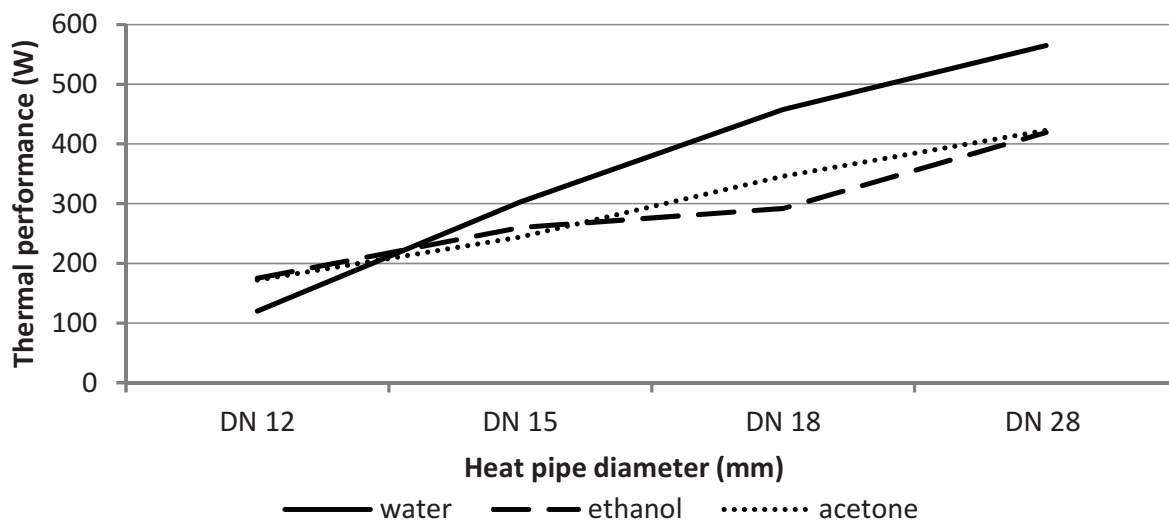


Figure 17. Dependence of heat pipe thermal performance on the working fluid and pipe diameter.

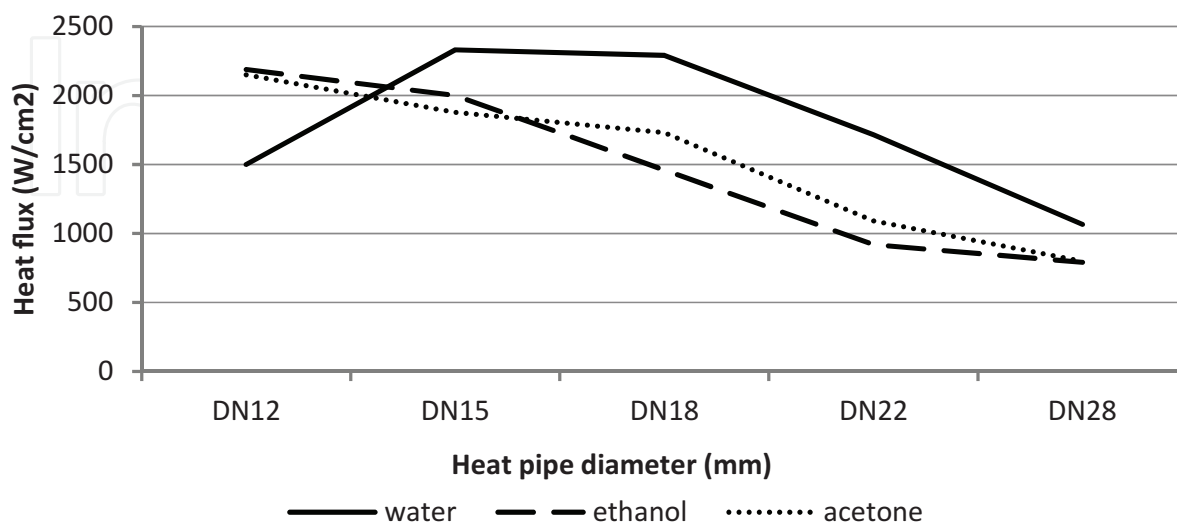


Figure 18. Dependence of heat pipe heat flux on the working fluid and pipe diameter.

fluxes. Heat pipe with working fluid water transfer higher heat fluxes than heat pipes with working fluid acetone and ethanol.

4.1.4. Working fluid flow visualisation in gravity heat pipe

Even though the theory about fluid boiling is complex described by many scientists, is hard to understand them, because boiling processes depends on many variable factors such as mass flow, vapour content and the temperature difference between fluid and the heating surface. This experiment explains working fluid flow in gravity heat pipe based on the boiling and condensation regimes and clarify phenomenon such as bubbles nucleation, liquid boiling, vapour and condensate flow interaction, vapour condensation and condensate flow down on the wall taking place inside during its operation.

4.1.4.1. Boiling regimes

In **Figure 19**, the characteristic course of boiling curve depending on the temperature difference between the evaporating working fluid and heating surface corresponding to the five known boiling regimes is shown.

Free convection evaporation: working fluid is in the liquid phase without bubbles and absorb heat transferred through the wall. The liquid close to the wall is heated and liquid at the liquid and gas interface start to evaporate.

Sub-cooled nucleate boiling region: the bubbles start nucleate in liquid phase of the working fluid due increase heat transfer between the wall and the working fluid. Created bubbles collapse in contact with the mass of liquid.

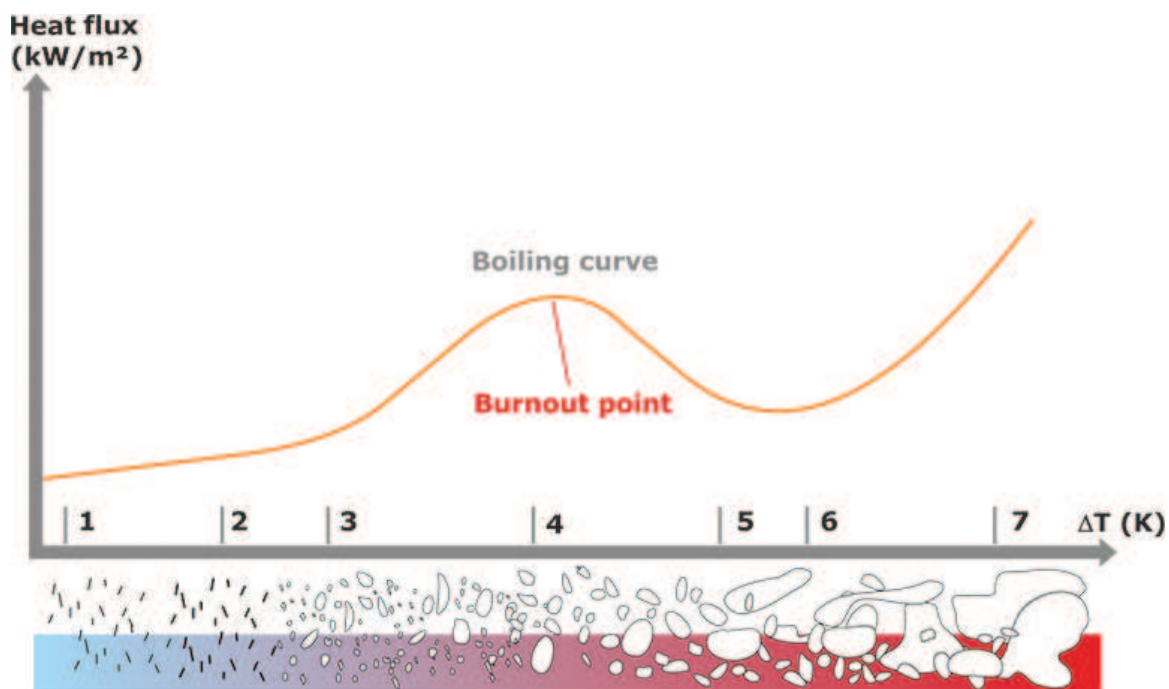


Figure 19. Boiling regimes.

Nucleate boiling region: this boiling region occur at temperature difference 3 K and is the most significant boiling region for heat transfer applications, because superheated liquid overcome surface tension of the working fluid. Increase heat transfer between wall and working fluid lead to frequent creation of bubbles which are unstable and in contact with sub-cooled liquid collapse.

Partial film boiling: further increase temperature difference cause quickly evaporation of liquid and allow another liquid access to the heated surface. This is unstable boiling regime and is not eligible, because vapour bubbles are create more frequent which act as an insulation and it cause heat transfer reduction.

Complete film boiling: at very high temperature difference between working fluid and wall a stable film of working fluid vapour on the wall is creating. Even though the film act as an effective insulation and heat transfer is minimal is this boiling region much more preferable than unstable partial film boiling.

4.1.4.2. Condensation regimes

Condensation is phase change of the working fluid from the vapour to the liquid. It occurs in condensation section on the wall heat pipe and is accompanied by heat and mass transfer. During condensation latent heat is released and thus increases the heat pipe efficiency.

In **Figure 20**, two types of condensation occur on the heat pipe wall are shown.

Film condensation: occurs when the working fluid condensate in form of continuous thin layer (film) liquid on the surface wall. The liquid film flows down the wall to the evaporator section due gravity and thus extend heat transfer.

Drop-wise condensation: occurs when the working fluid condensate in form of small liquid droplets on the surface wall. With the increasing vapour condensation, droplets grown and collect to the bigger drops until due gravity action flow down the wall to the evaporator. A new drop-wise condensation can proceed on free space after flowing down drops.

Even though the drop-wise condensation has 10 times larger heat transfer coefficient than film condensation, it is difficult usable in practice due short duration. In view, the heat transfer

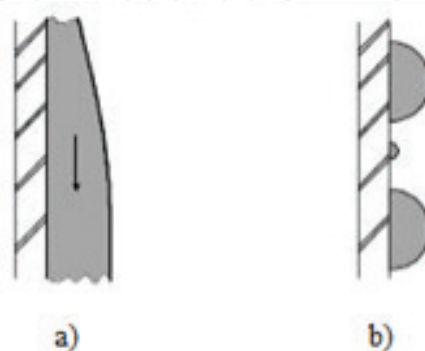


Figure 20. Condensation regimes: (a) film condensation, (b) drop-wise condensation.

coefficient is the continuous drop-wise condensation and film condensation with thin layer the most desirable condensation regimes in heat pipe.

The flow visualisation of the working fluid in gravity heat pipes was performed on two heat pipes made of glass with various inner diameter 13 and 22 mm. The total length of heat pipes is 500 mm and water was used as working fluid. Experiment consists of scanning the working fluid flow inside the glass heat pipe during its operation by high speed video camera. The results of the working fluid flow visualisation can observe boiling and condensation take place in heat pipe and can be helpful in two-phase flow or heat and mass transfer simulation by CFD method.

In **Figure 21**, heat pipes made for the experiment and experiment process of the working fluid flow visualisation in gravity heat pipe are shown. The heat pipe construction consists of borosilicate glass container, Cu cap on the bottom and brass filling valve on the top.

The borosilicate glass container of heat pipe was chosen because has smooth surface, ensure good visibility and is high temperature, chemical and water resistant. The heat pipes were manufactured by working fluid evaporation method. This is the simplest method how to make a heat pipe. At first is total heat pipe volume filled with working fluid and then is working fluid evaporated until the required volume. Thus it ensures only pure liquid and vapour phase of working fluid and no undesirable gases inside the heat pipe.

The results of the working fluid flow visualisation in heat pipe are shown in **Figure 22**. In **Figure 22a** and **b**, working fluid flow regimes in evaporator and condenser section of gravity heat pipe with inner diameter 13 mm are shown.

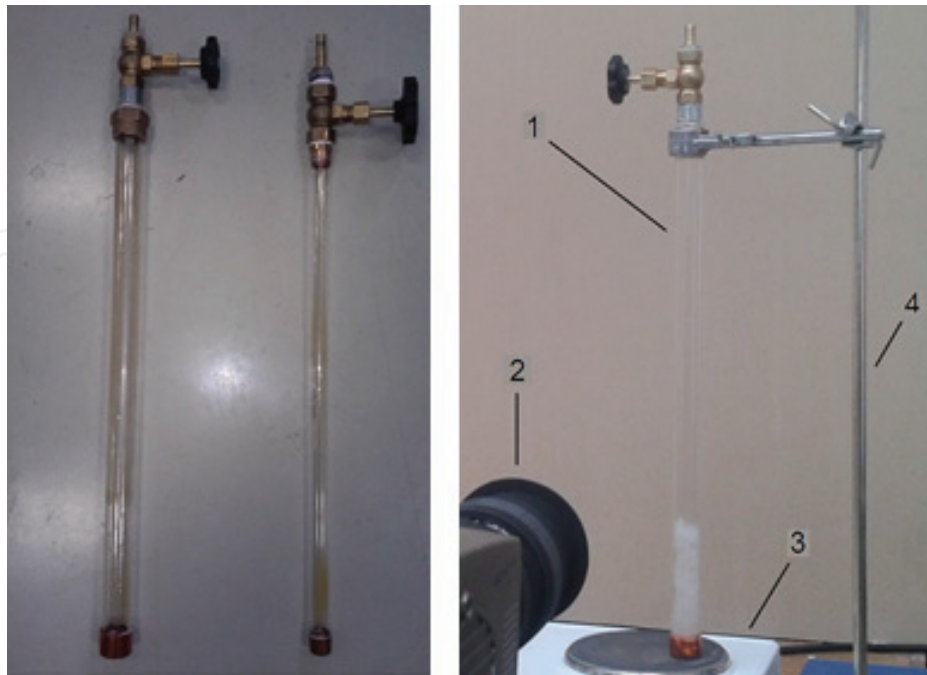


Figure 21. Working fluid flow visualisation in gravity heat pipe: (1) heat pipe, (2) video camera, (3) heat source, (4) stand.

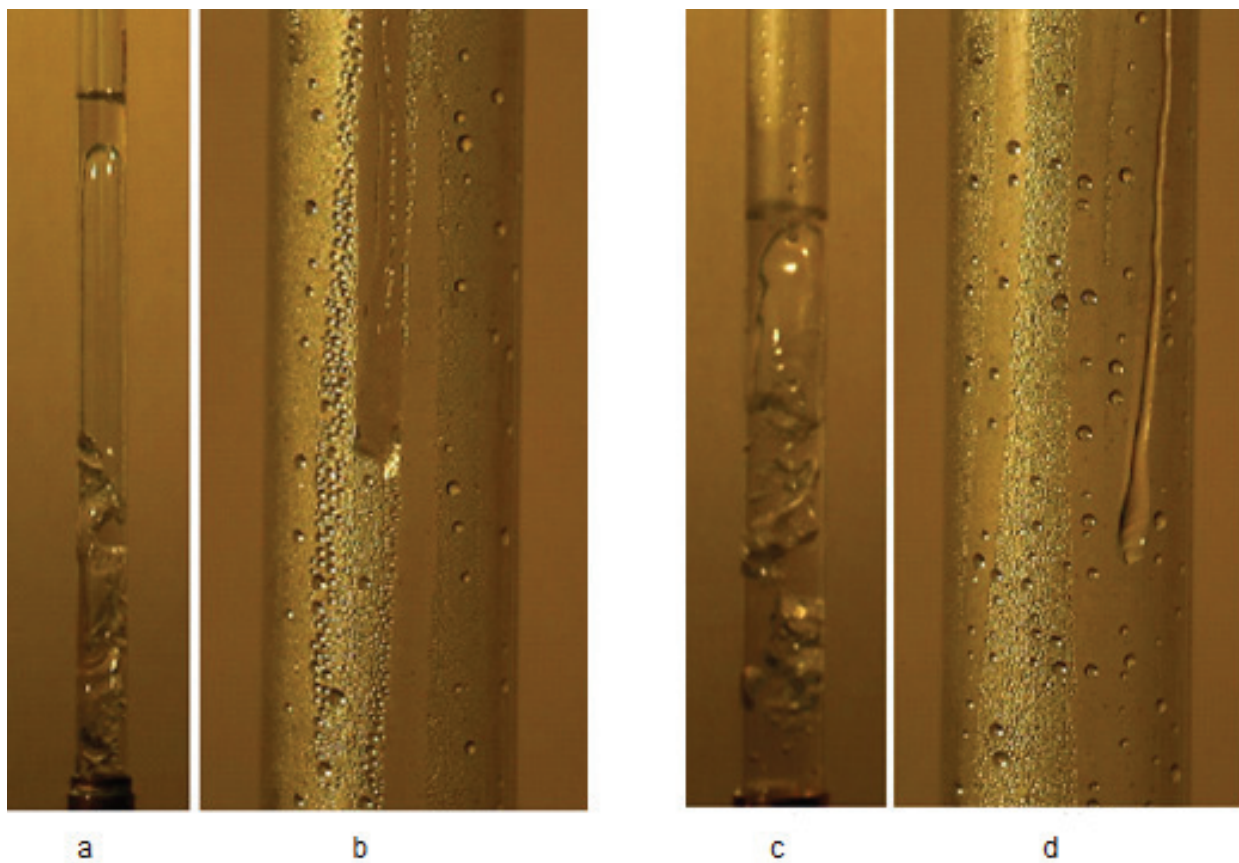


Figure 22. Boiling and condensation regimes of glass gravity heat pipe with working fluid water. (a) Evaporation section of heat pipe with inner diameter 13 mm, (b) Condensation section of heat pipe with inner diameter 13 mm, (c) Evaporation section of heat pipe with inner diameter 22 mm, (d) Condensation part of heat pipe with inner diameter 22 mm.

There you can see a typical film boiling regime with some big vapour bubbles on the bottom of heat pipe evaporator and one big vapour blanket push out liquid to the adiabatic section. In the condenser section you can see a typical drop-wise condensation when a small droplets of the working fluid are created on the surface wall. Once a time they are collect to the big drops, flown down the wall to the evaporator due to gravity and create a free space for a new drops.

In **Figure 22c** and **d**, working fluid flow regimes in evaporator and condenser section of gravity heat pipe with inner diameter 22 mm are shown. There you can show a similar film boiling regime as in heat pipe with the inner diameter 13 mm with the some big vapour bubbles on bottom of heat pipe evaporator In this case vapour did not push out liquid to the adiabatic section so high, what may a bigger heat pipe diameter cause. In the condenser section, you can see the same drop-wise condensation of the working fluid on the surface wall as in heat pipe with the inner diameter 13 mm. There was not observed influence of the heat pipe diameter on the condensation regime.

4.2. Wick heat pipe experiments

Wick heat pipe experiments deal with the influence of working position and quantity of working fluid on heat transport ability wick heat pipes. The experimental measurements was

performed with one heat pipes with grooved wick structures, three heat pipes with mesh screen wick structure (mesh 50,100 and 200), three heat pipes with porous sintered wick structure (metal powder 35 , 63 and 100 μm) and one heat pipe with composite wick structure (groove + mesh screen 50). All heat pipe has diameter DN 15, total length 0.5 m and working fluid water.

4.2.1. Determination of the working fluid quantity

At first was performed experiment focused on determination optimal quantity of working fluid in heat pipe. To determination optimal quantity of working fluid in wick heat pipe apply the same rules as in gravity heat pipe. This experiment was realised with heat pipe with mesh screen wick structure of DN 15, working fluid water and working fluid quantity in range 10 to 50%. In **Figure 23**, results influencing of working fluid quantity on heat pipe thermal performance at various working position are shown . The working position can be divided into three zones. Positive gravity action zone is represent by angle of inclination from vertical position 0–75°, zero gravity action zone (horizontal position) is represent by angle of inclination from vertical position 90° and negative gravity action zone is represent by angle of inclination from vertical position 105–180°.

In **Figure 24** results influencing working fluid quantity on heat pipe thermal performance at horizontal position are shown. This experiment show that the ideal quantity of working fluid is in the range of 10–30% of the total heat pipe volume and the best working heat pipe is heat pipe with 25% of the total heat pipe volume. Wick heat pipe with 40% is good operating in the gravity positive and zero action zone but in the negative gravity action zone. Wick heat pipe with working fluid quantity 50% and more are does not able heat transfer in zero and negative gravity action zone.

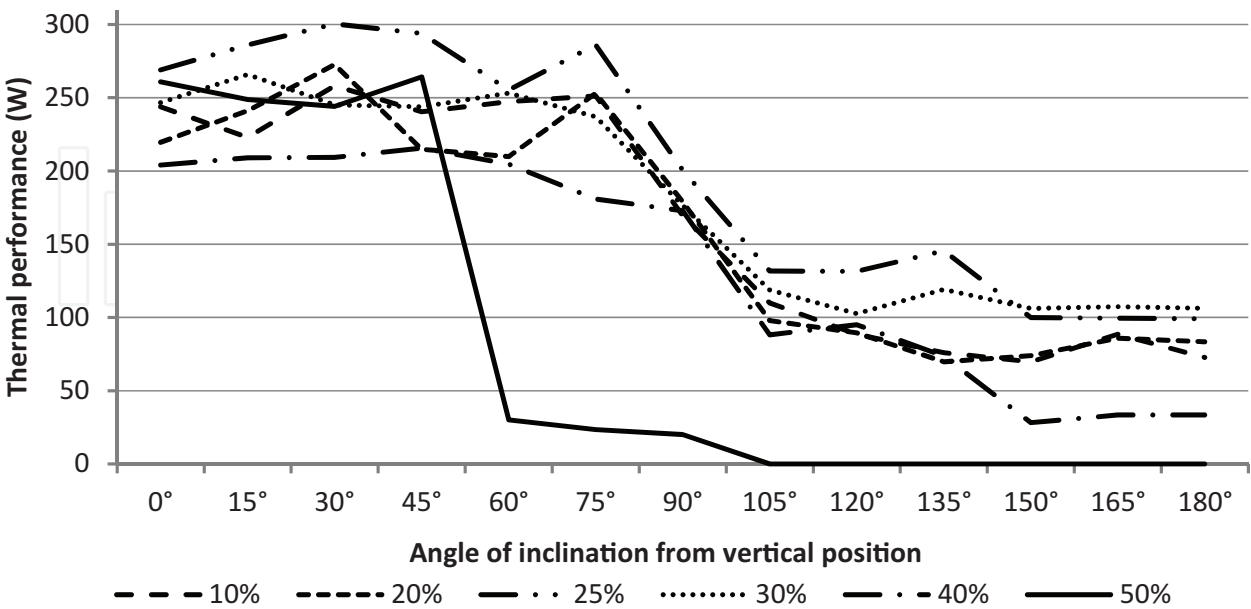


Figure 23. Dependence thermal performance on working position and various quantity of working fluid of wick heat pipe with mesh screen wick structure and water working fluid.

4.2.2. Influence working position on the heat transfer ability of heat pipe

In **Figure 25** influence of working position on the heat transfer ability of heat pipe with various wick structures (groove, mesh screen, sintered and composite) are shown. Working position of heat pipe can divided into three areas. Positive gravity action zone is represent by angle of inclination from vertical position 0–75°, zero gravity action zone (horizontal position) is represent by angle of inclination from vertical position 90° and negative gravity action zone is

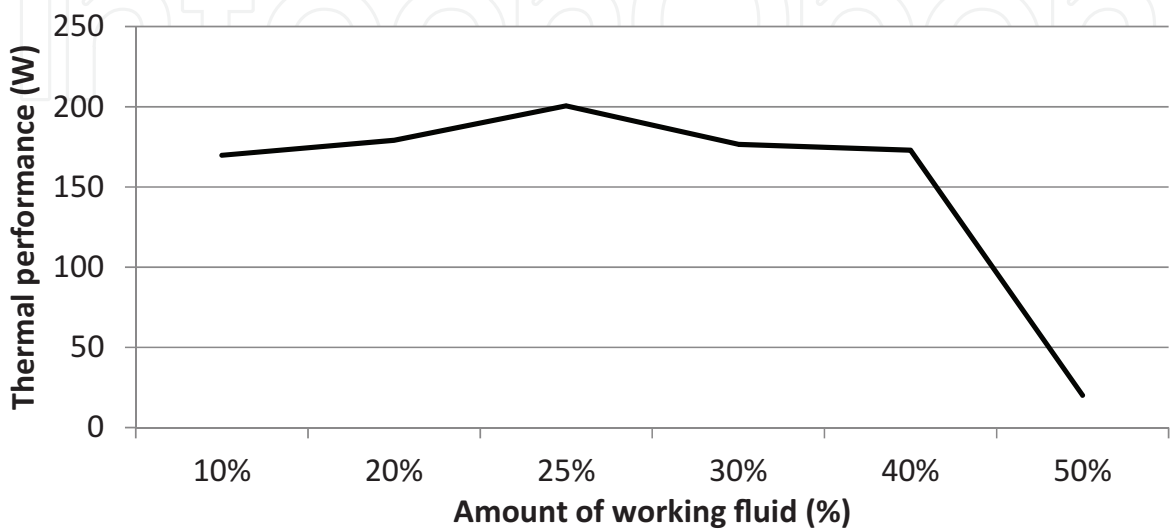


Figure 24. Dependence thermal performance on working fluid amount of wick heat pipe with mesh screen wick structure and water working fluid at horizontal position.

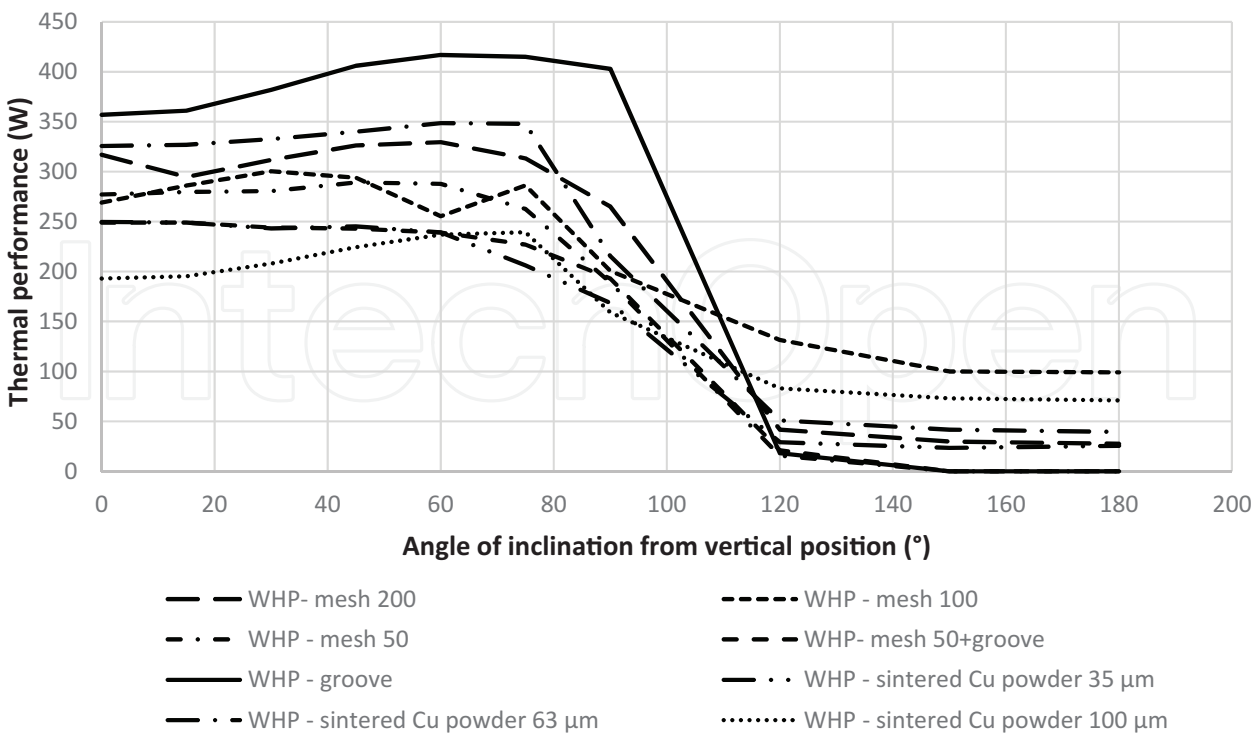


Figure 25. Dependence thermal performance on working position of wick heat pipes with various wick structures.

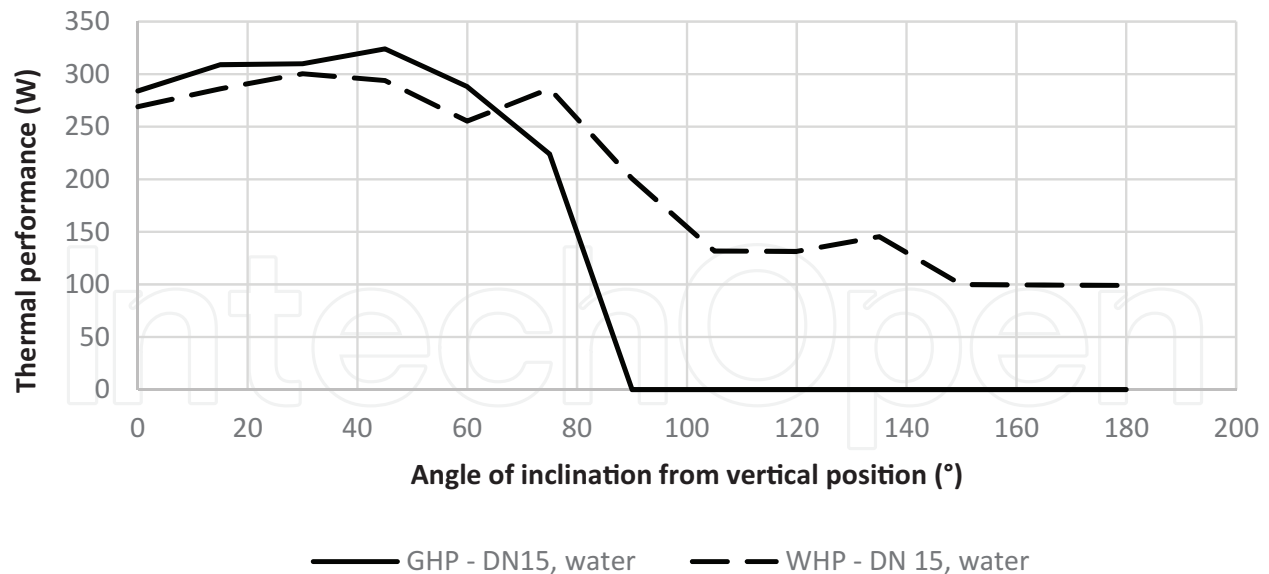


Figure 26. Dependence thermal performance on working position of gravitation heat pipe and wick heat pipe with mesh screen wick structure.

represent by angle of inclination from vertical position 105–180°. There is seen that all WHP has good ability heat transfer in positive and zero gravity action zone. The best ability shows WHP with groove wick structure. WHP with mesh screen wick structure show better ability than WHP with porous sintered wick structure. Zone with negative gravity action shows good ability heat transfer WHP with mesh and sintered wick structure. The best working heat pipes are WHP with wick structure mesh 100 and sintered 100 μm . WHP with groove wick structure a mesh 50 wick structure does not transfer heat. WHP with composite wick structure (mesh 50 + groove) show good ability heat transfer in zone of positive and zero gravity action but in the zone of negative gravity action does not heat transfer.

4.2.3. Influence of the working position on the heat transfer ability

In **Figure 26**, courses thermal performances transferred by WHP and GHP depending on working position are shown. At working position with positive gravity action in the region inclination angle from vertical position of 0–75° are courses of WHP and GHP are approx. similar when GHP is able transfer higher thermal performance than WHP. At the horizontal position when is the gravity action zero and in the vertical position with evaporator section above condensation section when is the gravity action negative are see differences when WHP is able transfer heat due the wick structure and GHP does not able transfer heat.

5. Heat pipe calculation

The heat flux transferred through the heat pipe depends mainly on the temperature difference and the corresponding thermal resistances. The real transferred heat is affected by the hydrodynamic and thermal processes that take place in the heat pipe at the various operating

conditions. The heat flux transferred by the heat pipe can reach limit values that depend on these processes. There are five known limitations that limit the overall heat transfer in different parts of the heat pipe depending on the working temperature. In **Figure 27**, an ideal model of all heat transfer limitations that define area of maximum heat flux transferred by heat pipe depending on operating temperature is shown.

5.1. Mathematical model

The mathematical model consist of calculation the heat pipe heat transfer limitation calculation. Heat pipe heat transfer limitations depending on the working fluid, the wick structure, the dimensions of the heat pipe and the heat pipe operation temperature. Each heat transfer limitation express part of total heat flux heat pipe, which is influencing hydrodynamic and thermal processes that occur in the heat pipe. Each limitations exists alone and they are oneself non-influence together. To design mathematical model for calculating heat flux transferred by heat pipe is necessary to know basic and derived parameters of the heat pipe and its wick structure and physical properties of the working fluid liquid and vapour phase.

5.1.1. Capillary limitation

Capillary limitation involves a limitation affect the wick heat pipe operation, which results from the capillary pressure acting on the condensed working fluid in the capillary structure. At the contact of liquid and wick structure surface, the capillary pressure is formed. This causes the liquid phase of the working fluid flow from the condenser to the evaporator. Decreasing the pores of the capillary structure increases the capillary pressure as well as hydraulic resistance. The capillary limit occurs when the capillary forces at the interface of the liquid and vapour phases in the evaporator and condenser section of the heat pipe are not large enough to overcome the pressure losses generated by the friction. If the capillary pressure in the heat pipe

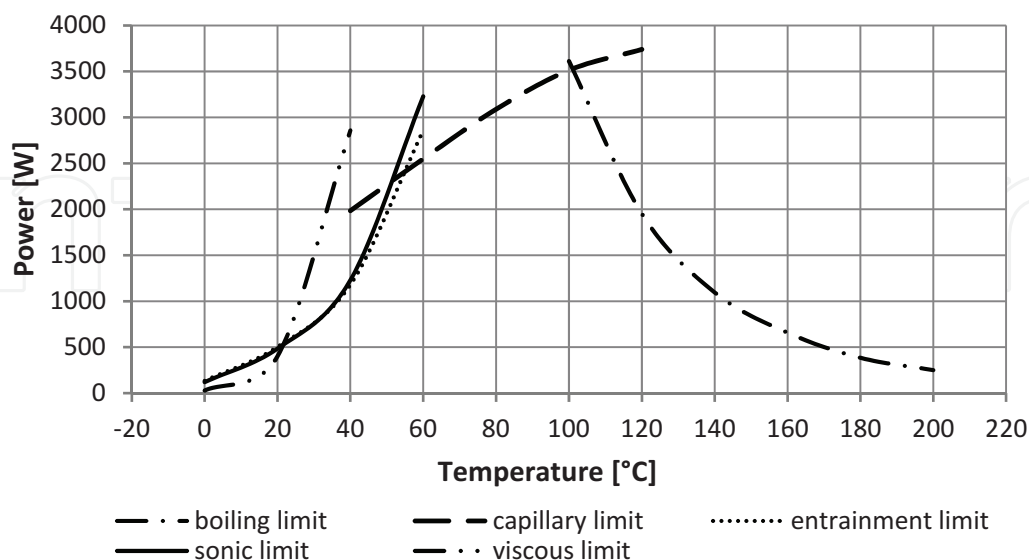


Figure 27. Heat transfer limitations of water wick heat pipe with sintered wick structure (heat pipe inner diameter 20 mm, total length 2 m, axial orientation 90°, sphere diameter of copper powder 0.85 mm, porosity 0.55, width of wick structure 6 mm).

during the operation is insufficient to provide the necessary condensate flow from the condenser to the evaporator, the capillary structure in the evaporator is dried and thus the further evaporation of the working substance is stopped. In general, the capillary limit is the primary limit that influences the heat pipe performance and is expressed by the relationship [12].

$$\dot{Q}_c = \frac{\sigma_l \cdot \rho_l \cdot l_v}{\mu_l} \cdot \frac{K \cdot A_w}{l_{eff}} \cdot \left(\frac{2}{r_{eff}} - \frac{\rho_l \cdot g \cdot l_t \cdot \cos \Psi}{\sigma_l} \right) \quad (6)$$

where A_w is the wick cross-sectional area (m^2), K is the wick permeability (m^2), μ_l is the liquid viscosity ($N \cdot sec \cdot m^{-2}$), ρ_l is the liquid density ($kg \cdot m^{-3}$), g is the acceleration due to gravity ($9.8 \cdot m \cdot sec^{-2}$), r_{eff} is the wick capillary radius in the evaporator (m) and l_t is the total length of the pipe (m) [13].

Furthermore, if the heat pipe has properly operate, the maximum capillary pressure have to be greater than the total pressure loss in the heat pipe and it is expressed by the relationship

$$(\Delta P_c)_{max} \geq \Delta P_{tot} \quad (7)$$

The maximum capillary pressure ΔP_c developed in wick structure of the heat pipe is defined by the Laplace-Young equation.

$$\Delta P_c = \frac{2\sigma}{r_{eff}} \cdot \cos \theta. \quad (8)$$

where r_{eff} is the effective pores radius of the wick structure and θ is contact angle liquid phase of the working fluid in wick structure, where $\theta = 0^\circ$ is the best wetting contact angle [5].

5.1.2. Viscous limitation

When the heat pipe operate at low operating temperatures the saturated vapour pressure may be very small and has the same range as the required pressure drop necessary to vapour flow from the evaporator to the condenser of the heat pipe. This results in a condition expressed by the viscous limit about balance of the vapour pressure and viscous forces in the capillary structure in the low velocity vapour flow. The most frequent cases of exceeding the boundary of the viscous limit occur when the heat pipe operate at temperature close the solidification of the working fluid. In this case, working fluid evaporation in the evaporator and heat transfer in the form of vapour flow through the adiabatic section into the condenser of the heat pipe did not occur. It is assumed that the vapour is isothermal ideal gas, the water vapour pressure on the end of the condenser is equal to zero, which provides the absolute limit for the pressure in the condenser. The viscous limit is referred as the condition of the vapour phase flow at low velocity and is expressed by the relationship

$$Q_v = \frac{\pi \cdot r_v^4 \cdot l_v \cdot \rho_v \cdot P_v}{12 \cdot \mu_v \cdot l_{eff}} \quad (9)$$

where l_v is the latent heat of vaporisation (J/kg), r_v is the cross-sectional radius of the vapour core (m), l_{eff} is the effective length of the heat pipe (m), μ_v is the vapour viscosity in the

evaporator ($\text{N} \cdot \text{secm}^{-2}$), P_v (Pa) is the vapour pressure and ρ_v (kgm^{-3}) is the density at the end of the heat pipe evaporator [14].

In case when the viscous limit is reached for many conditions, the condenser pressure could not be a zero. Then the following expression is applied

$$Q_v = \frac{A_v \cdot r_v^2 \cdot l_v \cdot \rho_v \cdot P_v}{16 \cdot \mu_v \cdot l_{eff}} \cdot \left(1 - \frac{P_{v,c}^2}{P_v^2}\right) \quad (10)$$

where $P_{v,c}$ is the vapour pressure in the condenser.

5.1.3. Sonic limitation

The sonic limit characterises the state in which the velocity of the evaporated vapour flow at the outlet of the evaporator reaches the sound velocity. Generally, this phenomenon occurs on the start of heat pipe operation at a low vapour pressure of the working fluid. Assuming that the vapour of the working fluid is the ideal gas and the vapour flow at the sound velocity throughout the heat pipe cross-section is uniform, the sonic limit is determined by the relationship (11). The sonic limit does not depend on the heat pipe orientation, type of the heat pipe and the same formula is applied for the gravity and wick heat pipe. The most difficult in the sonic limit determination is determining quantities of vapour density and pressure on inlet to the condenser [15].

$$Q_s = 0,474 \cdot A_v \cdot l_v \cdot (\rho_v \cdot P_v)^{0,5} \quad (11)$$

where ρ_v (kgm^{-3}) is the vapour density, P_v (Pa) is pressure at the end of heat pipe evaporator and A_v is the cross-sectional area of the vapour core (m^2).

The sonic limit is mainly associated with liquid-metal heat pipe start-up or low-temperature heat pipe operation due the very low vapour densities that occur in these cases. For the low-temperature or cryogenic temperatures, the sonic limit is not a typically factor, except for heat pipes with very small vapour channel diameters. The sonic limitation is referred as an upper limit of the axial heat transport capacity and does not necessarily result in dry-out of the wick structure in heat pipe evaporator or total heat pipe failure.

5.1.4. Entrainment limitation

Increasing the heat flux transferred by heat pipe increases the vapour flow velocity of the working fluid increases too and this result to a more pronounced interaction of the vapour and liquid phases inside the heat pipe. The interfacial surface becomes unstable and the viscous forces on the surface of the liquid overcome the forces of the surface tension. The wave are creates on the liquid phase surface at first from which the droplets are gradually tearing off. At a certain vapour flow velocity the liquid flow interruption into the evaporator section occur. The condenser section of heat pipe is overflow by vapour and liquid phase and the evaporator is overheated due to lack of the working fluid. The limit value of the heat flux at which is the heat pipe overflow corresponds to interaction limit. The entrainment limit calculation of the gravity heat pipe is based on the empirical correlation of a counter current air and

water film flow in a vertical tube. Entrainment limitation in gravitational heat pipe occur when the velocity of the liquid film approximates to zero and could be expressed by relationship [16]

$$Q_i = C^{x^2} \cdot A_v \cdot l_v \cdot \left[\rho_l^{-\frac{1}{4}} + \rho_v^{-\frac{1}{4}} \right]^{-2} \cdot [g \sigma_l \cdot (\rho_l - \rho_v)]^{\frac{1}{4}}, \quad (12)$$

$$C^{x^2} = 1,79 \operatorname{tgh} \left(0,5 Bo^{\frac{1}{4}} \right), \quad (13)$$

$$Bo = d_p \left[\frac{g(\rho_l - \rho_v)}{\sigma_l} \right]^{-2} \quad (14)$$

Entrainment limitation of the wick heat pipe is related to the condition when the vapour flows against the liquid flow in the wick structure, which may result in insufficient liquid flow in the wick structure [17]. Entrainment limitation of the wick heat pipe is expressed by relationship

$$Q_e = A_v \cdot l_v \cdot \left(\frac{\rho_v \cdot \sigma_l}{2 \cdot r_{c,ave}} \right)^{0.5} \quad (15)$$

where $r_{c,ave}$ is the average capillary radius of the wick structure and in many cases is approximated to r_{eff} , σ_l is the liquid surface tension (N/m).

5.1.5. Boiling limitation

When heating the surface of the heat pipe wall with a layer of liquid in the saturation boundary a three basic heat transfer regimes can occur. At low-temperature difference of the heated surface and interfacial surface of the liquid, a natural convection and evaporation from the liquid surface occurs. When increasing the temperature difference, a bubble boiling and gradually transformation to the film boiling occur. In heat pipe a surface evaporation at low heat flux densities and bubble boiling at higher densities occur. Although the heat transfer intensity is greatest in the bubble boiling, for most types of wick heat pipes the bubble boiling is not desired because interfere with the liquid wicking into the wick structure. On the other hand, in a heat pipe with a grooved capillary structure and a gravity heat pipe is bubble boiling favourable [18]. The heat flux in which the bubble boiling occurs in the wick heat pipes and the film boiling occurs in the gravity heat pipe is referred as the boiling limit. For the gravity heat pipe is expressed by the relationship [19]

$$Q_v = 0.16 \cdot A_v \cdot l_v \sqrt[4]{\sigma_l \cdot g \cdot \rho_v^2 \cdot (\rho_l - \rho_v)} \quad (16)$$

Determination of the boiling limit of the wick heat pipe is problematic, because it depends on a number of technological and operating conditions. The most reliable determination of the boiling limit is experimental determination for the particular wick structure and working fluid. Approximate determination of the boiling limitation for the wick heat pipe is expressed by the relationship [20]

$$Q_b = \frac{4\pi \cdot l_{eff} \cdot \lambda_{eff} \cdot T_v \cdot \sigma_l}{l_v \cdot \rho_v \cdot \ln \frac{r_i}{r_v}} \cdot \left(\frac{1}{r_n} - \frac{1}{r_{eff}} \right) \quad (17)$$

where λ_{eff} is the effective thermal conductivity of the wick structure composed of the wick thermal conductivity and working fluid thermal conductivity (W/m K), T_v is temperature of vapour saturation (K), r_v is the vapour core radius, r_i is the inner container radius (m) and r_n is the bubble nucleation radius in range from 0.1 to 25.0 μm for conventional metallic heat pipe container materials.

5.1.6. Heat pipe parameters

To calculate heat pipe heat transport limitations, it is needed to know thermophysical properties of working fluid in heat pipe, basic heat pipe parameters, thermal conductivity of heat pipe material, working temperature of heat pipe, axial orientation of heat pipe and other heat pipe parameters calculated from basic heat pipe parameters needed.

$$l_t = l_e + l_{ad} + l_c \quad (18)$$

$$l_{eff} = 0,5 \cdot (l_e + l_c) + l_{ad} \quad (19)$$

$$A_v = \pi \cdot r_v^2 \quad (20)$$

$$A_w = \pi \cdot (r_i^2 - (r_i - h)^2) \quad (21)$$

where l_t is total length of heat pipe (m), l_e is evaporation length of heat pipe (m), l_{ad} adiabatic length of heat pipe (m), l_c is condensation length of heat pipe (m), l_{eff} is effective length of heat pipe (m), A_v is cross-sectional area of the vapour core (m^2), A_w is wick cross-sectional area (m^2), r_v is cross-sectional radius of vapour core (m), r_i is inner container radius (m) and h is wick structure width (m).

The other parameters needed to calculate heat pipe heat transport limitations are basic parameters of sintered wick structure and other parameters calculated from basic parameters of wick structure.

$$r_{eff} = 0,21 \cdot d_s \quad (22)$$

$$K = \frac{d^2 \cdot \varepsilon^3}{150 \cdot (1 - \varepsilon)^2} \quad (23)$$

$$\lambda_{eff} = \lambda_l \frac{2 \cdot \lambda_l + \lambda_m - 2 \cdot (1 - \varepsilon) \cdot (\lambda_l - \lambda_m)}{2 \cdot \lambda_l + \lambda_m + (1 - \varepsilon) \cdot (\lambda_l - \lambda_m)} \quad (24)$$

where K is permeability (m^2), d is sphere diameter (m), ε is porosity (-), r_{eff} is effective radius of wick structure (m), λ_{eff} is effective thermal conductivity, λ_l is thermal conductivity of working fluid liquid and λ_m is thermal conductivity of wick material [21].

5.2. Verification of the mathematical model

The mathematical model was created according above equations of limitations and input heat pipe parameters. Results of mathematical model are graphic dependencies of heat transport limitations on heat pipe working temperature. Mathematical model results of heat transport limitations specific types heat pipe was compare with results from measurement of heat pipe performance at temperature 50 and 70°C. In **Figure 28** are graphic comparison results heat transport limitations determining total performance of heat pipe from mathematical model with measured performance of ethanol wick heat pipe with sintered wick structure and sphere diameter of copper powder 0.1 mm. Dotted line create boundary of heat pipe performance by capillary limitation and dashed line is boiling limitations. The full line is measured results of heat pipe thermal performance at temperature 50 and 70°C. In **Figure 28** is seen that the dotted line and full line are in the same region at temperature 50 and 70°C.

Results in the next **Figure 29** confirm verification of mathematical model, where measuring heat flux of wick heat pipe with grooved wick structure is in similar region as a calculation

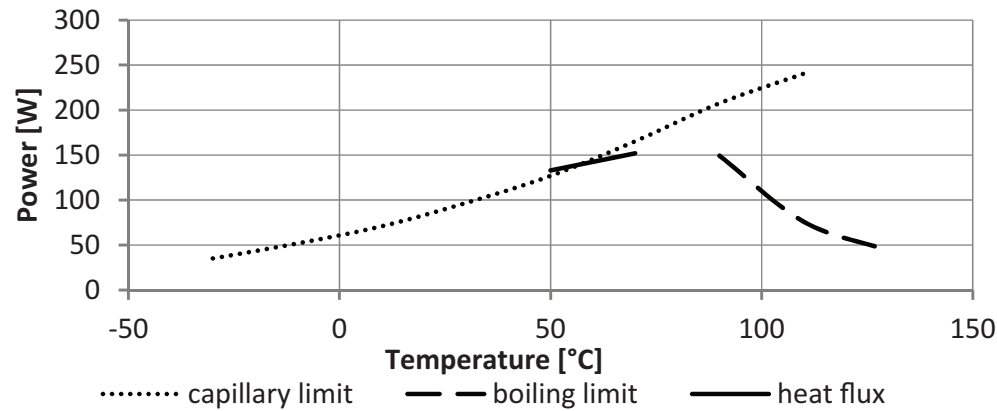


Figure 28. Verification of mathematical model by measuring of heat pipe performance (ethanol wick heat pipe with sintered wick structure and sphere diameter of copper powder 0.1 mm and axial orientation of heat pipe ψ 180°).

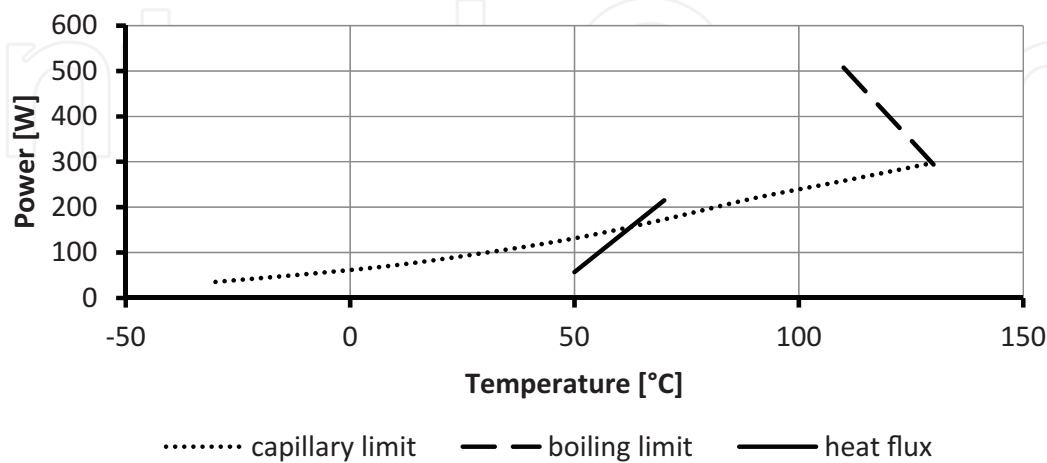


Figure 29. Verification of mathematical model by measuring of heat pipe performance (ethanol wick heat pipe with grooved wick structure length 0.3/width 0.2/pitch 0.3).

results of capillary limitation, which is determining limitation for this kind of heat pipe at temperature 50 and 70°C. There is seen that the capillary limitation is determining limitation at full working temperature range.

5.3. Results of heat pipe calculation

Results of the heat pipe calculation show interesting graphs of the maximal heat flux transferred by heat pipe depending on the wick structure parameters. It could be used in design optimization of the heat pipe wick structure. The curves present area of maximal heat flux transferred by heat pipe depends on operating temperature. In **Figures 30** and **31**, influence of groove dimensions on total heat pipe performance is presented. Heat transport limitations of wick heat pipe with grooved wick structure and groove dimensions (height 0.3 mm, width 0.2 mm and pitch 0.3 mm) created by mathematical model are presented. In **Figure 30**, influence of groove high from 0.3 to 0.9 mm on total heat pipe performance is shown. Heat pipe performance rising with groove high increase was seen. But increasing of groove height from 0.7 to 0.9 is the boiling limitation shown as a main limitation and at working temperature from 80 to 130°C has decrease tendency on heat pipe performance. According to graphic dependencies, the groove height of 0.6 is shown as an optimal height for this specific type of grooved wick heat pipe.

In **Figure 31**, influence of groove width from 0.2 to 0.9 mm on total heat pipe performance is shown. An extreme increase of heat pipe performance at temperature range from 40 to 90°C is seen. These temperature range determines the limitation a capillary limitation. At lower temperature of working temperature range is with increasing of groove width the main limitation sonic limitation. At higher temperature, boiling limitation as a main limitation and for groove

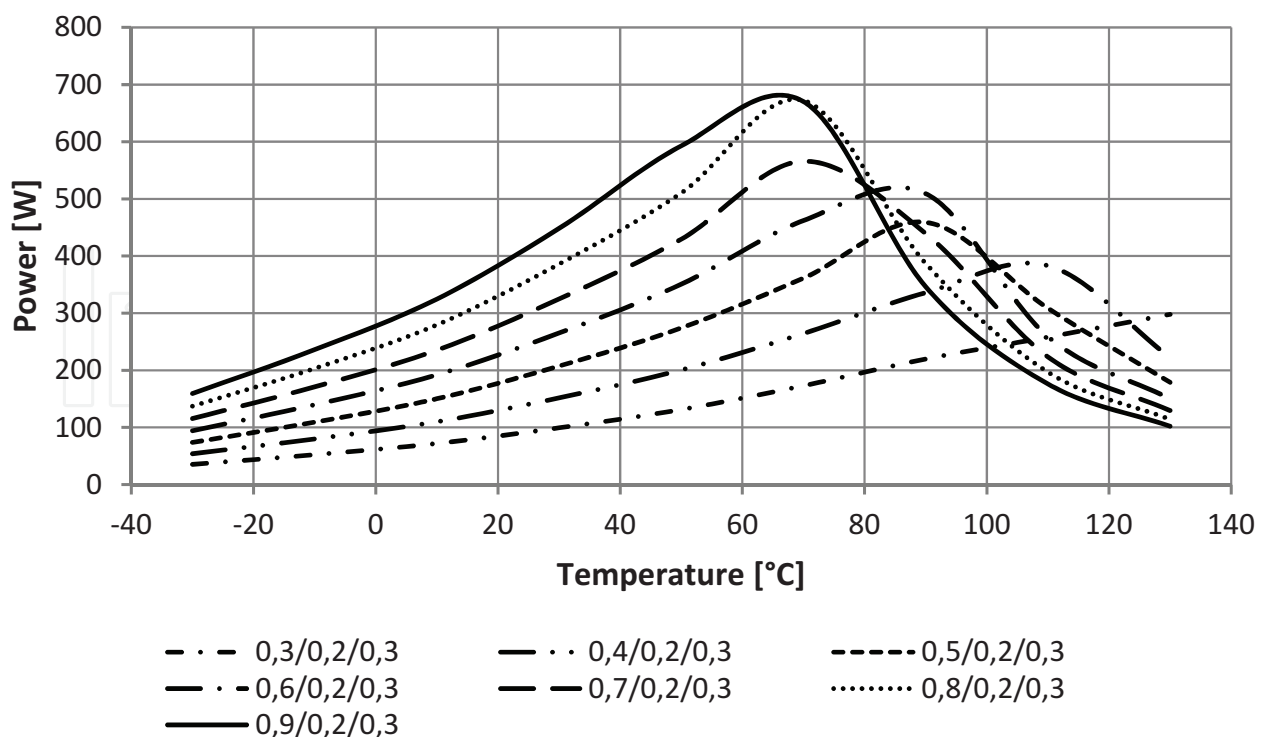


Figure 30. Dependence of heat pipe performance from groove length in heat pipe with grooved wick structure.

width is shown in the range of 0.6–0.9 for boiling limitation equal at temperature from 80 to 130°C. According to graphic dependencies, the groove width of 0.6 is shown as an optimal width for this specific type of grooved wick heat pipe.

In **Figure 32**, influence of wick structure width on heat pipe performance is shown. Wick structure width is an important factor, which influences heat pipe performance. There is seen that the heat pipe performance increase with the wick structure thickness in operating temperature region of –30 to 60°C. The capillary limitation is a main limitation for this region. On the other way, increase of the wick structure thickness decrease the heat pipe performance in

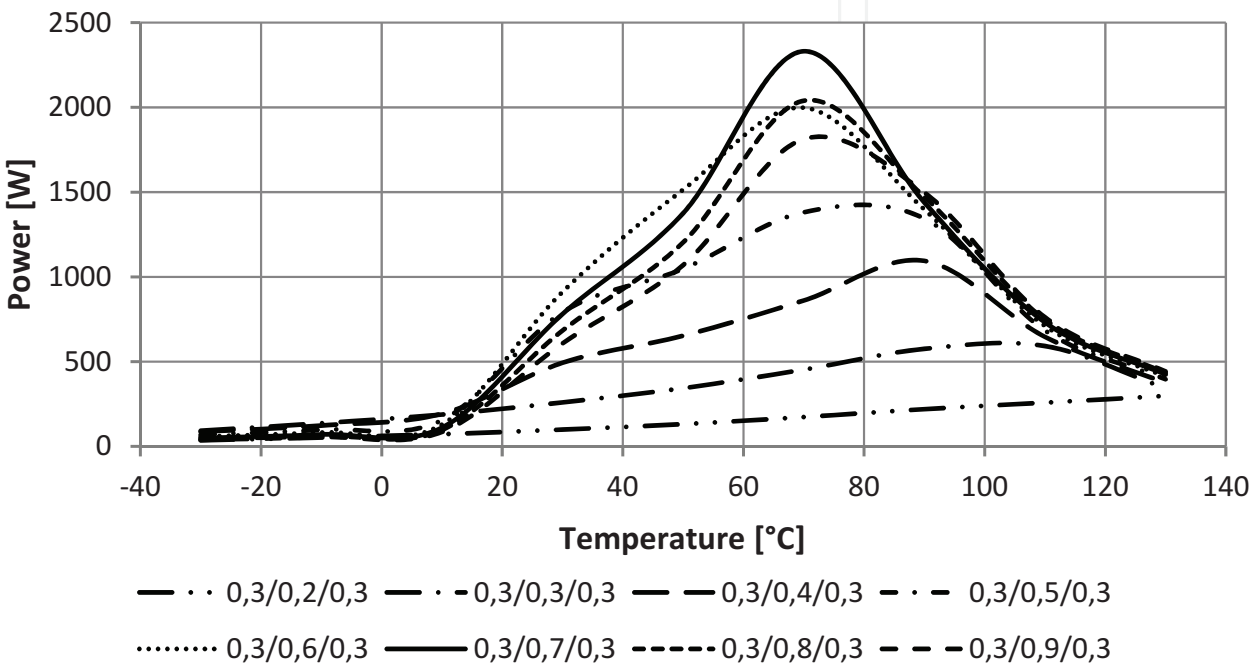


Figure 31. Dependence of heat pipe performance from groove width in heat pipe with grooved wick structure.

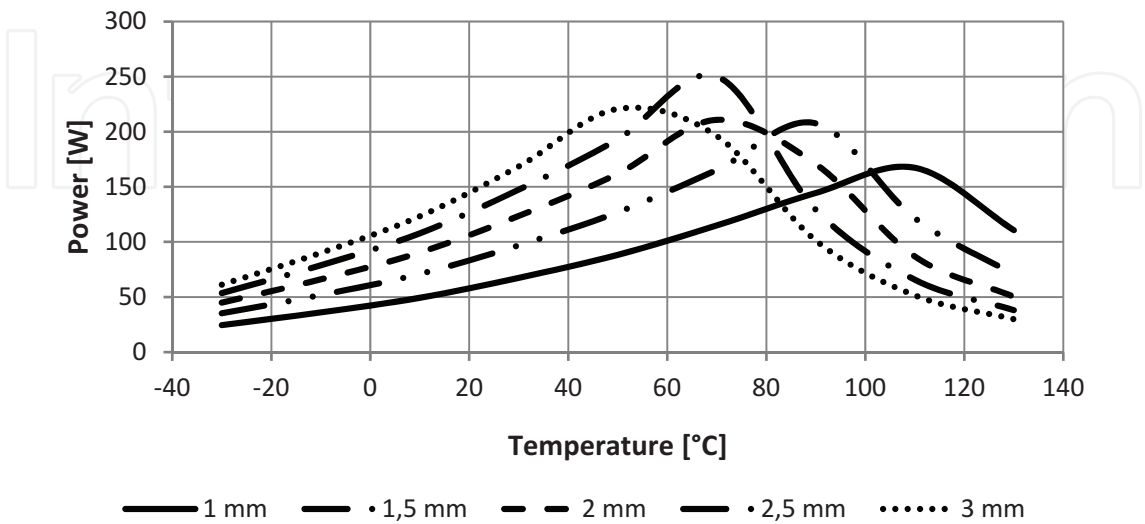


Figure 32. Dependence of heat pipe performance from wick structure width of the sintered wick heat pipe.

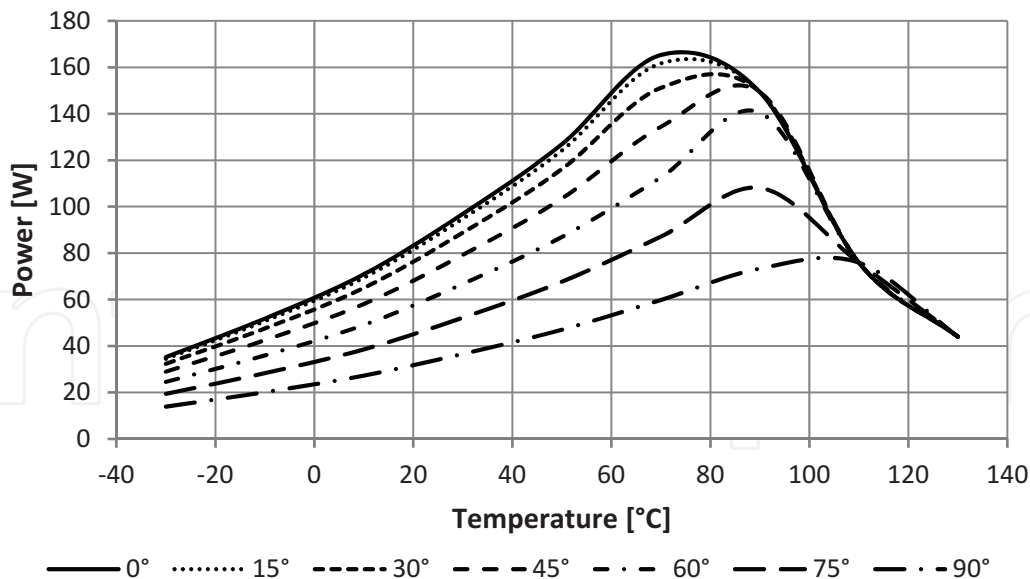


Figure 33. Dependence of heat pipe performance from position of the sintered wick heat pipe.

operating temperature region of 80–130°C. It may be caused by bubble nucleation in wick structure, when the returning liquid from the condenser section to evaporator section of heat pipe evaporates. In this case, the main limitation is boiling limitation.

In **Figure 33**, influence of the position heat pipe on their performance is shown. Wick in heat pipe ensure liquid return from condensation section to evaporation section of heat pipe and therefore wick heat pipe can operate at various tilt angles, even at horizontal position. The heat pipe performance decrease with higher tilt angle from vertical position. But even though according graphic dependencies of heat pipe performance on heat pipe position, it can say that heat pipe performance of wick heat pipe in horizontal position is only at half less as at vertical position.

6. Conclusion

The experiments performed with the heat pipes in this work gives several conclusions about influence working position on their heat transfer ability, where the gravity and capillarity of wick structures plays main role.

The results of performed experiments show how the gravity effect on the heat transport ability of gravity and wick heat pipe type at changing working position. Gravity heat pipe can operate only in working position with positive action of gravity. The heat transport ability of GHP with the change in working position from vertical (0°) to horizontal (90°) is changed too. There is an interesting finding that heat transport ability of gravity heat pipe with the increasing inclination angle up to 75° from the vertical position, does not change much even it could say that in the position from 0 to 60° slightly increase. With next increasing inclination angle from 75 to 90°, the heat transport ability of gravity heat pipe rapidly decrease to zero value. Wick heat pipe can operate in positive, zero and negative action of gravity, while the heat transfer ability of the wick heat pipe is uniform in area of the positive and zero action gravity.

In area of the negative action of gravity, the heat transfer ability of wick heat pipe gradually decrease, but still is able to transfer heat.

The other conclusion of this work is that with increasing heat pipe diameter, the thermal performance transferred by gravity heat pipe is increasing too. But this statement does not apply for the heat flux transferred per cm^2 of heat pipe cross-section area, because heat pipes with smaller diameter transferred higher heat fluxes per cm^2 of heat pipe cross-section area than heat pipes with bigger diameter.

Experiment of working fluid flow visualisation in gravity heat pipe show that the inner diameter of heat pipe does not have influence on the boiling and condensation regimes. In both cases, the film boiling in the evaporator section and drop-wise condensation in condenser section occur. The boiling regimes differ only in height of pushed liquid in to the adiabatic section. The pushed liquid height was in heat pipe of inner diameter 13 mm higher than in the heat pipe of inner diameter 22 mm. In both cases of drop-wise condensation, the small drops collect to the bigger drop and flow down the wall due gravity.

The mathematical calculation of the heat pipe, heat transport limitations show that the critical limitations influencing heat transfer ability of wick heat pipe are entrainment limitation, capillary limitation and boiling limitation. These limitations depends on thermophysical properties, wick and heat pipe parameters. The thermophysical properties of each working fluid are stable in temperature range and they cannot change. Changing the dimensions of wick structure is possible that optimise total heat flux transferred by heat pipe, because capillary pressure makes the wick structure depend mainly on the wick structure permeability. When design wick structure, be careful because increase pore dimension increase permeability but decrease capillary pressure which manage the working fluid circulation in heat pipe. Therefore the capillary limitation is the main heat transport limitation in wick heat pipe.

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