Czech Technical University in Prague

Faculty of Electrical Engineering
Department of Electrotechnology

MAGNETIC FIELD **CONTROL** *OF HEAT TRANSPORT IN HEAT PIPES*

Doctoral Thesis

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Abstract

This work deals with magnetic field effects on heat transport in heat pipes. Heat pipes are two phase thermal devices transporting heat by a close cycle of a working fluid within. They are able to transport heat over long distances with a low temperature drop and their efficiency can achieve of several magnitudes higher than that of passive copper systems. Thus, heat pipes are often used in high tech applications, like cooling of power electronic components, thermal management of technological processes or in medical devices. However, heat pipes are getting to be a standard thermal solution also in wide number of consumer electronics.

Several devices utilizing heat pipes need an active thermal management with some kind of heat flow regulation. In those cases heat pipes are modified into several constructions allowing variable heat conductance. Different approaches are available and well established now, however all with specific limitations. This work ascertains an alternative approach based on an interaction between a fluid contained within heat pipes and a magnetic field.

The magnetic field regulation of heat transport in heat pipes is still in an early stage of laboratory research and we do not know about any commercial application utilizing this type of control. During this work we have designed and realized several experimental heat pipe systems utilizing magnetic field based regulation and ascertain their behaviors and operation under magnetic field exposition. According to the experimental results it might be possible to significantly affect heat transport in selected heat pipe systems by magnetic field.

Abstrakt

Tato disertační práce se zabývá problematikou tepelných trubic ovlivňovaných magnetickým polem za účelem řízení schopnosti přenášet teplo ve směru jejich podélné osy. Tepelné trubice umožňují vysoce efektivní přenos tepla a v současné době nacházejí své uplatnění v celé řadě nejrůznějších aplikací, od chlazení elektronických zařízení a součástek až po nasazení v rekuperačních výměnících nebo chirurgických nástrojích a kosmické technice. V poslední době, v souvislosti s hromadnou výrobou tepelných trubic, se tento typ přenosu tepla stává běžný také ve spotřební elektronice.

Některé z těchto, ale i dalších aplikací vyžadují regulaci přenosu tepla, a proto jsou v některých případech tepelné trubice modifikovány tak, aby toto umožňovaly. V současné době je k dispozici několik variant, jak tohoto dosáhnout, každá ale s určitými omezeními. Tato práce zkoumá alternativní metodu řízení pomocí magnetického pole.

Podle dostupných informací tato technika nebyla zatím v praxi uplatněna a je zatím zkoumána pouze v laboratorních podmínkách. Popis návrhu a realizace těchto tepelných trubic, jakož i provedených vybraných experimentů, jejich zdůvodnění a vyhodnocení jsou uvedeny v této disertační práci a představuje také její hlavní přínos k současnému stavu vědy a poznání. Na základě výsledků těchto experimentů se zdá být reálné ovlivňovat transport tepla ve specificky navržených tepelných trubicích pomocí vnějšího statického magnetického pole.

Acknowledgements

There are many people who have been more or less involved in this project or just supported me, the work and the overall research effort in some manner. I would like to thank you all for your help and contribution to this work. Above all, I would like to express my gratitude to my supervisor doc. Jan Kuba for his big patient help. Doc. Kuba has been all the time in a close touch to this project and brought an important contribution to the final outcome. His marvelous research effort was always motivating me and all the others around to the further work. Additionally, I would like to appreciate an important support of my home Department of Electrotechnology and its members. And last, but certainly not least, I thank to my family for a plenty of time I could spend on this work.

Table of Content

1 Introduction

There is a well-known fact of an interaction between several matters and magnetic field represented by changes of their physical or chemical properties and behaviors. It was also experimentally ascertained that by special conditions it is possible to significantly affect convection of selected fluids, move them or stop. By this work we have applied these mechanisms and principles on special thermal systems – heat pipes to control their thermal characteristics.

Heat pipes are two-phase thermal devices allowing a very effective heat transport [20]. Usually, they are in a form of a closed tube with a fluid within continually evaporating at one end and condensing at the opposite end. So there is a close cycle with a vapor streaming one way and a liquid flowing back. Magnetic field applied on a heat pipe might be able to influence this cycle by special conditions.

This work deals with a new approach for the heat transport control in heat pipes based on magnetic field exposition. The interaction between static magnetic field and a fluid within a heat pipe may be capable to effectively regulate thermal characteristics of mentioned systems. This method has not been applied in any commercial application yet and also related research activities are very limited. Magnetic field control might be an alternative to several conventional methods currently available for that purpose.

Heat pipes operating under magnetic field exposition are very complex systems from the theoretical point of view. It is very complicated to create an accurate theoretical description or a mathematical model of such systems. From this reason we decided to create a real working heat pipe prototypes controlled by magnetic field and investigate their behaviours and operation experimentally.

By this work we have developed two basic approaches to the magnetic field control of heat pipes – Magnetic Trap Method and Magnetic Plug Method. Both methods have been experimentally ascertained and the effects on heat pipes operation evaluated. Several heat pipe prototypes were manufactured and tested. Selected results of the performed experiments are presented within this work. The experimental work represents the main innovative potential and contribution to the current state of knowledge and is the most important part of this work.

Heat pipes are getting to be widely used in a large number of applications. They are popular for many reasons. Absence of any moving parts makes them very silent. No need of any power feeding makes them passive and independent. Since the phase changes are associated with very high energy exchange and vapor convection is almost lossless, they are able to transport heat with very high efficiency. Furthermore, heat pipes getting cheaper as the production grows. Some of the heat pipes applications need a thermal control and hence it is so important to ascertain various possibilities of the heat transport control in heat pipes.

This work consists of 9 main chapters. It begins with an introduction to the work (chapter 1), description of current state of knowledge in the field of thermal systems interacting with some kind of magnetic field (chapter 2) and goals of the work (chapter 3). Then, general heat pipes characteristics and basic working principles are described (chapter 4), followed by a chapter focused on variable conductance heat pipes (chapter 5). The rest of this work deals with the ascertained magnetic field control methods and represents original theses and experiments. The magnetic field control method principles, its requirements and possibilities are described in the text (chapter 6). This is followed by experimental investigation of mentioned effects including description of development of tested heat pipes prototypes. Setup of realized experiments and selected results are presented there as well (chapter 7). The work is closed with a final conclusion (chapter 8).

2 Current State of Knowledge

Current state of knowledge, research and development in the field of heat pipes utilizing some kind of magnetic field system for their thermal control is summarized in the following text. Facts and data were obtained from studies and papers published in scientific literature and available by on-line web portals Science Direct (Elsevier) and Springer Link.

Possibilities of magnetic field application on heat pipes have been investigated from the very beginning of the heat pipe development. Several examples of such systems and approaches are presented in the following text. However, we do not know about any commercial application.

There are two important studies published in the past which are closely related to the magnetic field control of heat pipes. One of them is focused on static magnetic field influence on convection of vapours and gases in the free air [14]. The second one deals with a heat pipe filled with oxygen influenced by an electromagnet [15]. The both are further discussed in the following text more in detail.

There are also several studies focused on employment of special synthetic fluids with excellent magnetic behaviours – so called ferrofluids (more details in the section 6.4.2). A study investigating magnetic field enhancement of heat exchange in evaporator region of a heat pipe filled with a ferrofluid [19] is presented in the following text.

2.1 Magnetic Field Influence on Free Gas Convection

A study ascertaining influence of magnetic field on free convection of selected gases or steam matters [14] is presented in the following text. It has been observed that the fluid convection was reduced or stopped by interaction with external static magnetic field. It is important that these experiments were performed in the free space.

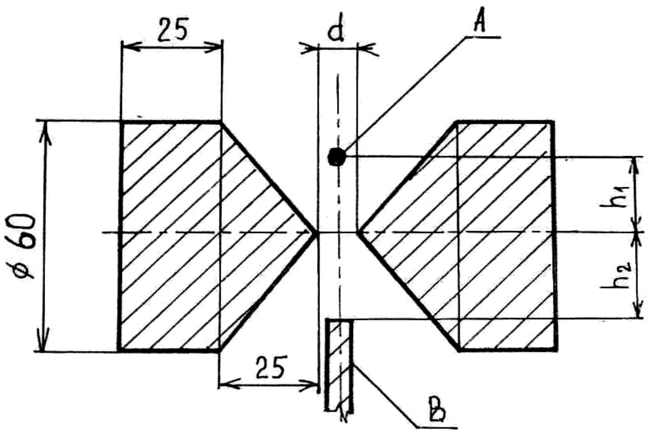


Fig. 2.1 Experimental arrangement of the free gas convection experiment

In this experiment gaseous matters flowing up through an air gap of an electromagnet were ascertained (see the Fig. 2.1). By strong magnetic field the motion of observed matters was disturbed or fully blocked. The mentioned effects were evaluated by temperature characteristics measured above the air gap (A).

It was clearly observed that the motion of all tested matters (pure hot air, combustion products of a spirit flame, water steam, and pure nitrogen steam) was significantly changed by the magnetic field exposition. It was also observed that the effect of magnetic field strongly depends on magnetic behaviours of the flowing matter and magnetic field parameters.

2.2 Magnetic Field influence on Cryogenic Heat Pipe Performance

A study investigating operation of a cryogenic heat pipe filled with liquid oxygen and operating under static magnetic field generated by an electromagnet [15] is presented in the following text. The experimental arrangement is shown in the Fig. 2.2. A vertically oriented gravitational heat pipe was placed in the electromagnet air gap. The top of the heat pipe was cooled by liquid nitrogen and the rest was exposed to the room temperature. The temperature of the heat pipe was measured in 7 points during its operation under various conditions.

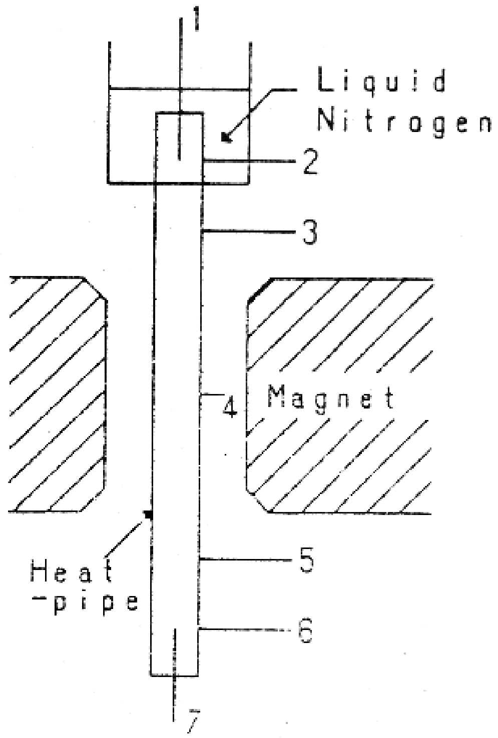


Fig. 2.2 Experimental arrangement of the cryogenic heat pipe

According to the presented results it was possible to significantly reduce heat flow in the heat pipe by static magnetic field of B = 1,0 T with gradient 5 to 50 T/m (Fig. 2.3). It was also found out the heat transport was disturbed when the magnetic induction B was 0,85 T and higher. This study was limited to the mentioned heat pipe design filled with oxygen and the electromagnet as a magnetic field source.

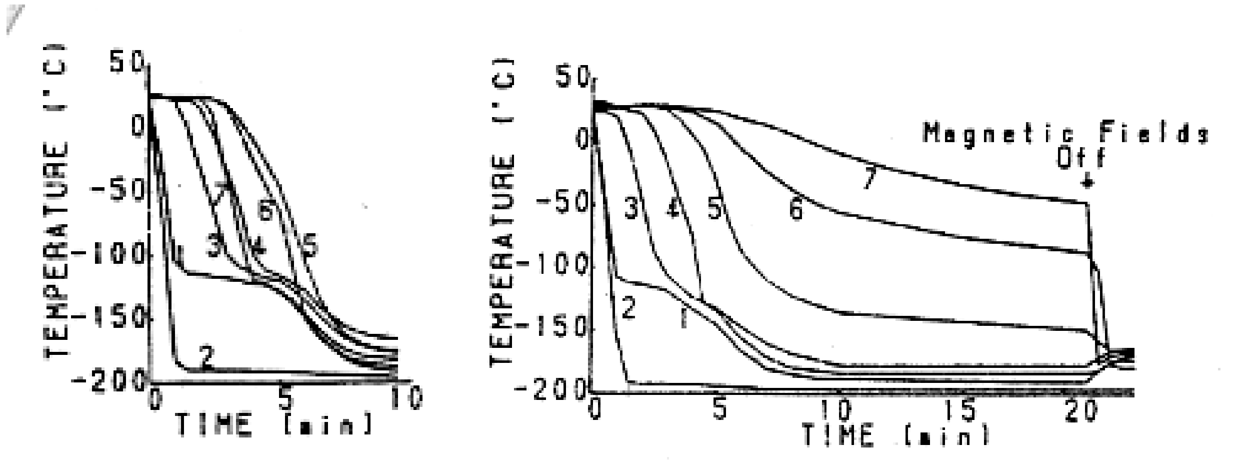


Fig. 2.3 Time dependence of temperature at seven points of cryogenic heat pipe [15]:
without magnetic field exposure (left)
with magnetic field exposure (right)

2.3 Magnetic Coupling Applied on Heat Pipes

There are also examples of mechanical control systems utilizing magnetic field [16]. An example of such system is presented in the Fig. 2.4. A wick inside a heat pipe is movable by magnetic coupling and can be connected and disconnected by this way. So it is possible totally stop the working cycle within. Another approach may be some kind of a valve reducing the vapor channel in a heat pipe. However, commercial applications or more detailed studies of these systems are not known.

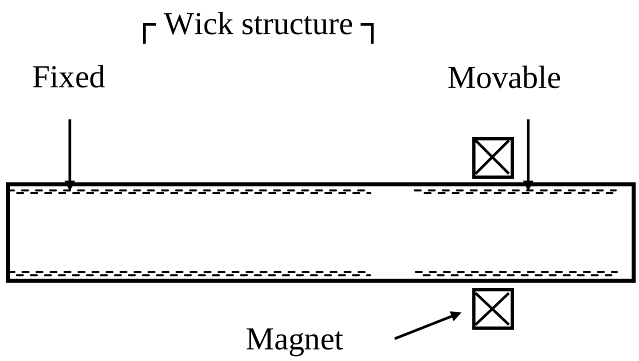


Fig. 2.4 Schema of a heat pipe with movable wick structure by magnetic coupling

2.4 Magnetic Field Enhancement of Heat Pipe with Ferrofluid

A study ascertaining heat pipes filled with citric ion stabilized ferrofluids operating under external static magnetic field [19] is presented in the following text. In the arrangement (Fig. 2.5) the evaporator region is exposed to a static magnetic field generated by Nd-Fe-B permanent magnets in various configurations. The magnetic field exposition initiates an additional liquid convection in the evaporator supporting heat exchange in this region.

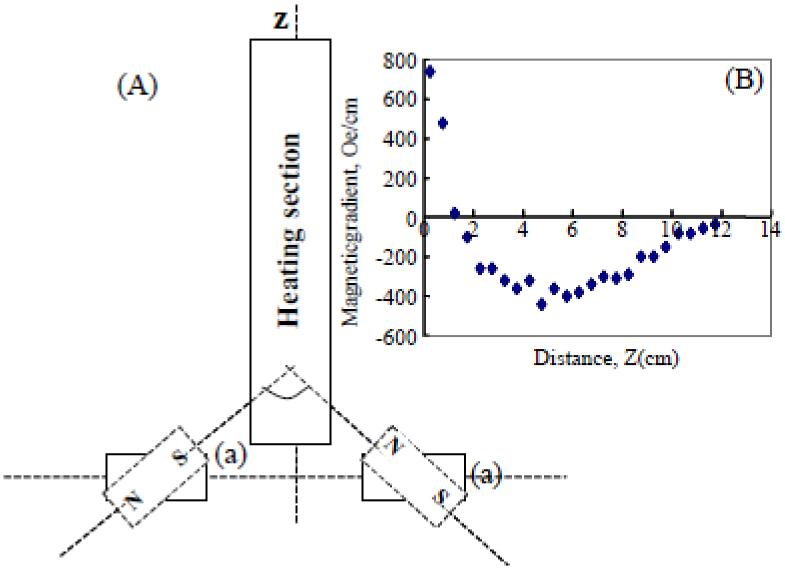


Fig. 2.5 Heat pipe with movable wick structure by magnetic coupling

According to the presented results, heat capability of the tested heat pipe operating under magnetic field exposition increased of up to 30% compared to that without any magnetic field exposition. At optimal conditions the presented heat pipe was able to achieve heat transport capability of 10% higher than that of a similar standard heat pipe filled with water only.

3 Goals of the Work

The main aim of this work is development of a method for control of heat transport in heat pipes by a magnetic field exposition and experimental evaluation of its possibilities. The work objectives include but are not limited to the followings:

Development of a method for heat transport control in heat pipes based on magnetic field exposition. The method shall be capable to significantly affect the heat pipe operation and its thermal characteristics. Additionally, it should be feasible by using passive permanent magnets systems instead of electromagnet sources with high energy consumption.

Experimental investigation of heat pipes utilizing proposed magnetic field control methods. Influence of such control systems on heat transport in heat pipes shall be ascertained. The experiments should be realized for various heat pipe constructions and overall system arrangements.

Design and manufacturing of heat pipe prototypes. For the experimental investigation it is necessary to create prototypes capable for operation under standard conditions. Their construction must also allow ascertaining of mentioned magnetic field effects on heat flow within. A suitable working fluid should be selected for that purpose as well.

Installation of an experimental arrangement for testing of mentioned effects in heat pipe prototypes. It shall allow heat pipes operation in selected mode and measurement of important heat pipe parameters, especially temperature and internal pressure. The arrangement and tooling shall also allow manufacturing of the prototypes.

Publishing of theses and results of the work. Papers based on this work shall be published in journals and proceeded at international conferences. Heat pipe prototypes and arrangements realized during the work might be also registered as Utility Models at Czech Industrial Property Office in Prague or as Functional Models at Czech Technical University in Prague. They may be also employed for educational aims.

4 Heat pipes

Heat pipes are thermal devices allowing very effective heat transport [15], [16], [17], [26], [27]. They are based on a two-phase fluid cycle inside a closed tube. First heat pipes are known from the 19th century as Perkins tubes using gravity for the liquid return (they are also called thermosyphon). In the 1960s the US space program needed effective and light-weight cooling systems operating in the 0-g environment. The Perkins tube was an ideal candidate but it was necessary to solve condensate return independently on the gravity. Thus, a capillary structure was added inside the tube. So a standard wicked heat pipe was developed (Fig. 4.1).

Fig. 4.1 Several examples of heat pipe applications and solutions

The fluid circulates in heat pipes while continually evaporating at one end and condensing at the opposite end. Since evaporation and condensation are very effective thermal processes, heat pipes are able to transport heat with very high efficiency and without any external power feeding. Currently available heat pipes are able to operate in a wide range of temperatures from a few Kelvins up to about two thousands Kelvins. Most applications need to work at ambient temperatures. Typical for this range is water filled heat pipe with effective thermal conductance up to 10^4 W·m^{-1}·K^{-1} and temperature drop less than 1 K·m^{-1} (for example, thermal conductance of copper is 380 W·m^{-1}·K^{-1}). Since there is a lower pressure inside a heat pipe, it is able to work from about 20 °C up to 250 °C.

Heat pipes are very simple in their construction without any moving parts and external power needs. They are quiet, reliable and needs no maintenance for years. Big advantage is their low weight, important especially for space and avionic applications. Since all the electronic devices and components are more and more miniaturized, it is also very beneficial that heat pipes can remove large amount of heat from a small area. On the other hand, they may have some difficulties at the start-up or with the wick performance. See the typical heat pipes characteristics in the Tab. 4.1.

Heat pipes are getting to be a common thermal solution in a wide number of applications. The absolutely most often are cooling of electronic components. Heat pipes can be found in laptops or other consumer electronic, power semiconductor modules, avionics, sensor systems or others. However, heat pipes are employed also in more specialized and less often applications like cryosurgery devices, tight temperature controlled material processing or cryogenic systems. The mass production of heat pipes reduces their cost and thus, further increase of heat pipe applications may be expected.

Tab. 4.1 Summary of heat pipe characteristic behaviours

Benefits	**Negatives**
High thermal conductance (high heat flux)	Operation temperature range limited by a used working fluid
Almost isothermal along the whole length (temperature flattening)	Position limitations
Passive device (No power feeding necessary)	Possible complications at start-up
Can work as a thermal transformer (small area heat in - large area heat out)	Could be more expensive compared to conventional systems
Heat source - sink isolation	
Simple construction and build in flexibility	
Quiet operation, no moving parts	
Long life and reliability (even in a hard environment)	
Control possibilities (can also operate as a thermal diode)	

4.1 Heat Pipe Operation

Let us discuss basic principles of heat pipes operation in the following text [20]. Heat is transported by a cycle of a working fluid within a closed tube (Fig. 4.2). Heating one end of the tube (evaporator with heat source) the fluid is boiling and continuously vaporizing. The generated vapour streams very fast through the tube and condensates on the colder wall at the opposite end (condenser with heat sink). The condensed liquid may return to the evaporator using gravity or through a wick. The working cycle continues as long as the temperature gradient between the evaporator and condenser is maintained.

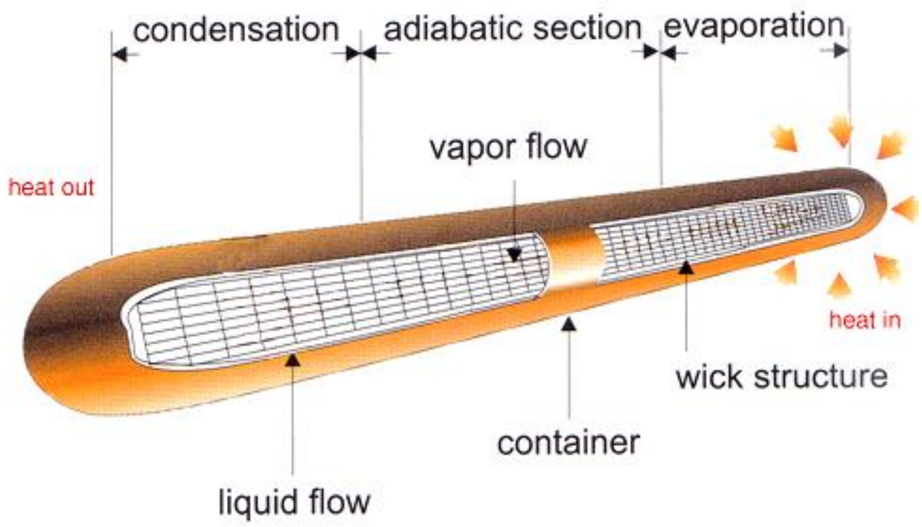


Fig. 4.2 Heat pipe operation schema

4.1.1 Condensate Return

Condensate return has a large impact on heat pipes operation and is often the limiting factor of its power capability. There are two basic types of heat pipes from the condensate return point of view:

- gravitational heat pipes (thermosyphon)
- wicked heat pipes (heat pipe with capillary structure)

In gravitational heat pipes the condensate returns back to the evaporator region due to the gravitational force. This type of heat pipes has a very simple construction but on the other hand also an important limitation - the evaporator must be always kept below the condenser.

Wicked heat pipes with an integrated capillary system are the most common type today. The wick is able to pump liquid even against gravity and so it allows much more independence in the heat pipe positioning (more about the wick systems in the section 4.2.3).

Except the above mentioned return systems, there are also some other techniques including axial rotation, osmotic or magnetic forces, etc. An example of a rotating heat pipe is presented in the Fig. 4.3. Those are widely used for cooling of electric engines or other rotating devices.

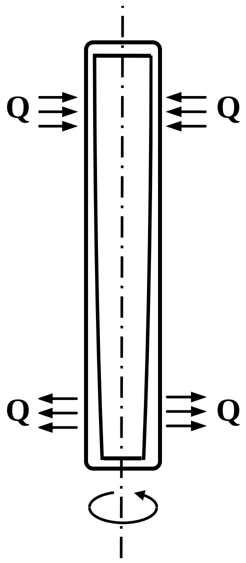


Fig. 4.3 Heat pipe with liquid return based on axial rotation

4.1.2 Thermal Resistance Model

Thermodynamic behaviours and properties of heat pipes can be described by equivalent thermal resistances. Their values depend on the heat pipe construction and operation mode. The overall thermal resistance of a simple cylindrical heat pipe is

$$R = R_1 + R_9 + R_P = R_1 + R_9 + \frac{\sum_{i=2}^{8} R_i}{1 + \frac{\sum_{i=2}^{8} R_i}{R_{10}}} \; ; \quad [\mathrm{K \cdot W^{-1}}] \tag{4.1}$$

consisting of 10 partial thermal resistances in serial-parallel combination, as seen in the Fig. 4.4.

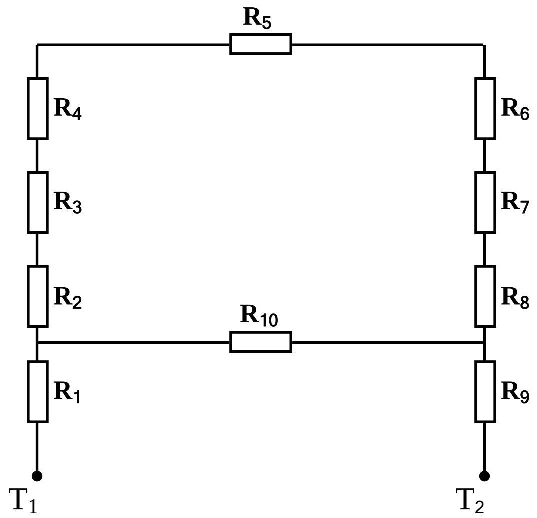


Fig. 4.4 Equivalent thermal resistances representing a heat pipe

Each thermal resistance is related to a specific part of a heat pipe with a specific heat transfer mechanism:

- **R_1** - Thermal resistance of the contact heat source – heat pipe container
- **R_2** - Radial th. resistance of the container wall in the evaporator region
- **R_3** - Radial th. resistance of the condensate film or wick in the evaporator region
- **R_4** - Thermal resistance of the liquid – vapor interface in the evaporator region
- **R_5** - Thermal resistance of the vapor column in the adiabatic section
- **R_6** - Thermal resistance of the vapor – liquid interface in the condenser region
- **R_7** - Radial th. resistance of the condensate film or wick in the condenser region
- **R_8** - Radial th. resistance of the container wall in the condenser region
- **R_9** - Thermal resistance of the contact heat sink – heat pipe container
- **R_{10}**- Axial th. resistance of the container wall (and wick)

The temperature drop of external resistances **R_1** and **R_9** are high, usually comparable with the rest of the heat pipe resistance (consisting from **R_2 - R_8**). They depend on quality of mechanical contacts heat pipe – heat source and heat pipe – heat sink. On the other hand, resistances of the liquid – vapor interfaces and of the vapor column (**R_4** – **R_6**) are very low (usually not measureable) and thus, they can be usually neglected.

There is also a parallel way for heat transport by axial heat conduction through the container wall (and wick). However, its thermal resistance **R_{10}** is much higher than that of the standard way provided by the working cycle and thus, it is relevant only when the heat pipe does not operate (residual heat flow at thermal diodes or variable conductance heat pipes).

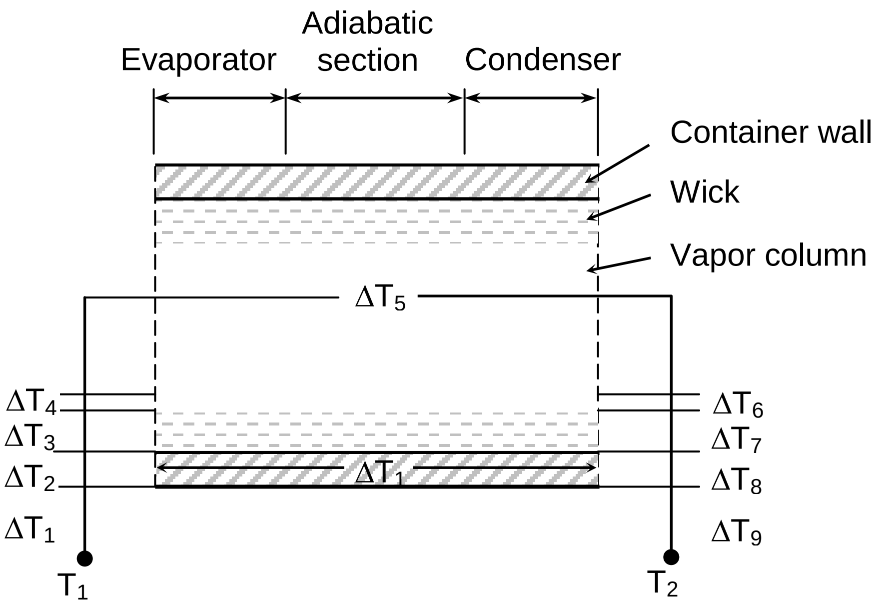


Fig. 4.5 Partial temperature drops ΔT along the heat pipe (cross-section view)

Every partial thermal resistance, described above, increase the total temperature drop, as graphically presented in the Fig. 4.5. Heat pipes are able to achieve low thermal resistance on long ways due to almost lossless convection of the vapour.

4.1.3 Heat Transfer in Heat Pipe

Since there is a difference between the evaporator temperature T_E (K) and the condenser temperature T_C (K), the working fluid circulates in the heat pipe and caries out the heat flux

$$P = \dot{m} \cdot L_V = \frac{T_E - T_C}{R}; \quad \left[W; \frac{kg}{s}, \frac{m^2}{s^2} \right] \quad \text{, where} \tag{4.2}$$

$\dot{m}$ - mass flow of working fluid,

L_V - latent heat of evaporation,

R - total thermal resistance of heat pipe.

Heat enters heat pipes at the evaporator region, usually by conduction from a heat source. Equivalent thermal resistance $\mathbf{R_1}$ is related to the heat transfer between the heat source and the heat pipe surface. It usually depends on the quality of thermal contact between a heat pipe and a heat source.

Then heat flows through the container wall by radial conduction. To ensure low $\mathbf{R_2}$, container material with high thermal conductance (usually copper if compatible with other heat pipe elements) and low wall thickness (but also respecting the mechanical stress at higher internal pressure) should be utilized.

Equivalent thermal resistance $\mathbf{R_3}$ represents heat transfer through the liquid film (gravitational heat pipes) or through the wick (wicked heat pipes). This resistance is significant especially at cryogenic heat pipes with low thermal conductance of fluids. At wicked heat pipes it depends also on the heat flux. For low values there is only conduction through the wick and natural convection of the liquid. At higher values bubbles are generated at the wall and the heat transport is increasing by latent heat of evaporation and supported liquid convection.

Then, heat is transferred by latent heat of evaporation at vaporization and condensation **($\mathbf{R_4}$ and $\mathbf{R_6}$)**. There is a large energy in this phase changes allowing heat pipe to work with very high efficiency. These thermal resistances are very low and may be neglected.

Between the evaporator and condenser heat is transported by the vapour convection. There is a pressure drop along the vapour column represented by the thermal resistance $\mathbf{R_5}$. However, this can be usually neglected. Thanks to this fact, heat pipes are able to transport heat over long distances with insignificant temperature drop (however, the condensate return must be assured).

In the condenser region the situation is very similar to that in the evaporator. Vapor condensates on the condenser surface with a low thermal resistance $\mathbf{R_6}$. Then it flows through the wick/liquid film ($\mathbf{R_7}$) and container wall ($\mathbf{R_8}$). From the outer surface of the condenser heat is usually conducted to a heat sink ($\mathbf{R_9}$). It may be useful to know typical values of the equivalent th. resistances - see the Tab. 4.2.

Tab. 4.2 Typical values of thermal resistances of a heat pipe

Resistance	Corresponding part	Typical value (K/W)	Comment
R1, R9	External heat transfer	10^1 - 10^3	
R2, R8	Radial of the wall	10^{-1}	
R3, R7	Radial of wick/liquid film	10^1	
R4, R6	Liquid-vapor interfaces	10^{-5}	Usually negligible
R5	Vapor column	10^{-8}	Usually negligible
R10	Axial of the wall	10^3	

4.1.4 Limits of Heat Pipe Operation

The heat pipe operation is limited by several factors illustrated in the Fig. 4.6. It is necessary to consider every single limit. Altogether they define the working area of a heat pipe and set up its maximal capability. Some of those limits are important at the start-up, some of them at higher temperatures and some of them are critical across the whole operating range.

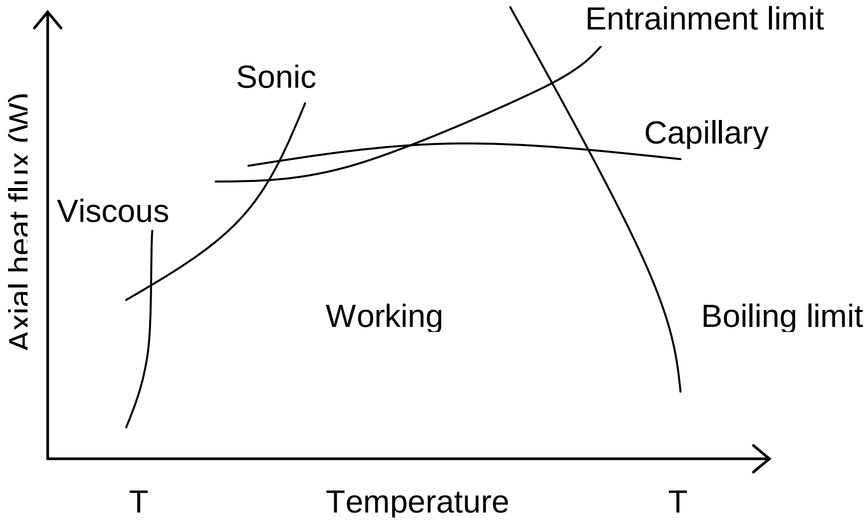


Fig. 4.6 Heat pipe operation limits

The **sonic limit** may be important at the start-up and also for some high temperature heat pipes when the vapor streams very fast and may reach the sonic speed.

The **viscous limit** (vapor pressure limit) is important for wicked heat pipes at the start-up. At low temperatures the pressure difference is insufficient to overcome the pressure drop in the wick.

The **capillary limit** is very critical for all wicked heat pipes and it usually limits the maximal heat flux across the whole temperature range. However, it can be partially eliminated by the gravity. Gravitational heat pipes are not limited by this limit at all.

Vapour streaming through the heat pipe can entrain the liquid droplets back to the condenser and prevent the liquid return. The **entrainment limit** is critical for the gravitational heat pipes.

The **boiling limit** is related to the radial heat flux in the evaporator region. When exceeding the limit, vapour bubbles are being created around the evaporator and thermal resistance is increasing.

4.2 Construction

Heat pipes are very simple in their construction. They always consist of a closed container (usually in the form of a cylindrical tube) and a small amount of working fluid within. Some kind of wick structure may be built-in inside the container. Special heat pipes may contain also additional components, e.g. some kind of valves in Variable Conductance Heat Pipes. Very important for heat pipes operation is that all the components must be chemically compatible and stable. In the Tab. 4.3 there are typical combinations of container materials and working fluids.

Tab. 4.3 Typical combinations of container materials and working fluids

Working Fluid	**Container Material**
Liquid Nitrogen	Stainless Steel
Liquid Ammonia	Nickel, Aluminum, Stainless Steel
Methanol	Copper, Nickel, Stainless Steel
Water	Copper, Nickel
Potassium	Nickel, Stainless Steel
Sodium	Nickel, Stainless Steel
Lithium	Niobium +1% Zirconium

4.2.1 Container

Heat pipe container is a hermetically closed envelope. A cylindrical geometry is most common, but other geometries are also possible, as seen in the Fig. 4.7. Heat pipes are often bendable to a specific geometry and may be adapted for several applications (however, not all wicks are flexible, espec. sintered structures are very fragile). The main container functions are listed below:

- Hermetic closure of internal heat pipe environment
- Radial heat flow through its wall (high thermal conductance required)
- Mechanical protection
- High internal pressure withstanding

Material of the heat pipe container must meet all the above mentioned requirements. The container must withstand the mechanical stress at the evacuation before filling and then high internal pressure at higher temperatures while being absolutely leak free. Material with high thermal conductance should be used to obtain low temperature drop.

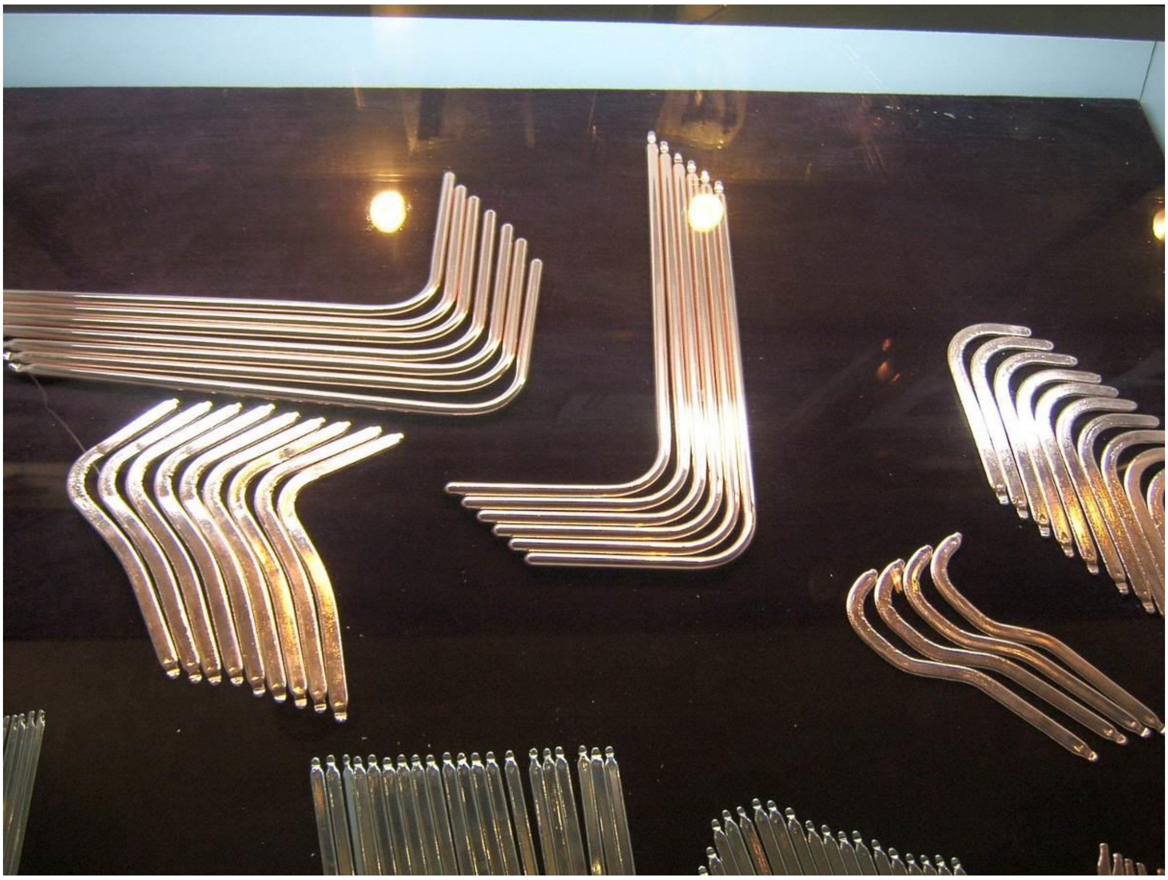


Fig. 4.7 Heat pipes with various shapes of containers

Typical materials used for heat pipe containers operating at various temperature ranges are listed in the Tab. 4.3. The most often container material is copper - traditional for water heat pipes. It has excellent thermal conductance, however, on the other hand the mechanical strength is relatively low (unsuitable for water heat pipes operating above 200 °C) and the mass density is also high (unsuitable for space and aircraft applications).

In some special cases, adiabatic section of the heat pipe can be made from different material with lower thermal conductance than that of evaporator and condenser. So the heat load and heat sink can be thermally cut off when the heat pipe does not operate. At some of our experiments the adiabatic section was made from glass to enable visual observation of the processes inside.

4.2.2 Working Fluids

Working fluid is an essential part of the heat pipe system. It must be compatible with other components (container, wick, event. others) and chemically stable (see typical combinations in the Tab. 4.3). The fluid choice follows from the heat pipe operation temperature. It must be in the range between the triple point T_T and the critical point T_C of the fluid. Other parameters of working fluid important for the heat pipe operation are shown in the Tab. 4.4, including their impact on the heat pipe operation. All these aspects must be taken into account to assure a reliable heat pipe operation.

Tab. 4.4 Working fluid parameters and their impact on the heat pipe operation

Working fluid parameter	**Required value**	**Related heat pipe parameter**
Latent heat	high	Heat transport capability
Thermal conductance	high	Radial temp. drop in wick/liquid film
Liquid and vapor viscosity	low	Pressure drop of vapor and liquid flow
Wick wettability	high	Wick filling
Surface tension	high	Wick capability
Health and safety	high	Application possibilities

The most common working fluid is water which is suitable for ambient temperatures (from about 20 °C to 250 °C) and has optimal behaviours for the two phase heat transport. For lower temperatures methanol, ammonia or some of permanent gases are used (see more in the 4.3.1). Above the water temperature range heat pipes are filled with dowtherm, mercury or some halides for example. For highest temperatures up to about 2000 °C alkali metals are used as a working fluid.

Working fluids used for low, ambient and high temperatures are strongly different in their parameters. Low temperature working fluids are generally less optimal than ambient or high temperature ones. Power capability comparison of heat pipes filled with various working fluids is presented in the Tab. 4.5.

Tab. 4.5 Power Capability of Heat Pipes with Typical Working Fluids

Working Fluid	**Axial heat flux (kW/cm^2)**	**Surface heat flux (W/cm^2)**
Liquid Nitrogen	0.067 (-163°C)	1.01 (-163°C)
Liquid Ammonia	0.295	2.95
Methanol	0.45 (100°C)	75.5 (100°C)
Water	0.67 (200°C)	146 (170°C)
Potassium	5.6 (750°C)	181 (750°C)
Sodium	9.3 (850°C)	224 (760°C)
Lithium	2.0 (1250°C)	207 (1250°C)

As mentioned above, every working fluid is able to work only in the limited temperature range between its triple and critical point. When the needed operating range is wider than a single working fluid can cover, two or more heat pipes with different working fluids may be arranged into a cascade. For example in some cryogenic systems it is necessary to cool down the system from ambient temperature to cryogenic temperature. Typical solution may be a cascade of an ethane heat pipe (300 K → 140 K) and an oxygen heat pipe (140 K → 60 K). Another way is to fill a single heat pipe with couple of different working fluids. However, this is not so often, because such customer solutions are much more expensive than mass produced heat pipes combined into a cascade.

Fig. 4.8 Various kinds of wick structures used in water heat pipes

4.2.3 Wick Structures

Most heat pipes have some kind of a built-in wick (wicked heat pipes) providing the condensate return from the condenser back to the evaporator. The wick is usually some kind of a fine porous structure or grooves (illustrated in the Fig. 4.8) or capillaries (a fibre wick in the Fig. 4.9). It can pump the liquid even against the gravity due to the capillary pressure. Thus, wicked heat pipes bring much more independence in their positioning and orientation. Moreover, the wick can be assisted by the gravity when the evaporator is below the condenser (gravity assist mode).

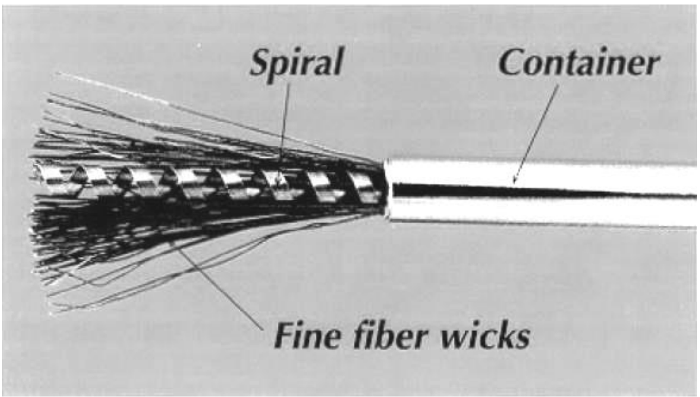
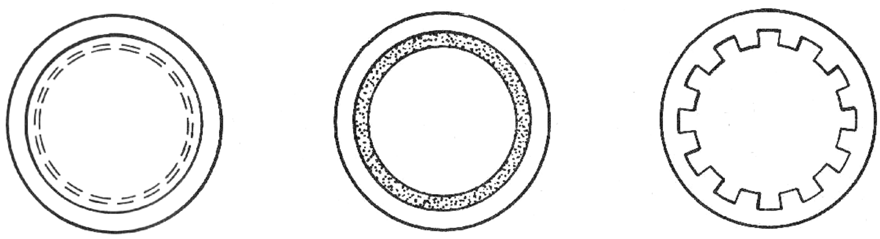


Fig. 4.9 Heat pipe with fiber wick for long way liquid return

There are several types of wick structures illustrated in the Fig. 4.10. The groove wick has the lowest capillary limit, but works best in the gravity assisted mode when the condenser is located above the evaporator and also in the space 0-g conditions. Sintered metal powders achieve highest capillary pressure, but with lower permeability and high risk of damage by bending. Mesh screen wick is simple for manufacturing and is somewhere between the previous mentioned. Basically, wicks need the followings:

- High capillary pressure (small surface pores)
- High permeability (large inner pores)
- Low thermal resistance (thin wick and high thermal conductance)
- Compatibility with other heat pipe components (espec. with working fluid)
- Wettability
- Self-priming
- Freeze-thaw tolerance
- Low cost
- Easy manufacturing



a) **b)** **c)**

Fig. 4.10 Basic types of wick structures

a) Mesh screen, b) Sinter, c) Axial grooves

At homogenous wicks (constant pores in the whole wick) a compromise of pore size must be chosen. The wick capability may be enhanced by increasing its thickness, but since the wick is located on the inner container wall, the radial thermal resistance will raise too. Composite or artery wicks should be considered in such cases.

Composite wicks consist of fine pore structures on the surface and large permeability structures inside (e.g. fine mesh screen on the surface with larger mesh screen inside). These inhomogeneous wicks enable high capillary pressure while keeping large transport capability.

However, it does not solve a problem with high thermal resistance of the radial heat flow through a wick.

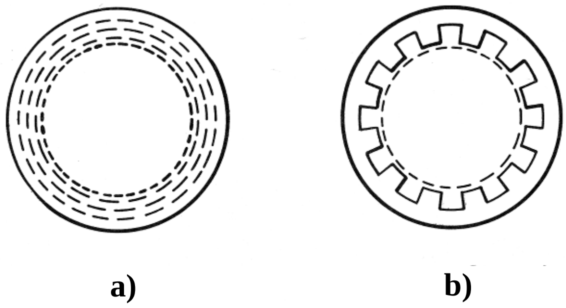


Fig. 4.11 Composite wick structures;

a) mesh screen composite (large pores inside, fine pores on the surface)

b) axial grooves covered by fine pores mesh screen

Other approach may be an artery wick, schematically presented in the Fig. 4.12. The liquid flows in one or more high permeable arteries covered by a very fine mesh screen creating high capillary pressure. Arteries are located in the middle of the heat pipe and on the walls there is only a thin wick structure distributing the liquid around. This arrangement allows very low thermal resistance of the radial heat flow through the wick.

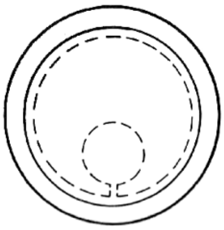


Fig. 4.12 Schema of arterial wick structure

4.3 Cryogenic Heat Pipes Specifics

An important part of this work is focused on experimental ascertaining of magnetic field influence on cryogenic heat pipes. Thus, cryogenic heat pipes and their specifics will be discussed more in detail in the following text. Cryogenic heat pipes are used for heat transport in the lowest temperature range. The upper temperature boundary is not strictly defined, generally, we speak about temperatures from 123 K (- 150 ˚C) down to about 5 K. Cryogenic heat pipes are based on the same principles as the others, however, their behaviours are significantly different.

Tab. 4.6 Working temperature ranges
of selected cryogenic heat pipes

Working fluid	**Temp. range (K)**
Ammonia	200K to 400K
Ethane	120K to 300K
Helium	3K to 5K
Methanol	200K to 400K
Nitrogen	65K to 120K
Oxygen	60K to 140K
Pentane	150K to 400K
Propylene	120K to 335K

Common working fluids employed in cryogenic heat pipes are nitrogen, oxygen, hydrogen, helium, methane, ethane or others. Some typical low temperature working fluids are presented in the Tab. 4.6. We have tested oxygen heat pipes operating in the range from about 60K to 140 K. There are some working fluids parameters which are critical especially in the low temperature range. Unfortunately those are usually very poor compared to the higher temperature fluids and furthermore, they also depend on the temperature:

- Latent heat of evaporation
- Surface tension
- Liquid – vapor density ratio
- Thermal conductance

Another critical factor of cryogenic heat pipes is the container robustness. It must withstand higher pressure while being stored at ambient temperature (all the working fluid is in the gaseous state). More robust container increases its weight which is an important parameter for space and aircraft applications and also the radial thermal resistance.

Finally there can be also a problem how to cool the heat pipe condenser because at very low temperatures the available methods are quite limited. Because of the above mentioned facts, cryogenic heat pipes attain lower capability and some additional aspects must be taken into account.

4.3.1 Cryogenic Working Fluids

Heat pipes are able to operate only in the temperature range between the triple and critical point of the used working fluid. However, at boundaries of this range heat transport capability is being reduced due to poor viscosity and surface tension. As mentioned above, cryogenic working fluids have poor thermophysical and other behaviours important for the heat pipe performance (see the Tab. 4.7). Impacts on the heat pipe operation will be described in the following text.

The low **latent heat of evaporation and condensation** constrain heat transport capability. Heat removed by a cryogenic fluid vaporization is much smaller than that of higher temperature fluids.

The low **surface tension** negatively affects the wick structure filling. This can be eliminated by smaller pore radius of a wick. However, this is usually not so critical in the 0-g environment (space applications). For the 1-g applications where the evaporator is placed above the condenser sintered metal powder wick or fine mesh screen should be utilized.

Cryogenic working fluids have also very low **liquid – vapour density ratio**. It means, more liquid is needed for generating the same value of vapour in comparison with water. The liquid flow passage must be more capable.

Low thermal **conductance** of cryogenic fluids may increase radial thermal resistance, especially when there is a thick wick or liquid film on the container surface. From this point of view, wick should be thin or special arterial structures placed in the middle of a heat pipe should be used.

Tab. 4.7 Thermophysical properties of selected cryogens
(* at 101,3 kPa; ** at 101,3 kPa and 15° C)

Temperatures / Cryogens	Triple point T_p (K)	Boiling point* T_b (K)	Critical point T_c (K)	Critical pressure p_C (MPa)	Liq. - vapor density ratio (-)	Latent heat of vaporization** L_V (Kj/Kg)	Thermal conductance** λ (mW/m.K)
He^4 Helium		4,22	5,2	0,228	748	20,3	142,64
H_2 Hydrogen	13,9	20,3	33,19	1,291	844	454,3	168,35
D_2 Deuterium	18,7	23,6	38,3	1,665	974	304,4	130,63
Ne Neon	24,559	37,531	44,49	2,651	1434	88,7	45,803
N_2 Nitrogen	63,148	77,313	126,19	5,091	691	198,38	24
CO Carbon monox.	68,09	81,624	132,8	3,499	674	214,85	23,027
Ar Argon	83,82	87,281	150,66	5,001	835	168,81	16,36
O_2 Oxygen	54,361	90,191	154,58	3,401	854	212,98	24,24
CH_4 Methane	90,67	111,685	190,56	4,642	630	510	32,81
Kr Krypton	115,94	119,765	209,43	5,502	699	107,81	8,834
Water	273,16	373,15	674	22,064	1243,78	2257	580

4.3.2 Container and Wick Design

Cryogenic heat pipes are usually filled with working fluids in the liquid state (at low temperature). However, they are usually stored at room temperatures causing an increase of internal pressure. Hence, stronger material, higher wall thickness or smaller heat pipe diameter must be utilized.

Several different wick types are well known from ambient temperature heat pipes. For cryogenic applications a wick must have superior parameters to compensate poor key properties of working fluids. The most important parameters are:

- High capillary pressure (needs small surface pores)
- High permeability (needs large inner pores)
- Low thermal resistance (needs thin wick made of a material with large thermal conductance)

Since cryogenic fluids have poor surface tension and low thermal conductance, composite or artery wicks should be utilized. The composite wick enables higher capillary pressure while keeping large transport capability. The arterial wick additionally allows lower temperature drop across the wall since it is located in the middle of the container. More details about wick structures find in the chapter 4.2.3.

5 Variable Conductance Heat Pipes

In the previous text we have discussed heat pipes without any control possibilities, working with the highest possible efficiency. This chapter deals with variable conductance heat pipes (VCHPs) [16]. By some kind of modification in heat pipe construction it is possible to change its heat transport efficiency (thermal conductance) and get some kind of thermal control - one way heat transport, temperature stabilization, active temperature control etc.

There are three basic groups of VCHPs different in their function, behaviours, construction and use. Their basic characteristics are presented in the Tab. 5.1 and further discussed in the following sections.

Tab. 5.1 Characteristics of basic VCHPs groups

Type of VCHP	Main Feature	Common Design	Typical Applications
Thermal Diodes	One way heat flow	Thermosyphon Wick modifications Liquid flow traps	Heat recuperations, cryostat systems
Stabilization Heat Pipes	Temp. maintaining	Noncondensable gas Additional liquid	Cooling of electronic components (espec. semiconductors)
Active Control Heat Pipes	Dynamic temp. control Thermal switch (on/off)	Noncondensable gas Vapour channel valve Magnetic coupling	Temp. control of technolog. processes Thermal key in cryogenic systems

5.1 Thermal Diodes

Thermal diodes are similar to semiconductor ones from the function point of view - they allow heat transport in one direction only. They have two operation modes - forward and reverse (see the Tab. 5.2). In the forward mode (higher temperature at the evaporator) the heat pipe operates standardly with high thermal conductance. When the evaporator temperature decreases below the condenser temperature the heat pipe switches into the reverse mode. The working cycle inside is stopped and only the residual heat may be transferred axially by conduction through the container. Some typical designs of heat pipe diodes are listed below and discussed in the following sections:

- Thermosyphon
- Heat pipe with an inhomogeneous wick structure
- Heat pipe with a wick trap

Tab. 5.2 Operation modes of heat pipe thermal diodes

Operation mode	Evaporator temp.	Condenser temp.	Eff. thermal conductance
Forward mode	higher	lower	high
Reverse mode	lower	higher	low

5.1.1 Thermosyphon

The simplest heat pipe diode may be a standard gravitational heat pipe (thermosyphon). It works as a thermal diode because it is able to work only when the evaporator is placed below the condenser. When the temperature gradient turns over (higher temperature up) the heat pipe is not able to operate. Gravitational heat pipe diodes are very simple, however, their positioning is limited.

5.1.2 Inhomogeneous Wick

Thermal diode can be realized also by a modification of the wick structure. A common solution is a wick with special inhomogeneous surface having high capillarity in the condenser region and low capillarity in the evaporator region. When operating in the reverse mode, vapor condensates in the evaporator where the wick performance is too poor to feed the evaporator.

5.1.3 Wick Trap

Another heat pipe diode construction is schematically shown in the Fig. 5.1. In this case a wicked reservoir is placed in the evaporator region. It is separated from the standard wick by a barrier with the vapor flow channel. In the forward mode fluid vaporizes from the reservoir and circulates in the heat pipe. In the reverse mode all the fluid condensates in the reservoir and no more is available for the heat pipe operation.

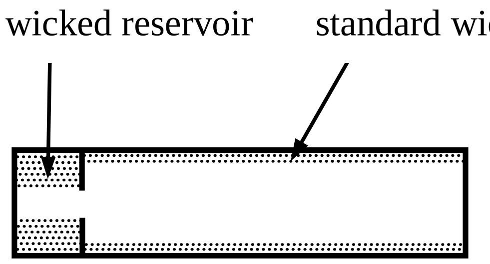


Fig. 5.1 Thermal diode with wicked reservoir as a working fluid trap

5.2 Stabilization Heat Pipes

Stabilization heat pipes are employed for maintaining stable temperature of devices mounted at the evaporator. The temperature may be kept at almost constant level even if the heat input varies in a wide range. The heat pipe effective thermal conductance depends on its temperature - the stabilization process is simply illustrated in the Fig. 5.2. At the beginning all parameters are in the stable state (part 1). Then an increase of temperature will cause an increase of thermal conductance (part 2). Heat pipe is now in the transient state with larger heat flux and device is cooled with higher efficiency. So the temperature is turning back to the starting value and thermal conductance will decrease on a new stable state (part 3).

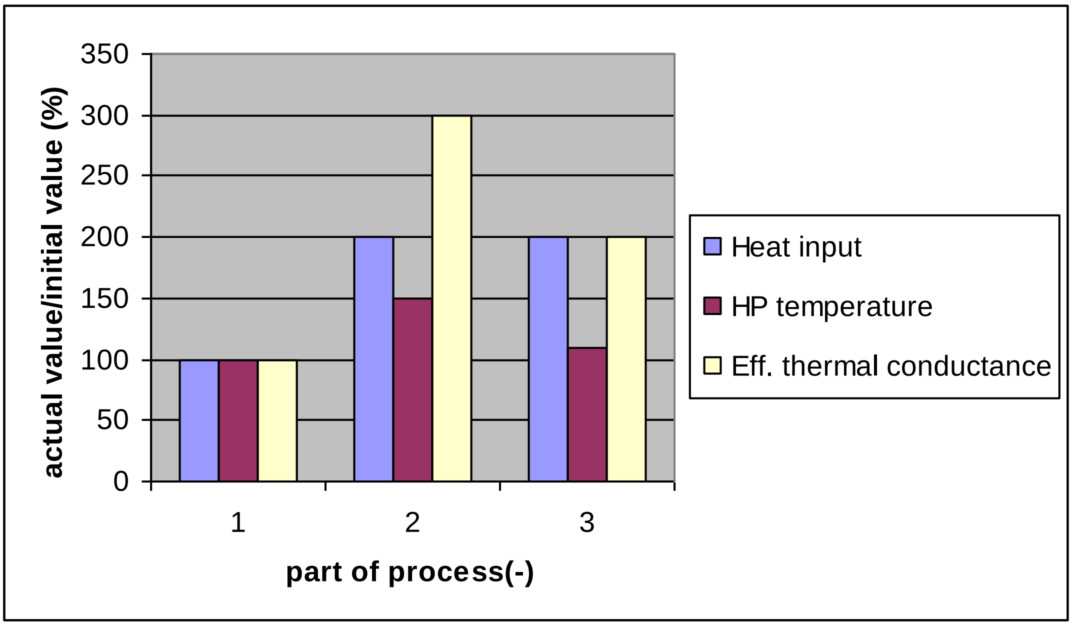


Fig. 5.2 Stabilization heat pipe operation;
1 - stable state, 2 - increasing of heat input, 3 - new stable state

Stabilization heat pipes are typically employed for cooling of semiconductors, precise electronics or detectors sensitive to temperature changes. Stable temperature is important also at inhomogeneous or multilayer structures made from materials with different temperature dilatation.

Stabilization heat pipes may be realized in several constructions, however, gas loaded type is absolutely dominant on the market and thus, it will be described in detail in the following sections.

5.2.1 Gas Loaded Heat Pipes

Gas loaded heat pipes are the absolutely most common in the segment of variable conductance heat pipes. Simply construction and excellent performance makes them very popular for thermal designers. This control effect was first observed in standard stainless steel-sodium heat pipes. After start up a noncondensable gas was generated and pressed by the vapor stream into the condenser region. A part of the condenser was then filled by the gas and unavailable for the working cycle anymore. The working fluid could condense on the reduced surface only and the heat flow proportionally decreased.

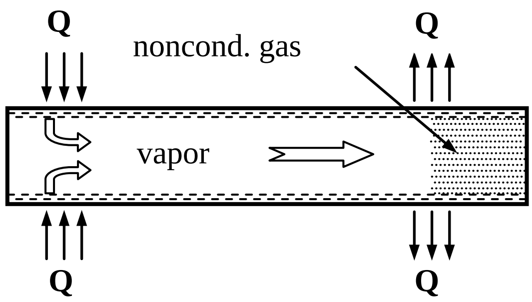


Fig. 5.3 Gas loaded heat pipe - basic type

At the Fig. 5.3 there is a schema of the gas loaded heat pipe. In this simple case, the construction is identical to a standard heat pipe, only some amount of a noncondensable gas (nitrogen, argon etc.) is added into the heat pipe during the filling. The noncondensable gas must be compatible with other heat pipe components and must not condense within the operation temperature range.

Stabilization process in the gas loaded heat pipe is presented in the Fig. 5.4. During the operation the noncondensable gas is situated at the end of the condenser region due to the vapor stream. Its volume negatively depends on the working fluid pressure. When the pressure is rising the gas is pressed deeper to the condenser. So larger condenser surface is available for condensation and larger amount of heat can be transported.

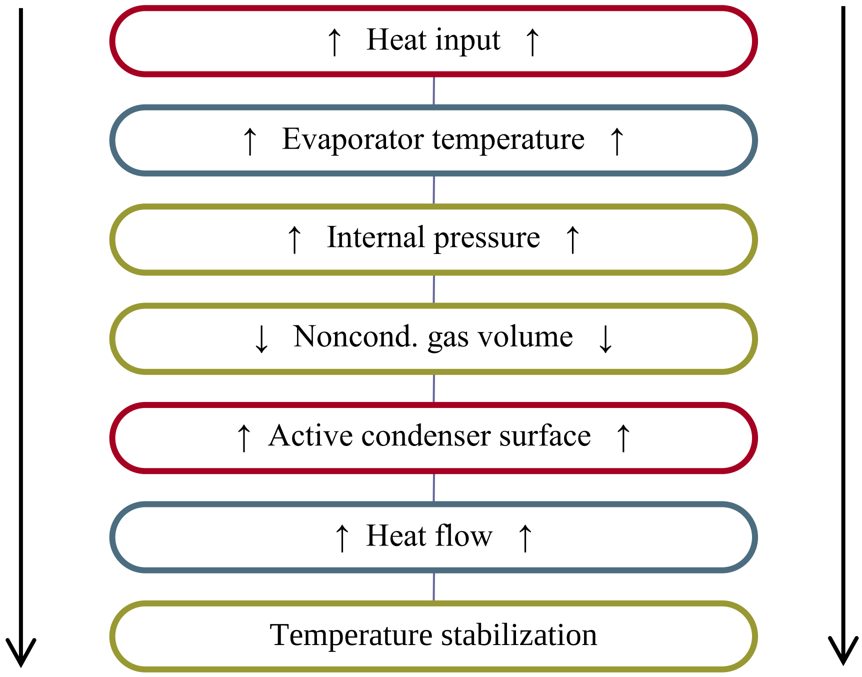


Fig. 5.4 Stabilization process diagram of gas loaded heat pipes (starting from the top)

Since the vapor pressure depends very strongly on the heat pipe temperature drop, the vapor-gas boundary in the condenser region moves even by a small temperature change. For example, in liquid metal heat pipes the vapor pressure varies as the 10th power of temperature. Thus, gas loaded heat pipes response very fast on even small temperature fluctuations.

There are more possible constructions of gas loaded heat pipes. The gas reservoir may be located at the condenser or at the evaporator or totally separated from the heat pipe, the condenser region may be specially shaped (enlarged) etc. At all the types, it is necessary to prevent diffusion of large amount of working fluid into the reservoir or it must be assured its return back to the heat pipe. Hence, the reservoir should be wicked or a equipped with a semipermeable plug at its gate.

Noncondensable gas may occur also in a standard heat pipe as a negative side effect of material incompatibilities or poor cleanness of heat pipe components.

5.3 Active Controlled Heat Pipes

Active controlled heat pipes allow absolute temperature regulation because the effective thermal conductance may be adjusted during their operation. Compared to the stabilization heat pipes (passive control), they offer some important benefits:

- Absolutely free choice of the referential temperature point
  (an electronic temperature sensor can be placed long away from the heat pipe)
- Simple and operative adjustment (electronic programmable regulator)
- Precise control of desired temperature level (faster and tighter response)

These features may be beneficial for some technological processes, electronic devices or cryogenic adiabatic systems. Gas loaded heat pipes are absolutely major, however, in some cases this method cannot be employed:

- Not enough space for the gas reservoir
- Heat flow cut off needs to be realized in the evaporator region
- Incompatibility of a noncondensable gas with other components

In those cases alternative control methods needs to be employed. Some of them will be also discussed in the following sections.

5.3.1 Gas Loaded Heat Pipes

Gas loaded active control system is based on the same principles already explained in the chapter 5.2.1 about stabilization heat pipes. In this case, some kind of the feedback system must be employed. A representative example is schematically shown in the Fig. 5.5. An external heater is placed on the gas reservoir and connected to a control unit. The gas volume depends on its temperature and so the effective thermal conductance can be regulated.

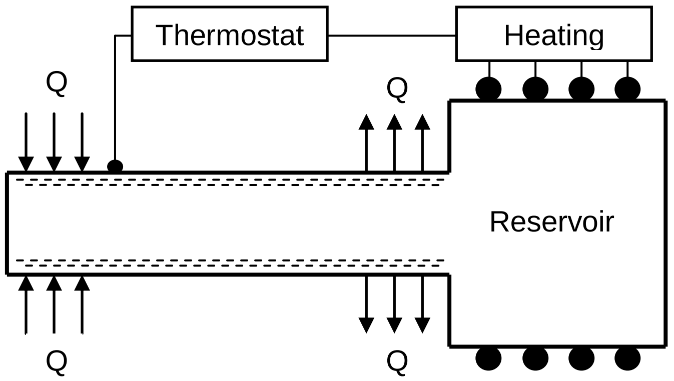


Fig. 5.5 Schema of gas loaded heat pipe with active control

However, the active feedback control needs an external power feeding. This negotiates one of the most important heat pipes features - power independence.

5.3.2 Vapor Channel Throttling

This method is based on throttling of the vapor channel by a mechanical valve. It is schematically illustrated in the

Fig. 5.6. The valve is connected with a bellows filled by a liquid. According to the temperature the bellows varies in its length resulting in changing of the vapor channel cross-section.

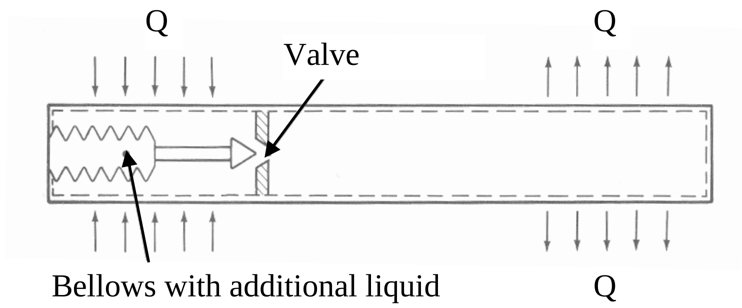


Fig. 5.6 Thermal control by vapor channel throttling

5.3.3 Magnetic Field Methods

There are also several methods how to influence heat flow in heat pipes by an external magnetic field. Most of them are based on magnetic action on movement of mechanical elements inside a heat pipe. This way it is possible to open and close a mechanic valve in the vapor channel, connect and disconnect the wick or move some other elements. An example of a heat pipe with a disconnectable wick is presented in the Fig. 5.7.

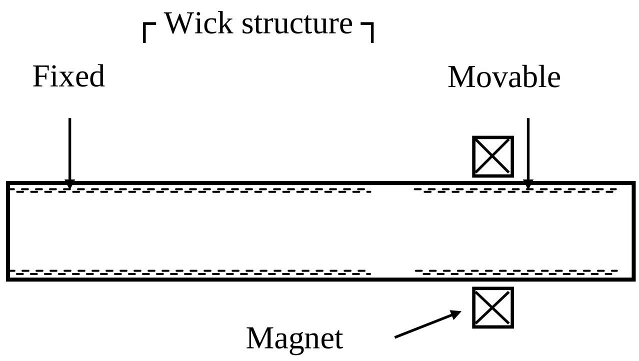


Fig. 5.7 Heat pipe with wick structure movable by external magnetic field

This work deals with a new approach for the heat transport control in heat pipes based on magnetic field interaction with a fluid within a heat pipe. This technique is further described in the following text in detail.

6 Magnetic Field Control

This work deals with a new approach to the heat transport control in heat pipes. It might be an alternative to several conventional methods discussed in the previous chapter. It is based on a force interaction between a static magnetic field and a fluid with suitable magnetic behaviours within a heat pipe. By specific conditions it is possible to catch or move the fluid by magnetic field or make a barrier for the fluid flow. Furthermore, using special magnetic fluids, so called ferrofluids, a fluidal seal can be created as well. We assume that some of these effects have a high potential to significantly reduce heat transport in special heat pipes.

By this work we have proposed two basic control approaches:

- Magnetic Trap Method
  (magnetic working fluid + external magnetic field)
- Magnetic Plug Method
  (conventional working fluid + additional magnetic fluid + internal magnetic field)

The both methods are based on an interaction between static magnetic field and a fluid within a heat pipe. However, there are important differences between them. Magnetic Trap Method utilizes an external magnetic field source and can be applied on a heat pipe with standard composition, only suitable magnetic working fluid must be within. On the other hand, Magnetic Plug Method has the magnetic field source placed directly in a heat pipe and furthermore an additional magnetic fluid must be within. The Magnetic Plug Method has been developed especially for the utilization with ferrofluids – special synthetic liquids with extraordinary magnetic behaviors.

The both magnetic field control methods need to meet some special requirements. Very important and usually most difficult is to find a suitable fluid with sufficient magnetic properties capable to interact with applied magnetic field. The interaction depends also on the magnetic field – the stronger field, the stronger interaction. Additionally, the heat pipe container must be made from a nonmagnetic material. The both methods including these important preconditions are further discussed in the following sections in detail.

Applying a magnetic field control on a heat pipe we are getting a very complex system with many variables related to the magnetic field distribution, working fluid properties, heat pipe construction or its operation mode. Mathematic models and calculations are very complicated and less accurate because of extreme complexity of such a system. Hence, only a limited theoretical description is presented in the following text.

6.1 Magnetic Trap Method

The Magnetic Trap Method is based on an interaction of a strong static magnetic field and a working fluid inside a heat pipe. The magnetic field source creates a force trap collecting the working fluid near the source. Typical for this method is that it works with heat pipes containing only the working fluid. So, the fluid must work as a heat transport medium (like a standard working fluid) and furthermore interact with magnetic field (like magnetic fluid). This is really difficult to meet together and there are not many suitable fluids available for this purpose (see more in the section 6.4).

Magnetic Trap Method will be described on a gravitational heat pipe filled with oxygen as a working fluid and exposed to a static magnetic field generated by permanent magnets. Without any magnetic field exposition the working fluid can circulate in the heat pipe as usual (Fig. 6.1a). When the heat pipe is exposed to the magnetic field (Fig. 6.1b), the liquid oxygen flowing down a wall starts to be attracted by magnetic forces to the field source. After a while the liquid is collected in the magnetic trap (**B**) and the liquid flow to the evaporator is reduced or even stopped. This sets up a new limit for the maximal heat flow of the heat pipe. When the whole fluid is collected in the magnetic trap, the evaporator dries out and the working cycle is totally interrupted.

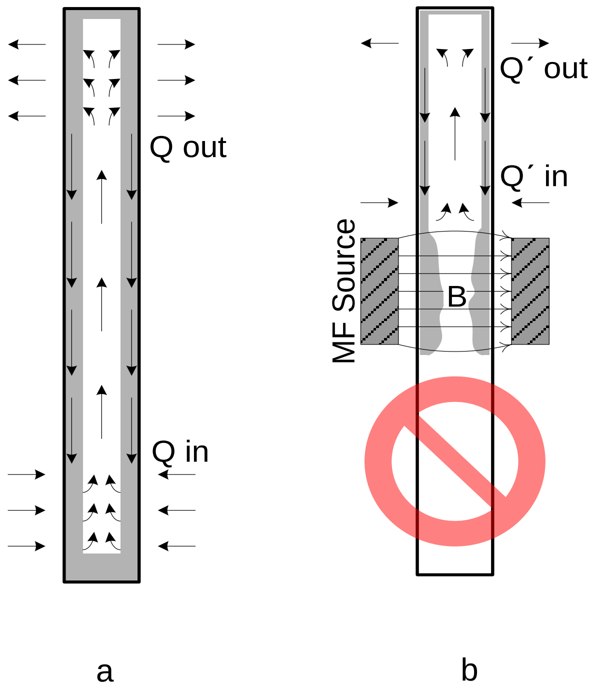


Fig. 6.1 Operation of heat pipe filled with pure oxygen;
a - standard operation
b - magnetic trap operation

6.2 Theoretic Description

In the following text Magnetic Trap Method is briefly described from the theoretical point of view [25]. However, this is a pretty hard business and thus, its scope is limited.

6.2.1 Prerequisites Necessary for Building the Model

The process of transport of magnetic fluid in the considered heat pipe at the presence of magnetic field is characterized by a relatively complicated interaction of several forces acting on its particles. In order to obtain sufficient information for their quantification a qualitative analysis of the situation in the pipe in the presence of external magnetic field was performed, as is illustrated in the Fig. 6.2.

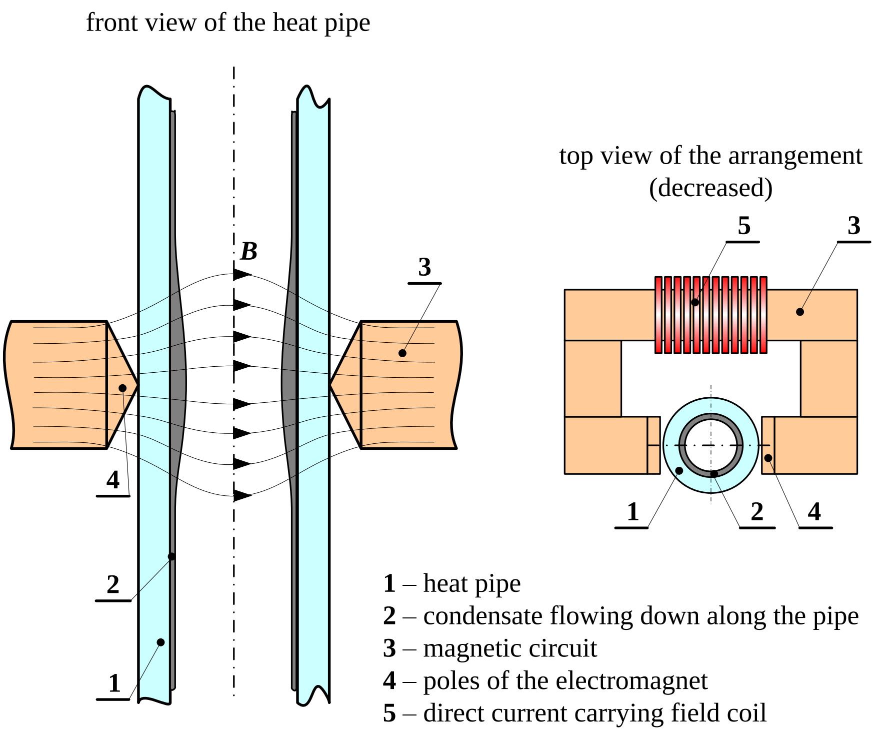


Fig. 6.2 Arrangement of the heat pipe with the electromagnet

Without the presence of external magnetic field, the cooling medium, condensing in the upper part of the heat pipe, flows freely down along the internal surface of the heat pipe. Its movement is only influenced by the gravitational force, surface tension and (at a small extent) also by wettability.

Consider now that the magnetic field ($\boldsymbol{B}$) starts growing from zero. In the vicinity of the tapered magnetic poles (**4)** of the electromagnet the field is characterized by a steep gradient oriented toward the edges of the tapered poles of the magnetic circuit. Here the particles of the condensate are influenced by magnetic forces oriented in the same direction. And when the axial component of this magnetic force together with the analogous component of the force generated by the surface tension exceed the corresponding pressure and gravitational forces, the particle stops flowing down and takes part in forming a relatively stable droplet. The volume of the droplet increases with growing magnetic field and after reaching a predetermined value of magnetic flux density in the axis of the heat pipe the droplet fills in its whole cross section, preventing the condensate from continuing flowing down. Now, the operation of the heat pipe is practically stopped because of no transport of heat (provided that the total weight of the condensate does not exceed the magnetic and tension forces).

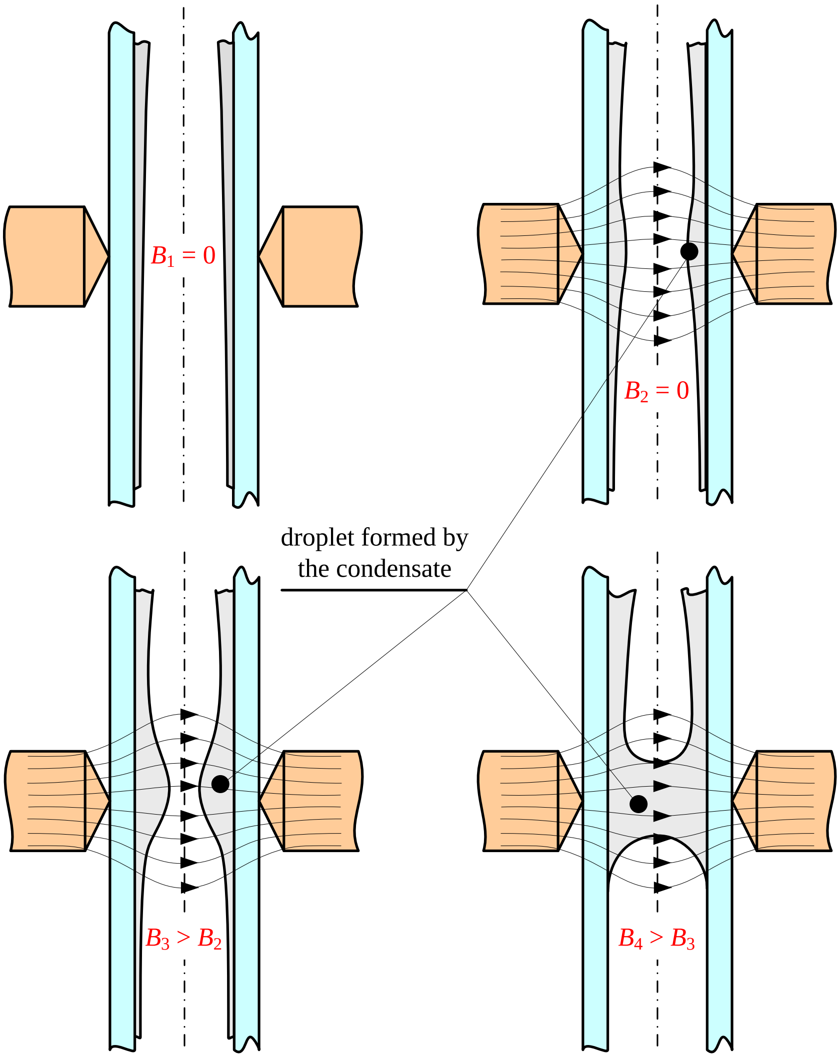


Fig. 6.3 Droplet of condensate formed by forces acting on it for increasing magnetic field
left up: situation without external magnetic field
right up: small external magnetic field, the droplet starts growing
left down: higher magnetic field, the droplet continues growing
right down: high magnetic field, the droplet fills in the whole pipe preventing the condensate from flowing down

In the axis of the pipe there the magnetic forces vanish (due to anti-symmetry of the arrangement). In case that the droplet fills in the whole cross section of the pipe, the column of the condensate in the axis and its vicinity is kept in balance only by the surface tension.

The magnetic field-dependent evolution of the situation in the heat pipe is shown in the Fig. 6.3. The distribution of magnetic force lines in particular sub-figures must be considered only orientative; the presence of magnetic fluid, in fact, leads to changes in their distribution together with the change of the shape of the droplet.

Mathematical modeling of this dynamic three-dimensional (see Fig. 6.2) coupled problem would be extremely complicated. The first serious difficulty is to find the shape of the free surface of the droplet in the given magnetic field. Even when the relative permeability of magnetic fluid is low (usually $\mu_\mathrm{r} \in \langle 2-5 \rangle$), the shape of the droplet affects the local distribution of magnetic field in the heat pipe and vice versa. Of great importance are also two more aspects. First, the viscosity of fluid may depend on the applied magnetic field and the same may hold for its surface tension. Finding these dependences (and their including into the task) represents a pretty hard business and producers of such fluids often provide only incomplete information (the above quantities, for example are used to be described by constants or – in better cases – by simple curves).

Full dynamic models of this kind are still generally insolvable by the existing tools, although some partial computations could probably be successfully carried out by the professional code Fluent (whose availability, however, is beyond my possibilities). That is why it was decided to suggest a simpler 2D model for description of the above phenomena and verify some important results by experiments.

6.2.2 Simplified Model of the Problem

The task will be modeled in the Cartesian coordinates x, y as a 2D problem, see Fig. 6.4. Thus, it is considered infinite in the direction of the z-axis. The droplet is considered a static body, the dynamic phenomena being neglected. This means that its shape is rigid and no fluid is supposed to flow into it or out of it. In other words, in the course of investigation its curved surface remains unchanged.

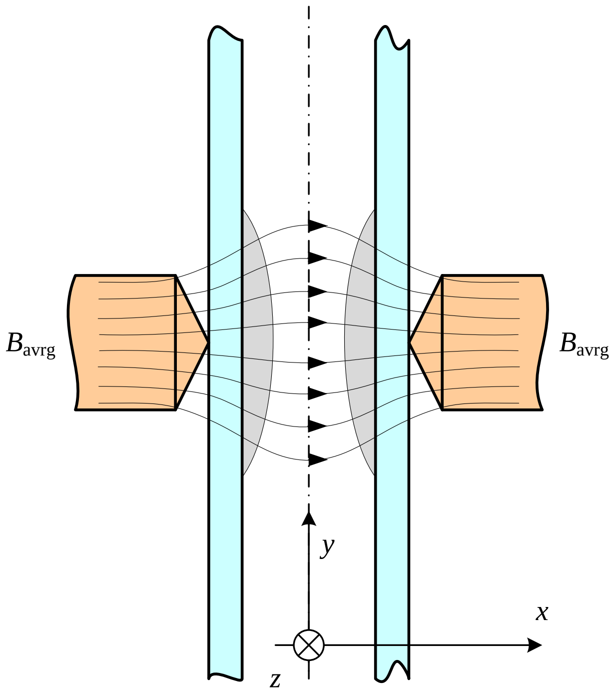


Fig. 3.

Fig. 6.4 Simplified model

In the first step it is necessary (for the given average saturation B_{avrg}) to estimate the basic shape of the droplet, i.e., to define its surface. Next step is determining the distribution of magnetic field between the walls of the heat pipe, its volumetric energy and volumetric magnetic forces within the droplet. Further task is represented by finding the balance of forces acting on the droplet, namely the mentioned magnetic forces, gravitational forces and forces produced by the surface tension of fluid (these may be functions of the local magnetic saturation). If the balance is not satisfied, the whole process is repeated with a smaller droplet (when the gravitational forces are higher than magnetic and surface tension forces) or a larger droplet (when the gravitational forces are lower). In this way we start a nonlinear iteration process in the course of which the surface of the droplet is modified using the regula falsi (or another appropriate) method. This process is finished at the moment when the balance of the above forces is satisfied with a prescribed tolerance.

The particular steps of this algorithm are explained in more details in the following paragraphs.

6.2.3 Magnetic Field in the System

The distribution of magnetic field in the investigated part of the system (see Fig. 6.4) obeys the equation for the magnetic vector potential $\boldsymbol{A}$ in the form

$$\operatorname{curl}\left(\frac{1}{\mu}\operatorname{curl}\boldsymbol{A}\right)=\mathbf{0} \tag{6.1}$$

where μ denotes the magnetic permeability. The magnetic vector potential has only on component $A_z(x,y)$ in the z-direction. Equation (6.1) is solved in an area surrounded by the artificial boundary PSRQ. The boundary has to be determined in the manner that its increase no longer affects the field distribution within the heat pipe.

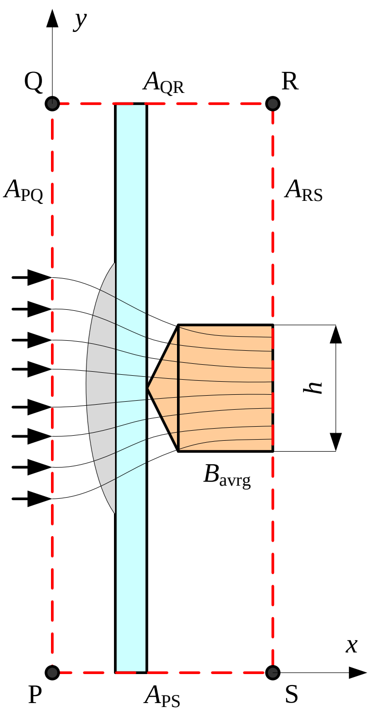


Fig. 6.5 Model for computation of magnetic field

Equation (6.1) has to be supplemented with correct boundary conditions. It is clear that the parts PQ and RS of the boundary are characterized by the perpendicular entry of force lines, so that

$$\frac{\partial A_{z,\mathrm{PQ}}}{\partial x}=\frac{\partial A_{z,\mathrm{RS}}}{\partial x}=0\,. \tag{6.2}$$

Now we can choose

$$A_{z,PS} = 0, \qquad A_{z,QR} = h \cdot B_{avrg}. \tag{6.3}$$

The right condition in (6.3) secures that the average magnetic flux density in the magnetic core (provided that it is not oversaturated) is really the prescribed value B_{avrg}.

After obtaining the distribution of quantity $A_z(x,y)$ we determine the distribution of magnetic field strength $|H(x,y)|$ following from the formula

$$H(x,y) = \frac{1}{\mu}\sqrt{\left(\frac{\partial A_z(x,y)}{\partial x}\right)^2 + \left(\frac{\partial A_z(x,y)}{\partial y}\right)^2} \tag{6.4}$$

and distribution of the volumetric energy $w_m(x,y)$ of magnetic field

$$w_m(x,y) = \frac{1}{2}\mu H^2(x,y). \tag{6.5}$$

The volumetric magnetic force $\boldsymbol{f}_m(x,y)$ acting on a particle of the droplet at point x,y is then given as

$$\boldsymbol{f}_m(x,y) = -\text{grad}\, w_m(x,y), \tag{6.6}$$

which yields

$$\boldsymbol{f}_m(x,y) = -\mu\left(H_x\, \text{grad}\, H_x + H_y\, \text{grad}\, H_y\right). \tag{6.7}$$

In order that the magnetic force is high, the field in the droplet should be characterized by a high gradient. And that high gradient is achieved just by using the tapered magnetic poles.

Further theoretical solving of this coupled problem would be extremely complicated. It is difficult to find the shape of the free surface of the droplet in the given magnetic field. Even more, the viscosity and surface tension of fluid may depend on the applied magnetic field. Due to these facts, the mentioned systems are further ascertained in the experimental way only.

6.3 Magnetic Plug Method

This section describes in a limited scope an alternative magnetic field control method developed for use with ferrofluids. It is a serious problem to find a suitable working fluid meeting all requirements of heat transport and magnetic interactions as requires the Magnetic Trap Method. A possible way out is to employ special magnetic fluids – ferrofluids. Unfortunately, ferrofluids brings some complications related to their boiling and thus, they cannot be used for the Magnetic Trap Method.

The Magnetic Plug Method is based on a principal of a fluidal seal, widely used in many technical devices. In this case, a heat pipe contains a standard working fluid and a plug covered by a ferrofluidal seal. Now it is not necessary to find a universal fluid suitable for heat transport and magnetic control together. A typical combination of fluids may be water as a working fluid and an oil ferrofluid as a seal. Temperature range of the heat pipe must be always kept below the boiling point of the utilized ferrofluid. So the side effects of ferrofluid boiling will not occur.

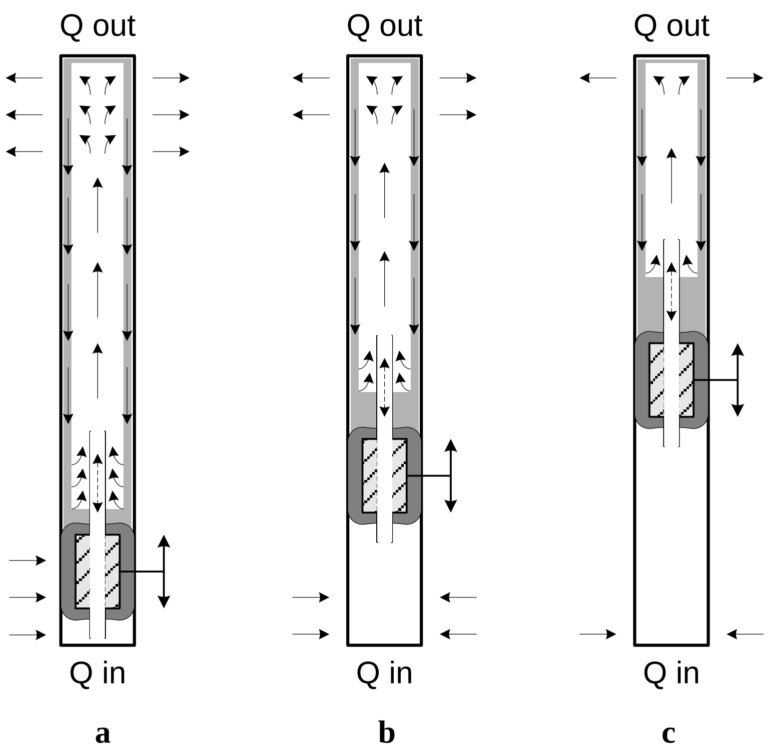


Fig. 6.6 Magnetic plug control system operating in following modes;
a - normal operation, b - reduced operation, c – heat flow cut off

The magnetic plug control system has been also experimentally ascertained by this work (see more in the section 7.3). A heat pipe arrangement with this control system is presented in the Fig. 6.6. In the heat pipe, there is a plug open for the vapor stream but closed for the liquid. By axial positioning of the plug it is possible to control active surface of the evaporator and regulate the heat flow. In the lowest position (a), the liquid can flow down to the evaporator and the heat flow is maximal. Pulling up the plug (b, c), the liquid is stopped above the evaporator and heat flow is more or less reduced. The positioning of the plug may be simply realized by a magnetic coupling between the permanent magnet inside and a ferromagnetic object outside the heat pipe.

In the Fig. 6.7 there is a schema of the plug employed in an experimental heat pipe. It consists of a toroidal permanent magnet(s) covered with a ferrofluid strongly held around by magnetic field. Thus, a gap between the magnet and container wall is perfectly sealed for the liquid flow of the working fluid. In the magnet axis there is a channel allowing the vapor stream to move through. The vapor channel is additionally extended on both sides with a tube preventing the liquid return.

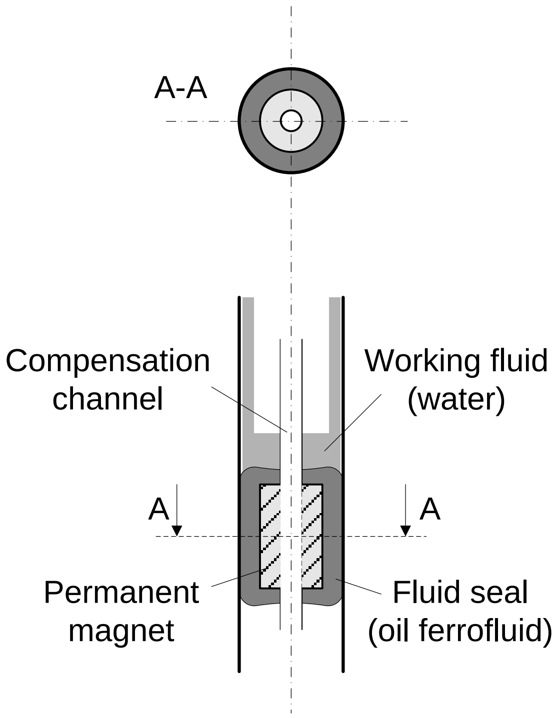


Fig. 6.7 Schema of magnetic plug in detail

6.4 Working Fluids

A suitable fluid with excellent magnetic behaviours is absolutely necessary for all kinds of magnetic field control. The liquid must allow moving or catching by static magnetic field, even against gravity or other forces acting in the heat pipe during its operation. The fluid must also withstand a hard heat pipe internal environment. It must be compatible with other heat pipe components, long time stable, ecological and health safe.

Unfortunately most of common heat pipe working fluids have poor magnetic properties, absolutely insufficient for the magnetic field control methods. However, there is one known exception - oxygen. That is a standard working fluid employed in cryogenic heat pipes. An alternative might be also some ferrofluid - synthetic liquid compound with strong magnetic behaviours.

6.4.1 Conventional Working Fluids

There is a large variety of working fluids commonly employed in heat pipes. Unfortunately, most of them are absolutely unsuitable for magnetic control methods because of their poor magnetic behaviours, as seen in the Tab. 6.1. The only one exception is oxygen - standard low temperature working fluid operating from about 60 K to 140 K.

Tab. 6.1 Magnetic susceptibility of selected heat pipe working fluids

Fluid	χ (-)
Nitrogen	$-6{,}3\cdot10^{-6}$
Ammonia	$-2{,}6\cdot10^{-6}$
Ethanol	$-7{,}9\cdot10^{-6}$
Water	$-9{,}1\cdot10^{-6}$
Mercury	$-29\cdot10^{-6}$
Sodium	$7{,}2\cdot10^{-6}$
Lithium	$14\cdot10^{-6}$

Oxygen has strong magnetic properties, unique among all other natural fluids. Magnetic properties of oxygen have a strong temperature dependence, as seen in the Tab. 6.2. The magnetic susceptibility of gaseous oxygen is low but it dramatically grows when changing into the liquid. Thus, it is suitable for the Magnetic Trap Method and it was also widely experimentally ascertained during this work.

Tab. 6.2 Magnetic susceptibility of oxygen in dependence on temperature

T (K)	**χ (-)**	**Phase**
10	$40\cdot10^{-6}$	solid
35	$110\cdot10^{-6}$	solid
50	$300\cdot10^{-6}$	liquid
300	$2\cdot10^{-6}$	gas

Due to the high reactivity of oxygen, it is necessary to keep so called LOX clean. It means, all components coming into a direct contact with oxygen must be free of any oil, grease or other organic compounds. Also materials as aluminium, titanium or steel are incompatible with oxygen. On the other side, copper (Cu), brass (Cu+Sn), bronze (Cu+Zn) or monel (Ni+Cu) are recommended. The risk grows with higher pressure and is enormous when the oxygen is in the liquid state (the molecule concentration is maximal). Hence, it is rather replaced by other permanent gases like nitrogen when possible, however, not suitable for magnetic field control.

6.4.2 Ferrofluids

Ferrofluids are synthetic colloidal solutions with very interesting behaviours. Their magnetic susceptibility can reach up to about $\chi \approx 10$ (several magnitudes higher than that of oxygen). Ferrofluids can be moved or caught by static magnetic field, even against the gravity or other forces as seen in the Fig. 6.8. That makes them very interesting for magnetic field control methods.

Fig. 6.8 Oil ferrofluid hangs under permanent magnet

Ferrofluids are made of very fine solid particles (magnetite, maghemite, ferrite etc.; about 10 nm in diameter) dissolved in a carrier liquid (mineral or silicon oil, kerosene, water etc.). They behave like very strong paramagnetics (magnetization saturation does not remain without an external magnetic field) and thus, they are called superparamagnetics.

Unfortunately ferrofluids have some important problems. The particles like to agglomerate in the liquid. This is prevented by thermal Brown movement, surfactants additives (long string polymers covering the particles around the particles) or electrostatic repulsion cause by the same polarity charge. Anyway, their lifetime and stability is lower and a common ferrofluid is able to work about few years. Furthermore, higher temperatures (above about 70 °C) and temperature changes deteriorate their function even faster.

There can occur also some other problems in heat pipes. In wicked heat pipes fine wick pores may be blocked by small particles. Very serious is also boiling of a ferrofluid which may lead to separation of solid particles in the evaporator. From this point of view ferrofluids are more suitable for use in gravitational heat pipes using Magnetic Plug System. In this case the ferrofluid does not boil and utilized as the fluidal seal only. Heat pipes filled with ferrofluids (see Tab. 6.3) have been also experimentally tested. For more details about the experiments see the sections 7.2.5 and 7.3.

Tab. 6.3 Parameters of a water based ferrofluid EMG 705 supplied by Ferrotec and employed in an experimental heat pipe

Parameter	**Value**
Appearance	Black-brown fluid
Carrier Liquid	Water
Nominal Particle Diameter	10 nm
Saturation Magnetization	22 mT
Viscosity (at 27°C)	<5 mPa·s
Density (at 25°C)	1.19 10^3 kg/m^3
Initial Magnetic Susceptibility	4.04
Magnetic Particle Concentration	3.9 % vol.
pH	8-9
Nature of Surfactant	Anionic

6.5 Magnetic Field Generation

The other essential part of all magnetic control systems is obviously a magnetic field source. In order to generate a sufficient force interaction with a working fluid, magnetic field must have relatively high magnetic induction B (approx. 10^{-1} - 10^{1} T) and its gradient (approx. 10^{2} A/m). Basically, two types of magnetic field sources may be employed - an electromagnet or permanent magnets. The both systems have some benefits and negatives, discussed in the following text in detail. Requirements of the magnetic field source depend on the type of a used control method (Magnetic Trap / Magnetic Plug) and also on specifics of the each heat pipe (see the Tab. 6.4). Magnetic field can be also generated by electromagnets with superconductive coils, however, they are unsuitable for practical applications of the given systems.

Tab. 6.4 Relation between selected heat pipe parameters and required magnetic field strengths

Parameter of heat pipe -	**Value**	**Magnetic field strengths**
Outer diameter of container	low	low
	high	high
Magnetic susceptibility of working fluid	low	high
	high	low
Quantity of working fluid	low	low
	high	high

6.5.1 Electromagnet

Magnetic field generated by an electromagnet allows high magnetic induction and simple regulation by the current through the coils. It is very useful for laboratory experiments where the magnetic parameters must be often variably adjusted. Unfortunately, an electromagnet is usually a very large and heavy device with a high energy consumption. From this point of view it is not very suitable for practical applications.

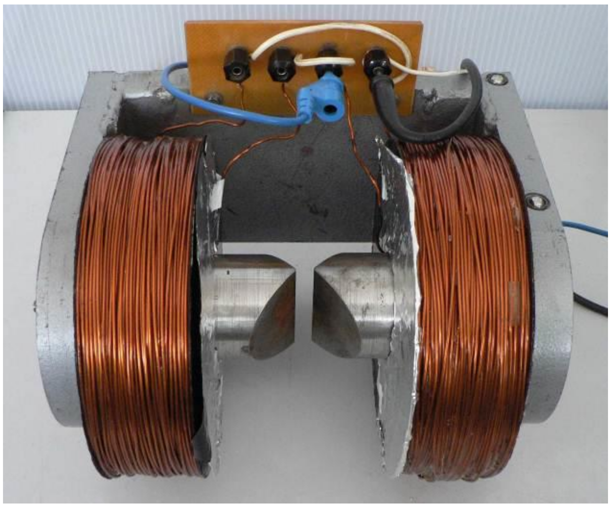


Fig. 6.9 Electromagnet with edge form magnetic poles in longitudinal position

A two coils electromagnet employed in our experiments is presented in the Fig. 6.9. The electromagnet was provided by columnar poles made from soft carbon steel (60 mm in diameter), alternatively in the form of an edge (angle 120° and radius 1 mm) or a hollow, as seen in the Fig. 6.10. The edge poles allow variable position to the heat pipe, from longitudinal to transversal. Distance between the poles was adjustable from 0 mm to 12 mm. The magnetic induction in the middle of a 12 mm air-gap achieved up to 1,3 T and was continuously regulated. The maximal gradient of magnetic induction was about 300 T/m at the poles edges.

a) **b)**

Fig. 6.10 Variable magnetic poles in edge (a) and hollow form (b)

There is one more electromagnet system which might be used for the magnetic field control method. A multisection coil wound up directly on the heat pipe might provide the plug positioning along the heat pipe. By switching the coil sections one by one in the line it may be possible to move the plug inside the heat pipe. However, this technique has not been experimentally ascertained within this work.

6.5.2 Permanent Magnets

Permanent magnets are now able to challenge with electromagnet systems. New magnetic materials, based especially on Neodymium-Ferro-Bore compounds (Nd-Fe-B), are able to generate strong magnetic fields. We have experimentally approved sufficient behaviours of permanent magnet systems for the magnetic field control methods.

A permanent magnet source is lighter than an electromagnet one does not need the power feeding. On the other side, regulation is more difficult in this case and must be realized by the magnets movement, usually realized by a servomotor (or manually during the laboratory experiments).

A possible arrangement employed for the Magnetic Trap System is schematically shown in the Fig. 6.11. It consists of two rectangular permanent magnets made from Nd-Fe-B (dimensions 40 mm x 20 mm x 10 mm and Br = 1,30T Hc = 859 kA/m) and a magnetic circuit in the U-shape made from a soft carbon steel. Magnetic induction in the middle of the 12 mm air-gap achieved up to 0,6 T, with the maximal gradient about 100 T/m at the magnet edges.

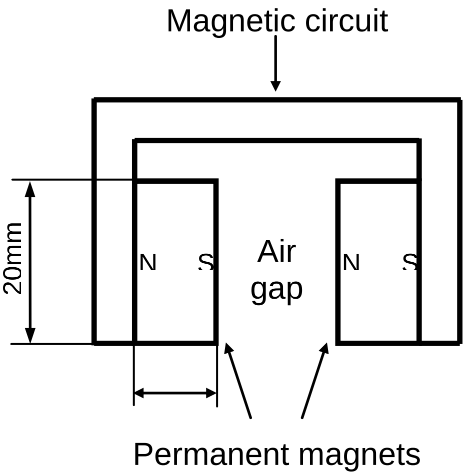


Fig. 6.11 Magnetic field source in horizontal cross-section and the utilized rectangular permanent magnet (40mm x 20mm x 10mm)

In the Fig. 6.12 there is an example of the magnetic field source employed in the Magnetic Plug System. Practically, it may consist of single one or more toroidal permanent magnets in the line. Outer diameter (OD) of the magnet should be little bit lower than the inner heat pipe diameter. Hence for a heat pipe with inner diameter (ID) 8 mm, permanent magnet with OD between 6 and 7 mm is suitable. The length of the magnet should be longer than its OD to assure the plug stability within the heat pipe. The hole through the magnet must allow to build in an extension tube preventing the fluid return through the magnet. The tube should have ID at least 1 mm to allow pressure compensation during the plug positioning or residual vapour flow.

Fig. 6.12 Permanent magnets suitable for the magnetic plug

7 Experimental

We have experimentally ascertained the magnetic field influence on heat pipes operation of various constructions and working fluids. As mentioned in the previous text, we have worked out two basic approaches to the magnetic field control of heat pipes - Magnetic Trap Method and Magnetic Plug Method. The both have been implemented into several heat pipe prototypes and their impact on the operation has been investigated. The experimental ascertaining is the most important part of this work and it also brings the major contribution to the improvement of the current state of knowledge.

The major focus of the experimental work was put on ascertaining of the magnetic field influence on heat pipes operation, however, some related aspects were observed as well. Heat pipe prototypes of various constructions and working fluids were tested. First experiments were focused on investigation of a common heat pipe operation and related processes. This was performed on water and ethanol heat pipes of gravitational type with a special glass design allowing visual observation. Following experiments were focused especially on magnetic field effects and required working fluids with strong magnetic behaviours. Heat pipes filled with oxygen or several types of ferrofluids were tested. Most of the experiments were performed on gravitational heat pipes, however, several prototypes of wicked heat pipes were constructed and tested as well.

Before the experiments could be realized we had to do lots of preliminary work. There were no commercial heat pipes suitable for our aims available on the market. Hence, we had to design and create our own prototypes. For manufacturing and testing it was also necessary to adapt or develop some special technologies and procedures and install various experimental arrangements.

At the beginning of this chapter preliminary setup of experiments, preparation of tested prototypes and testing arrangements is described. After that, selected experiments with results are presented, each in a separate section. The experiments are sorted in two groups – Magnetic Trap Method based and Magnetic Plug Method based.

7.1 Design of Experiments

Several heat pipe prototypes have been designed and manufactured for the experimental ascertaining of the mentioned magnetic field control methods. Original manufacturing procedures and equipment had to be prepared for that purpose. An example of a typical experimental setup is presented in the Fig. 7.1. It allows preparation and further investigation of heat pipes of different materials, shapes and working fluids.

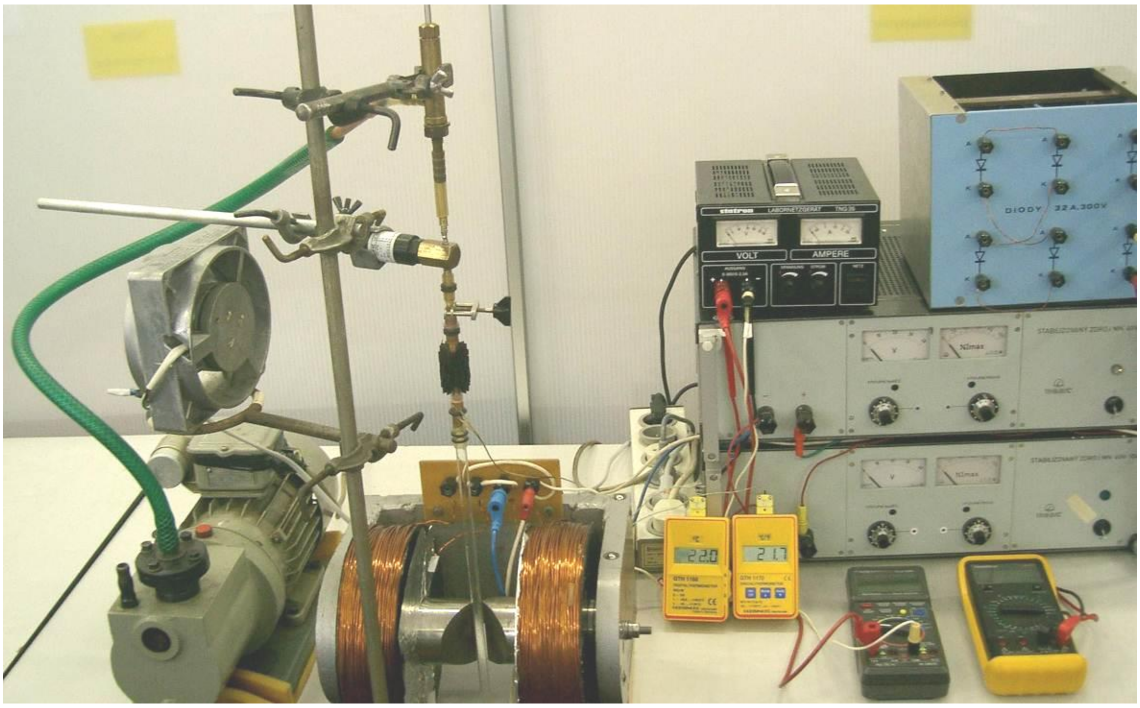


Fig. 7.1 Typical arrangement for ambient temperature experiments

Magnetic field effects on heat transport in heat pipes were quantitatively evaluated by a comparison of heat pipe temperature drop achieved with and without magnetic field exposition.

7.1.1 Design and Manufacturing of Experimental Heat Pipes

Experimental heat pipes of various types, shapes and mechanical construction were manufactured for evaluation of magnetic field effects. They were usually made of common copper or brassy tubes, sometimes with an additional transparent tube in the middle allowing a visual observation. Tested heat pipes may be sorted into two major groups:

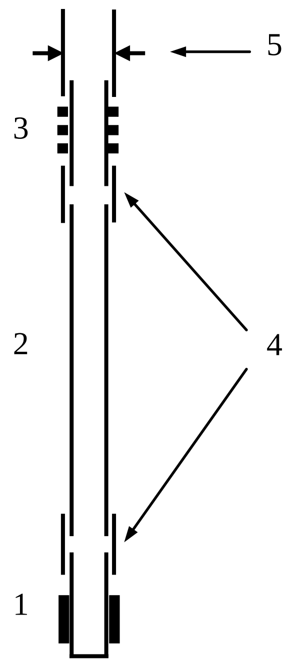
- Ambient temperature heat pipes
- Cryogenic heat pipes

There is a big difference in construction requirements between these groups. Cryogenic heat pipes operating at low temperatures were already discussed in the section 4.3 in detail. The most critical factor related to their construction is high pressure (10 MPa or more) which may occur inside at ambient temperatures. Hence, robustness of the container must be higher.

On the other hand, construction of ambient temperature heat pipes is quite simple and allows more flexible arrangement of various components, e.g. combination of copper ends with a transparent adiabatic part.

7.1.1.1 Ambient Temperature Heat Pipes

A concept of an ambient temperature heat pipe is schematically shown in the Fig. 7.2. It may consist of a single tube or more tubes coupled by rubber hoses. In the evaporator and condenser region a material with high thermal conductance is preferred (copper, brass, etc.). A glass adiabatic section may be integrated for visual observation in between.



1 - Heating wire

2 - Transparent adiabatic part (optional)

3 - Fin radiator

4 - Rubber tubings

5 - Rubber hose with clamp on

Fig. 7.2 Schema of experimental heat pipe for ambient temperature range

The evaporator end of heat pipe prototypes was mechanically deformed and hermetically closed by soldering. The condenser end was usually equipped with a rubber hose and a clamp allowing repeatable filling, degassing and other procedures. See construction details in the Fig. 7.3.

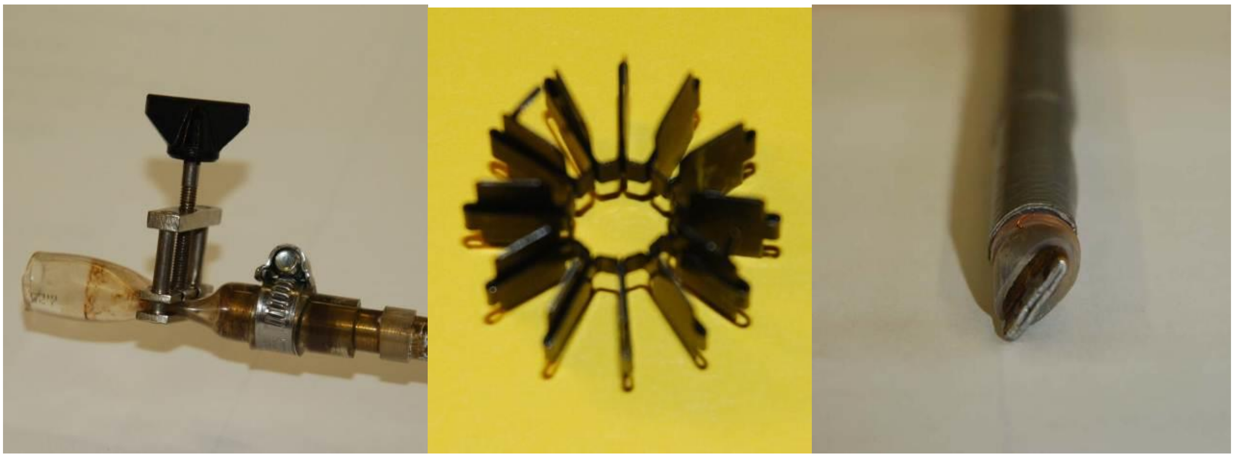


Fig. 7.3 The condenser end with a rubber extension and a clamp; fin radiator optionally placed on the condenser region; the evaporator end

Heat pipes consisting of more parts were coupled by rubber tubings with a silicon grass for better assembling and tightness. Tightness could be further increased by flexible O-rings or similar parts put over the tubings.

The heat input was loaded by an isolated copper wire (OD = 0,3 mm) wounded directly on the heat pipe container. The winding was fixed between rubber outhangs by a bandage of an adhesive tape. The heat output was realized so that the rest of the heat pipe was exposed to an external environment. Optionally, fin radiators assisting the heat output might be fixed on the condenser region.

Fig. 7.4 Evaporator end with a heating wire

Ambient temperature heat pipes were filled by a specific quantity of a working fluid from a syringe. The optimal quantity for gravitational heat pipes was about 10 % of its total volume. Then, the heat pipe was connected to a rotational vacuum pump (Labortechnik Ilmenau MLW-2DS1) through thick-walled rubber tubes. Internal pressure of the heat pipe was so decreased to about 2 kPa and continually evacuating for a few minutes by. The working fluid slowly boiled at lower pressure in the heat pipe and noncondensable gases contained in the fluid and on the internal container surface were removed out. After finishing this, the heat pipe was closed by the clamp and it was ready for testing.

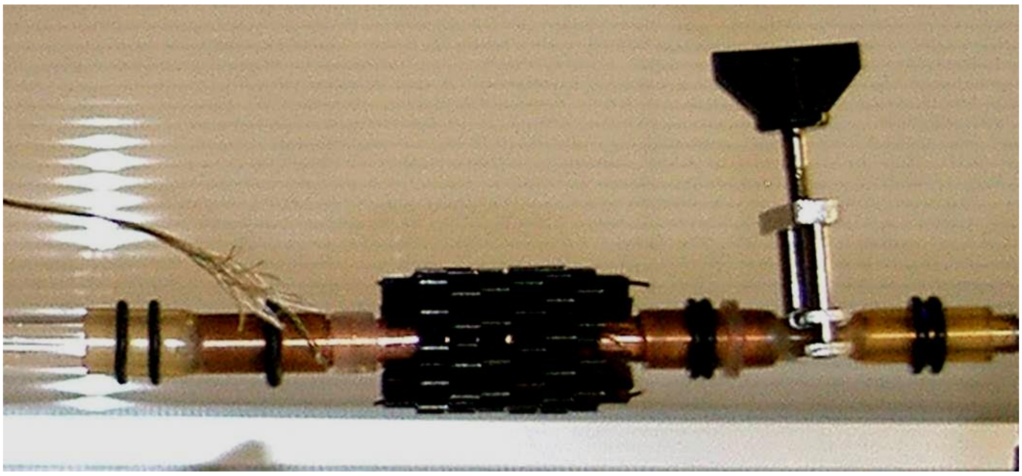


Fig. 7.5 Condenser end with fin radiators and clamp closure,
coupled with transparent adiabatic section by rubber tubings and O-rings

7.1.1.2 Cryogenic Heat Pipes

An example of a cryogenic heat pipe with a wick utilized in our experiments is presented in the Fig. 7.6. In this case, it was made by refilling of a standard wicked heat pipe for ambient temperatures. Both end of the container were closed by copper plugs mechanically compressed by hand crimpers and soldered by the Sn-Pb solder. Copper capillaries passing through the both plugs connected the heat pipe with a filling system and a manometer.

Experimental gravitational heat pipes were usually made of a standard tube made from copper or brass which are both compatible with oxygen. Other procedures were identical to the wicked heat pipe discussed in the previous paragraph. All the components being in contact with oxygen had to be free of any oil, grease or other organic compounds, as discussed in the section 6.4.1.

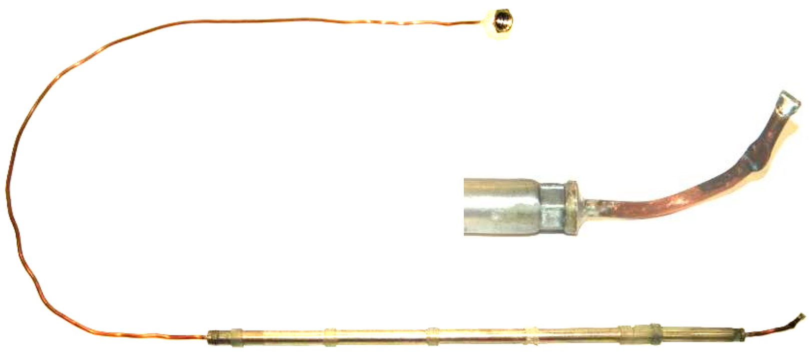


Fig. 7.6 Cryogenic heat pipe with capillary connections, heat pipe closure in detail

All tested cryogenic heat pipes were filled with pure oxygen from a pressure vessel (maximal pressure up to about 12 MPa). Heat pipes were connected to the vessel by the filling capillary with a screw joint. The manometer was coupled to heat pipes by another one capillary. Before filling heat pipes were flushed through by oxygen for a few seconds to remove all noncondensable air (the manometer end was open). After that the manometer end was closed and heat pipes were filled with a desired oxygen quantity, estimated by the filling pressure. The filling capillary was mechanically deformed and pressed. Then it was cut off from the pressure vessel and soldered. Finally, heat pipes tightness was tested by the soap water.

7.1.2 Testing Arrangement and Accessories

Investigation of heat pipes required a special arrangement consisting of several components. It was different for ambient temperature heat pipes and cryogenic heat pipes. Using this arrangement, we were able to simulate heat pipes operation in selected mode and measure important heat pipe parameters, especially temperature and internal pressure.

A typical arrangement for testing of ambient temperature heat pipes is presented in the Fig. 7.7. It consisted of the following main parts:

- Magnetic field source (see more in the section 6.5)
- Two power supplies Mesit MN40V−10A (S_2) in parallel connection (10 A each) for feeding the electromagnet (not used with permanent magnets)
- A power supply Statron TNG35 (S_1) for feeding the heating wire on the heat pipe evaporator
- Axial fan Mezaxial 3112 (optional)
- Standard digital multimeters for voltage and DC current measurement
- Temperature and pressure measurement (discussed in the following section)

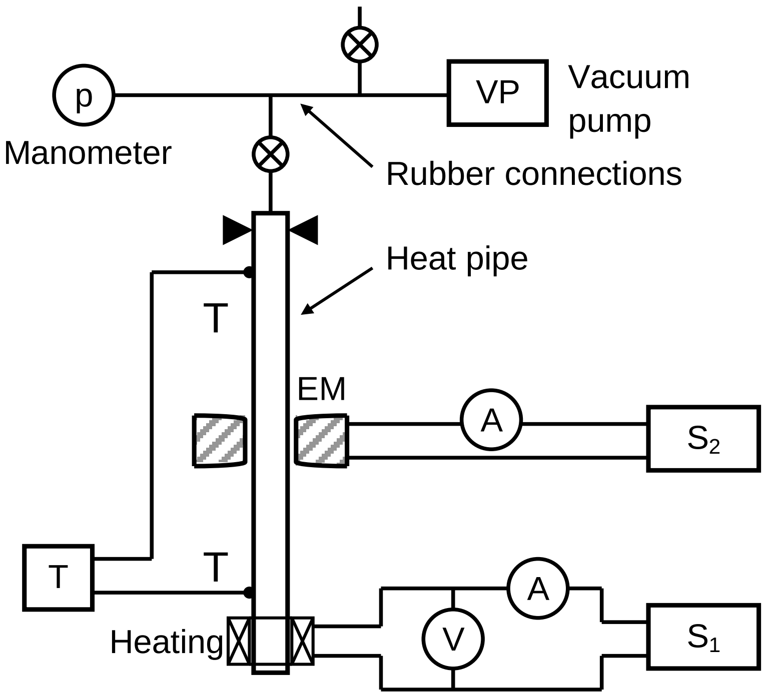


Fig. 7.7 Testing arrangement for ambient temperature heat pipes

A typical arrangement for testing of cryogenic heat pipes is schematically shown in the Fig. 7.8. It consisted of the following main parts:

- Magnetic field source (see more in the section 6.5)
- Two power supplies Mesit MN40V−10A (S_2) in parallel connection (10 A each) for feeding the electromagnet (not used with permanent magnets)
- Liquid nitrogen reservoir and related accessories
- Axial fan Mezaxial 3112 (optional)
- Standard digital multimeters for voltage and current measurement
- Temperature and pressure measurement devices (discussed in the following section)

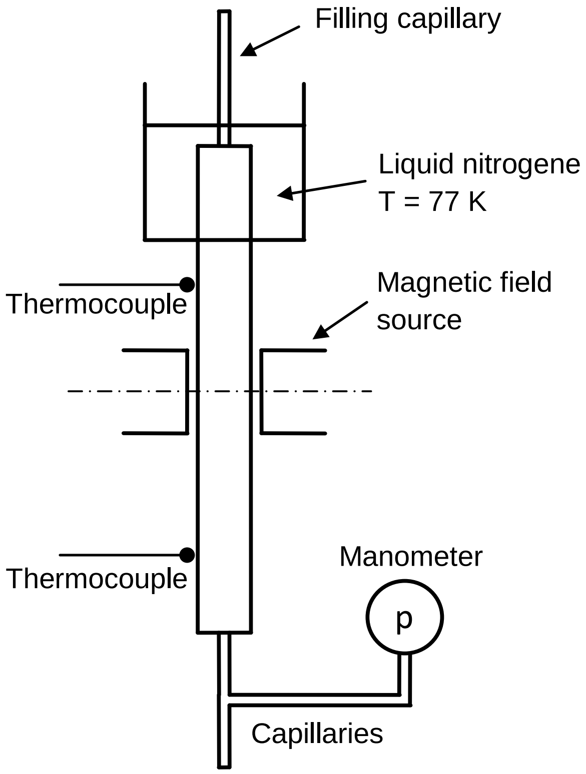


Fig. 7.8 Testing arrangement for cryogenic heat pipes

7.1.3 Measurement System

The performed experiments were quantitatively evaluated by measurement of selected heat pipe parameters. Most important was the temperature measurement and additionally also pressure was monitored within heat pipes. However, the pressure was controlled especially during filling and degassing procedures. Some aspects were also ascertained by visual observation in heat pipes with a glass tube in the adiabatic part.

Universal monitoring system Comet MS5 was preferred for the measurement (Fig. 7.9). However, also single devices with manual data recording were utilized for simple or short term experiments. The Comet system allowed comfortable monitoring of temperature in more points along a heat pipe as well as of its internal pressure. It consisted of a multichannel data logger connected to a PC, five K-type thermocouple inputs (resolution 0,1 °C, accuracy ± 0,3 %) and a voltage input processing a signal from the digital manometer (resolution 0,01 V, accuracy ± 0,1 %).

Fig. 7.9 Universal measurement system Comet MS5

7.1.3.1 Temperature Monitoring

Temperature along heat pipes was measured by K-type thermocouples placed directly on the outer container surface. Thermocouples were thermally coupled by silicon grease and fixed by elastic rubber rings. For low temperature measurement (cryogenic heat pipes) the thermocouples were calibrated by a Pt thermometer because of their nonlinearity.

In some cases manual measurement was utilized, especially when temperature was monitored in two points only. Digital thermometers Greisinger type GTH 1150 and GTH 1170 (resolution 0,1 °C, accuracy ± 0,05 %) connected to the thermocouples were employed (Fig. 7.10).

Fig. 7.10 Digital thermometer and manometer Greisinger

7.1.3.2 Pressure Measurement

Pressure within heat pipes was monitored alternatively by the following types of manometers connected to heat pipes by rubber tubes (ambient temperature heat pipes) or by copper capillaries (cryogenic heat pipes).

Heat pipes tested in the early experiments were connected to the manual manometer Prema (range up to 25 MPa, resolution 0,1 MPa, accuracy ± 2,5 %). In the following experiments digital manometer Greisinger GMH 3151 (Fig. 7.10) was utilized. This manometer was connected the data logger via digital output. The probe GMSD250BAE for absolute pressure measurement was utilized (range up to 250 bar resolution 0,1 bar, accuracy ± 0,2 %).

7.1.3.3 Magnetic Field Measurement

Digital gaussmeter Lake Shore, type 410 with a transversal Hall probe was used for all measurements of magnetic field induction B.

7.2 Magnetic Trap Method Experiments

The major focus of the experimental work was put on the Magnetic Trap Method. It was ascertained in several experiments different in the heat pipe construction, magnetic field source, working fluid or the overall arrangement. Some of the experiments are presented in the following sections.

7.2.1 Water and Ethanol Heat Pipes Experiment

In the early experiments gravitational heat pipes filled with deionized water or pure ethanol were tested [12]. The goal was investigation of heat pipes operation principles, including some start-up or other abnormalities. Manufacturing and adjustment of heat pipes operation were optimized during this experiment. The magnetic field influence was also ascertained, but without any expectations in this case, because of weak magnetic properties of used working fluids. Their magnetic susceptibility is listed below:

- Water .... χ = -9,1·10-6 Ethanol ..... χ = -7,9·10-6

A heat pipe with a special construction allowing visual observation was made for this purpose. The electromagnet with edge magnetic poles was used as a source of static magnetic field. The experiment was repeated several times with different setup, selected results of the measurement are presented in the following text and figures.

Tab. 7.1 Experiment specifications

Parameter	**Value**
Magnetic control method	Magnetic Trap
Heat pipe	Gravitational
Orientation	Vertical
Working fluid	Water, ethanol, empty
Operation temperatures	Ambient
Container (length x OD/ID)	Copper/glass (500 mm x 8/6 mm)
Magnetic field	Electromagnet, 0 T / 1,5 T, 300 T/m

7.2.1.1 Experimental Installation

The overall installation is shown in the Fig. 7.11. The tested gravitational heat pipe was oriented vertically in the middle between the electromagnet columnar poles in the edge form. The magnetic induction B in the middle of the electromagnet air-gap was being adjusted in the range from 0 T to 1,5 T with the gradient up to 300 T/m at the poles edges (for more details about the electromagnet setup see the section 6.5.1). The heat pipe temperature was measured by two digital thermometers Greisinger with K-type thermocouples fixed at the evaporator (T_1) and at the condenser (T_2). Three power supplies were employed - two in parallel arrangement feeding the electromagnet and one feeding the evaporator heating. The pressure inside the heat pipe was adjusted by the rotational vacuum pump connected by a rubber tube. The condenser was cooled by forced air convection of the axial fan.

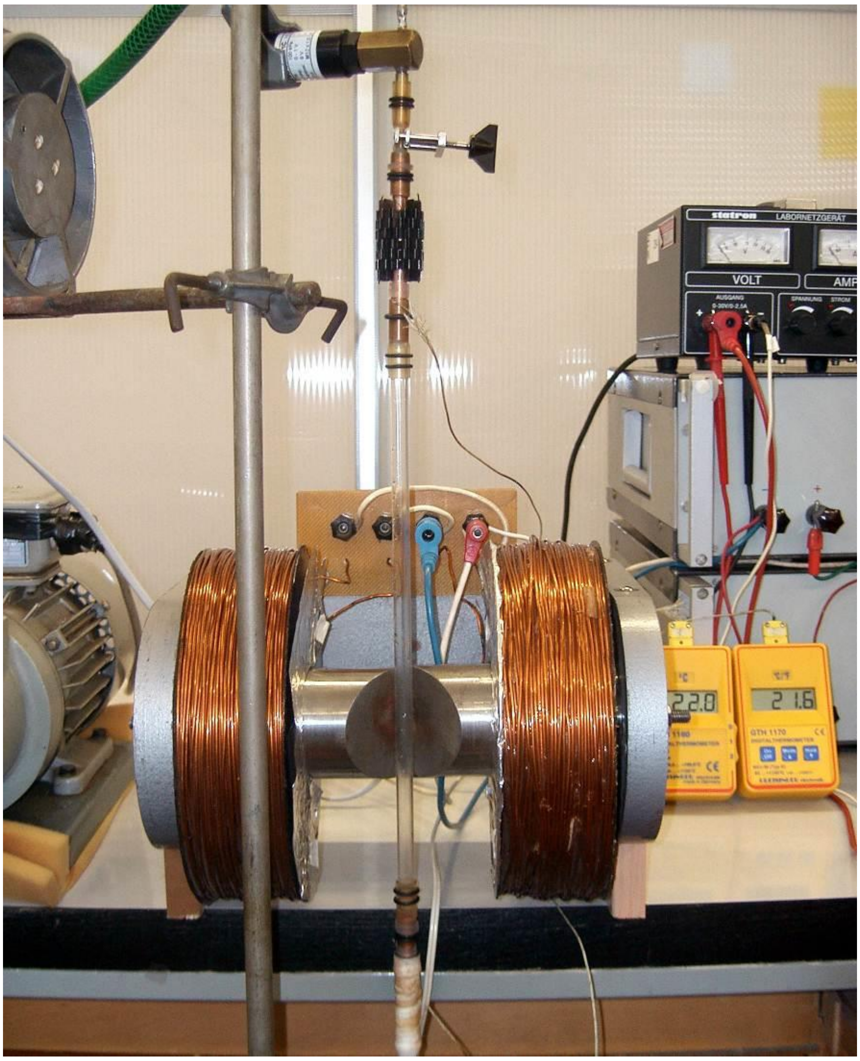


Fig. 7.11 Experimental heat pipe with transparent adiabatic section situated between the electromagnet poles

The gravitational heat pipe tested in this experiment is schematically shown in the Fig. 7.12. It consisted of three parts - copper evaporator (1), adiabatic section made of glass (2) and copper condenser (3). All sections were connected together by rubber tubings (4). Special construction of the heat pipe allowed visual observation of processes inside and variability in the heat pipe configuration as well. Total length of the heat pipe was 500 mm, OD 8 mm and wall thickness 1 mm. The evaporator and the condenser were 80 mm long. The heating wire (5) was wound directly on the evaporator and the condenser was equipped with fin radiators. A mechanic valve (6) at the condenser end allowed repeatable filling. The heat pipe was filled with a small amount of a working fluid - water or ethanol (optimum was 1,0 ml to 1,5 ml).

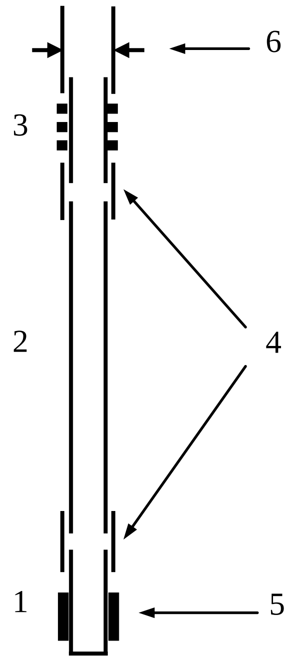


Fig. 7.12 Schema of the heat pipe

7.2.1.2 Measurement

Due to the absolute beginning of the experimental work lots of parameters important for the heat pipe operation had to be optimized. Hence, the experiment was repeated many times until the heat pipe operated appropriately. The processes within the heat pipe were observed and evaluated also visually.

The evaporator was heated by the power of 10 W and the rest of the heat pipe was exposed to the forced convection of the room air (23 °C). The magnetic field intensity was regulated by a current through the electromagnet coils. The temperature was measured in two points - at the evaporator and at the condenser - by manual manometers. The heat transport efficiency was determined from the temperature drop along the heat pipe. The measurement was repeated for the following configurations:

- Water working fluid, without magnetic field exposition
- Water working fluid, with static magnetic field of 1,5 T and gradient 300 T/m
- Ethanol working fluid, without magnetic field exposition
- Ethanol working fluid, with static magnetic field of 1,5 T and gradient 300 T/m
- Without any working fluid (empty heat pipe), without magnetic field exposition

7.2.1.3 Results and Discussion

Temperature characteristics of tested heat pipes are presented in the following figures. In the each figure there are three couples of curves - continuous line for the standard operation, dash line for the operation with magnetic field and dot line for the empty heat pipe without any working fluid. The T_1 (red lines) represents the evaporator temperature and the T_2 (blue lines) represents the condenser temperature.

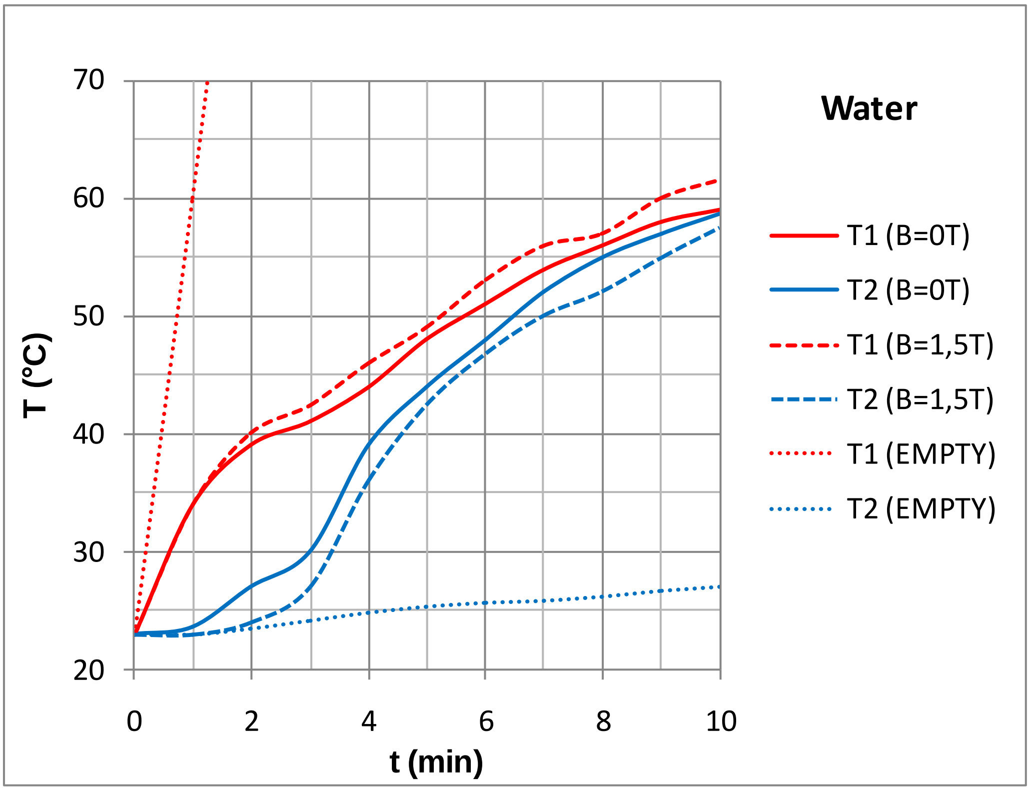


Fig. 7.13 Heat pipe with water as working fluid

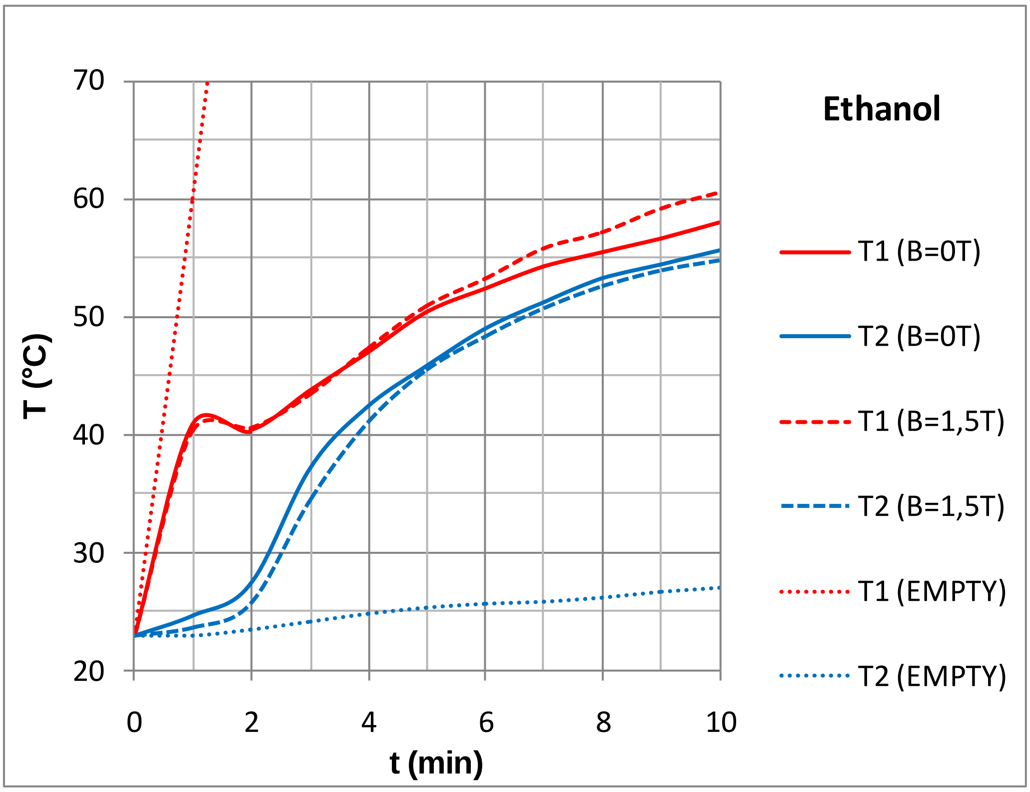


Fig. 7.14 Heat pipe with ethanol as working fluid

The characteristics are very similar for the both working fluids. It is clearly seen that the both heat pipes operated correctly with a small temperature drop and high efficiency. The start-up process, followed by isothermalisation of the whole heat pipe, is well remarkable at the beginning of curves.

According to our assumptions, performance of the both heat pipes was almost independent on the magnetic field exposition. The difference between the curves with and without magnetic field exposition is insignificant, comparable with the measurement error. The low magnetic field sensitivity of tested heat pipes was caused by weak magnetic properties of used working fluids. Magnetic field was not able to get over the gravity and catch the liquid in the magnetic trap.

The operation processes within heat pipes were also visually observed through the transparent adiabatic part. Intensive boiling effects were observed, mostly during the start-up phase. The liquid was pushed up high above the evaporator (the higher liquid inventory the more intensive liquid effects).

About one hour after the start-up a noncondensable gas was detected inside the heat pipe in the adiabatic part at the condenser region. The vapor-gas boundary was clearly seen through the glass adiabatic part. The condenser was so closed for the working fluid and heat transport which leaded to decreasing of its temperature to the ambient value. Amount of the noncondensable gas depended on the operation mode (the more intensive operation the faster gas generation) and also on leakages of the heat pipe (often problematic when utilizing rubber tubings). The noncondensable gas was being removed from the heat pipe by repeated evacuation by the vacuum pump.

7.2.2 O_2 Heat Pipe with Electromagnet Experiment

In this experiment [6], possibilities of the Magnetic Trap Method utilizing a conventional electromagnet have been ascertained. Oxygen was chosen as a working fluid because of its suitable magnetic properties (find more in the section 6.4.1). Because this was the first experiment dealing with cryogenic heat pipes, some procedures and adjustments had to be optimized.

An experimental gravitational heat pipe filled with pure oxygen was made and a special testing arrangement for the cryogenic temperature range was installed as well. Find basic parameters and specifications of the experiment in the Tab. 7.2. We have found out that the heat transport efficiency of the heat pipe was rapidly decreased by the magnetic field exposition, as presented in the following results.

Tab. 7.2 Experiment specifications

Parameter	**Value**
Magnetic control method	Magnetic trap
Heat pipe	Gravitational
Orientation	Vertical
Working fluid	Oxygen
Filling pressure	9 MPa (at 295 K)
Operation temperatures	Cryogenic
Container (length x OD/ID)	Copper (270 mm x 8/6 mm)
Magnetic field	Electromagnet, 0 - 1,25 T, max 300 T/m

7.2.2.1 Experimental Installation

The experimental installation is shown in the Fig. 7.15. The gravitational heat pipe was positioned vertically between the electromagnet columnar poles in the edge form. The upper part of the heat pipe (condenser) was placed in a polystyrene vessel with a liquid nitrogen (LN_2) bath. The middle of the heat pipe was exposed to the static magnetic field with the magnetic induction B adjusted in steps from 0 T to 1,25 T (in the middle of an air-gap) and with the gradient up to the 300 T/m at the poles edges (see the section 6.5.1). The heat pipe temperature was measured in two points (10 mm above the magnetic field zone and 100 mm bellow that) by two digital thermometers Greisinger with K-type thermocouples. Additionally, the internal pressure of the heat pipe was measured by an analog manometer Prema connected through a capillary.

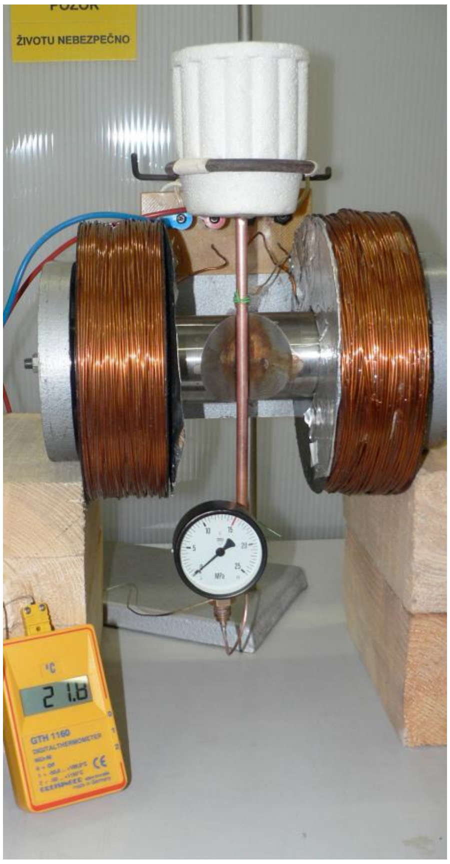


Fig. 7.15 Experimental installation of cryogenic heat pipe between electromagnet poles

Arrangement of the tested heat pipe is shown in the Fig. 7.16. The heat pipe was made of a copper tube (length 270 mm, OD 8 mm, wall thickness 1 mm). The copper capillaries (OD 2 mm, wall thickness 0,5 mm) on the both ends of the heat pipe provided the connection with a filling device and the manometer. The filling pressure was 9 MPa at the room temperature 295 K.

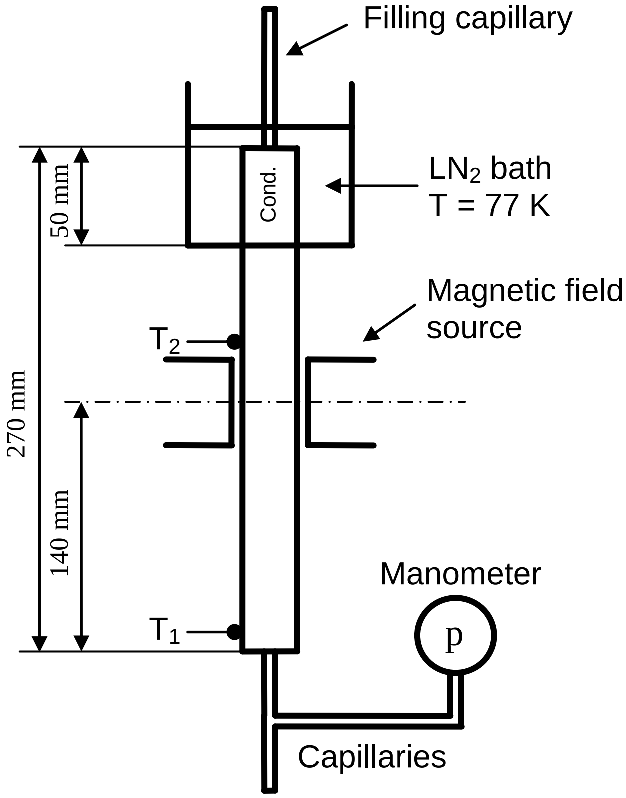


Fig. 7.16 Schema of the cryogenic heat pipe

7.2.2.2 Measurement

Preliminary setup of the cryogenic heat pipe was extremely difficult, above all the filling and closing procedures, as discussed in the chapter 7.1.1. The measurement started with filling the LN_2 into the polystyrene vessel on the top of the heat pipe. The condenser started to be chilled to the temperature of 77 K from this moment and the rest of the heat pipe (the whole evaporator) was exposed to the room temperature (295 K). The magnetic field intensity was adjusted by the current of the electromagnet coils and the temperature drop of the heat pipe was measured. The experiment was repeated several times for various magnetic field setups and for the empty heat pipe without any working fluid.

7.2.2.3 Results and Discussion

The magnetic field influence on the heat transport and also the general function of the heat pipe have been ascertained during this experiment. The temperature characteristics and pressure curves measured on the tested heat pipe are presented in the following figures. At the time t = 0 the top of the heat pipe started to be chilled by LN_2. The temperature T_1 (red lines) belongs to the lower part of the heat pipe (below the magnetic field zone), the temperature T_2 (blue lines) belongs to the upper part (between the magnetic field zone and the LN_2 bath), as illustrated in the Fig. 7.16. The p - curve (black dash lines) represents the pressure inside the heat pipe, dependent on the phase changes of the oxygen from the gas to the liquid and vice versa.

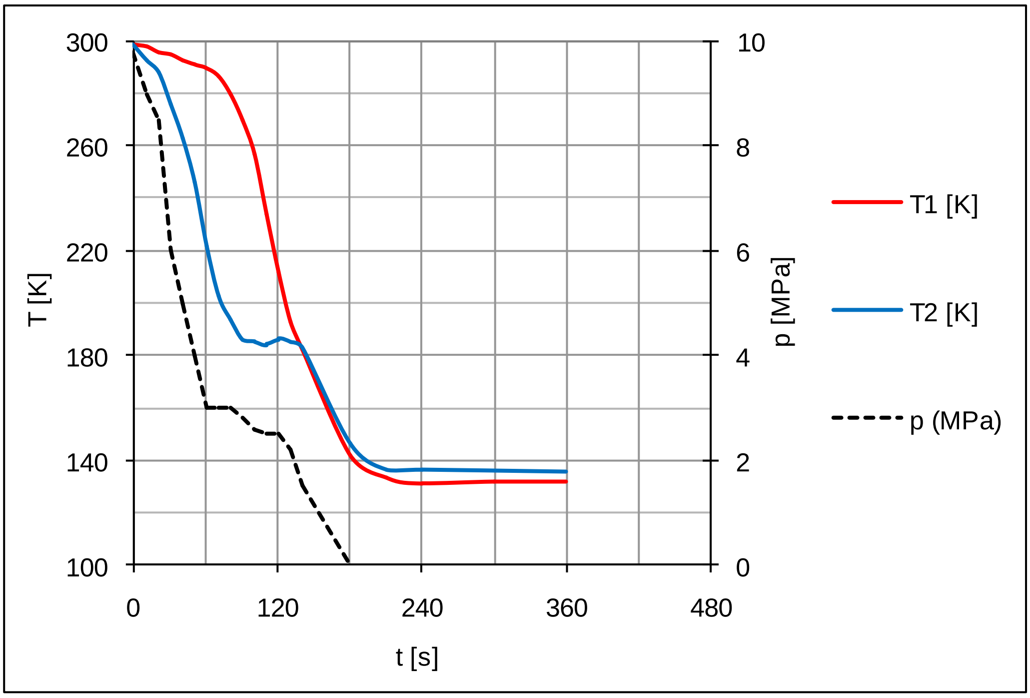


Fig. 7.17 Characteristics of standard heat pipe operation without any magnetic field exposure

Characteristics of the heat pipe without any magnetic field exposure are presented in the Fig. 7.17. The temperature of the whole heat pipe started to fall immediately after the condenser cool down. The heat pipe started to operate in about two minutes, when approached the oxygen operation range. In about four minutes it became almost isothermal along the whole length with a maximal temperature difference about 5 K.

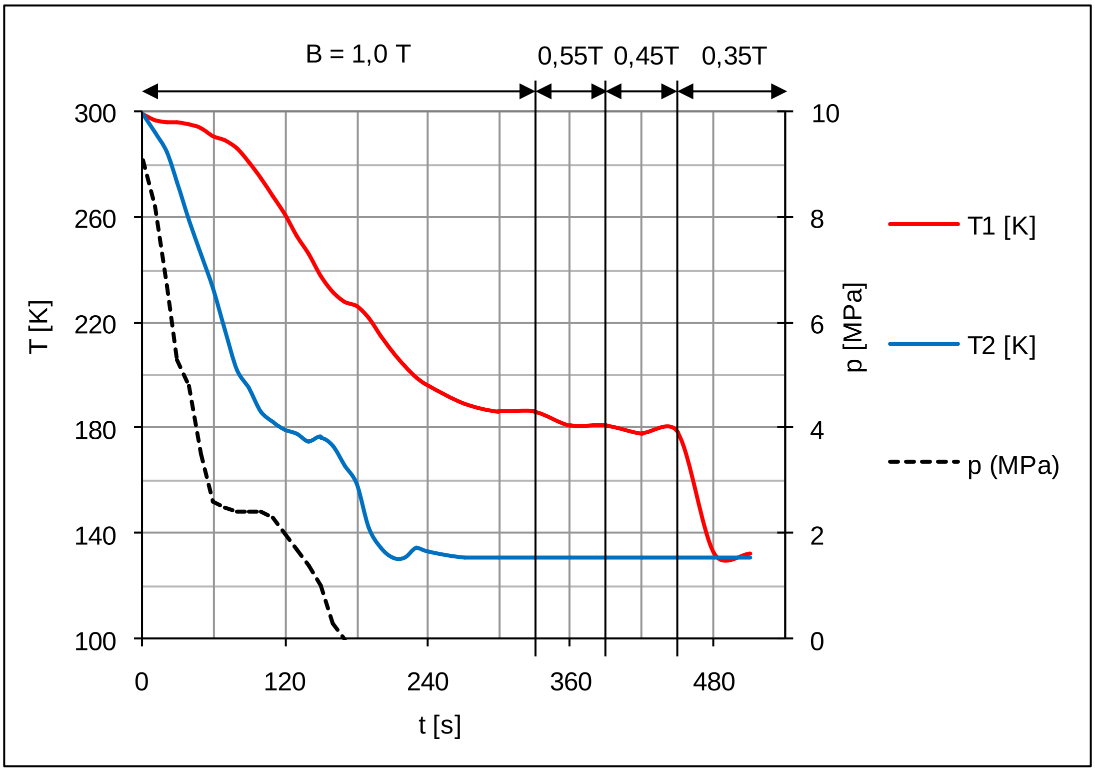


Fig. 7.18 Characteristics of heat pipe operating under variable magnetic field

Under the magnetic field exposition, the heat pipe operation was clearly different from the previous case, as seen in the Fig. 7.18. Initially, the magnetic field induction B was set up to 1,0 T and the maximal temperature difference was about 56 K. Obviously the heat flow was restricted by the magnetic field exposition. When decreasing the induction, temperature difference was slightly decreasing as well but the heat flow was still significantly reduced. A dramatic change came when the B decreased below 0,4 T - the T_1 fell down in a moment and became equal to the T_2. The heat pipe started to operate normally with and insignificant temperature drop at that moment. Obviously, there is a strong boundary below which the magnetic field is not able to influence the heat pipe operation any more.

Additionally, the pressure inside the heat pipe was observed during the whole heat pipe testing. It correlates to the phase changes of oxygen during the cool-down at the beginning of the experiment. An interruption of decreasing is noticeable on the pressure curve at the moment of the operation start-up.

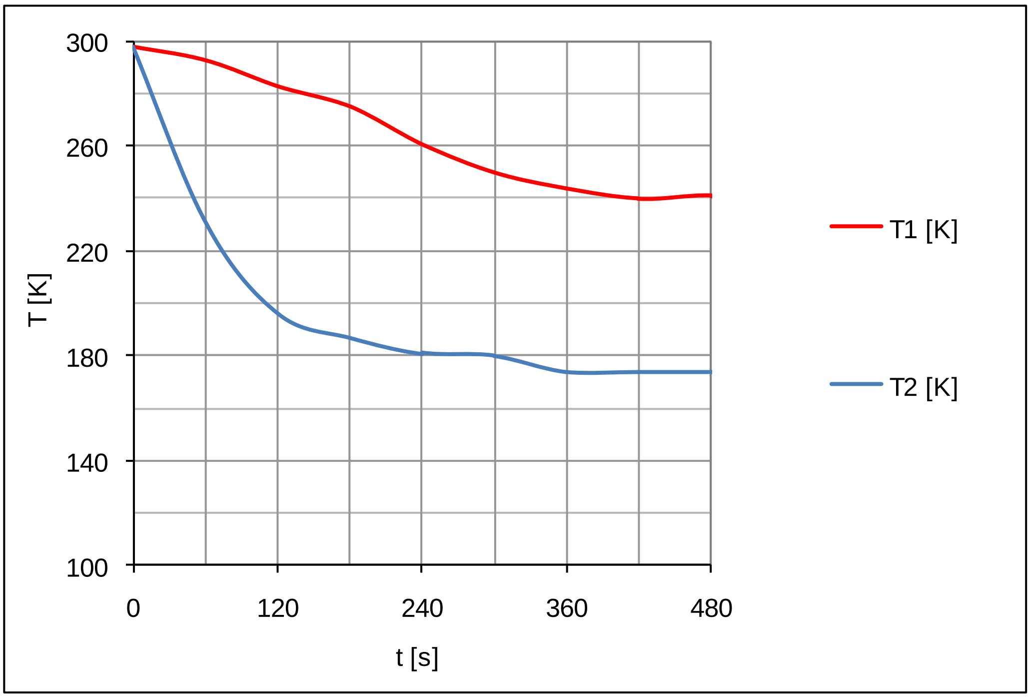


Fig. 7.19 Temperature characteristics for empty heat pipe

Thermodynamical behaviors of a heat pipe may be influenced also by thermal conduction of its container. This is absolutely negligible when the heat pipe operates, but it becomes relevant when the heat pipe operation is restricted. In such case, even a small residual heat flow through the container may dramatically affect the temperature characteristic of a heat pipe.

Hence, the above mentioned cryogenic heat pipe without any working fluid was also tested. The measured temperature characteristics are shown in the Fig. 7.19. The temperature difference of the empty heat pipe in the stable state was about 65 K compared to the 56 K achieved by the magnetic trap. It follows that under the magnetic field exposition heat transport was provided mostly by thermal conduction of the copper wall with only a small contribution of the heat pipe working cycle.

7.2.3 O_2 Heat Pipe with Permanent Magnet Source Experiment

In this experiment, the major focus was put on an alternative magnetic field source based on permanent magnets [8]. Magnetic Trap Method was applied on the gravitational heat pipe and its performance was investigated. Additionally, an influence of the working fluid quantity within the heat pipe was ascertained as well.

The experimental setup was very similar to the previous experiment presented in the section 7.2.2. The main difference was in the utilized magnetic field source. Instead of an electromagnet, strong permanent magnets were employed now. Additionally, the heat pipe container was longer and made from brass with lower thermal conductance than that of copper.

Selected results of the Magnetic Trap Method applied on the gravitational heat pipe operating with a variable working fluid quantity are presented and discussed in the following text in detail.

Tab. 7.3 Experiment specifications

Parameter	**Value**
Magnetic control method	Magnetic trap
Heat pipe	Gravitational
Orientation	Vertical
Working fluid	Oxygen
Filling pressure	8 / 4,5 / 1,8 MPa (at 297 K)
Operation temperatures	Cryogenic
Container (length x OD/ID)	Brass (470 mm x 8/6 mm)
Magnetic field	Permanent magnets, 0 / 0,6 T, max 100 T/m

7.2.3.1 Experimental Installation

The experimental installation was very similar to the previous experiment shown in the Fig. 7.15. But now, the static magnetic field was generated by permanent magnets, already discussed in the section 6.5.2. Two standard Nd-Fe-B permanent magnets (dimensions in millimeters – 40 x 20 x 10) were coupled by a magnetic circuit as shown in the Fig. 7.20. The magnetic induction B achieved about 0,6 T in the middle of an air-gap with the gradient up to 100 T/m at the magnets edges. The magnetic field was regulated by positioning of the magnets. The temperature and pressure measurement was identical to the previous experiment, except the thermocouples position - 50 mm above and 200 mm bellow the magnetic field zone.

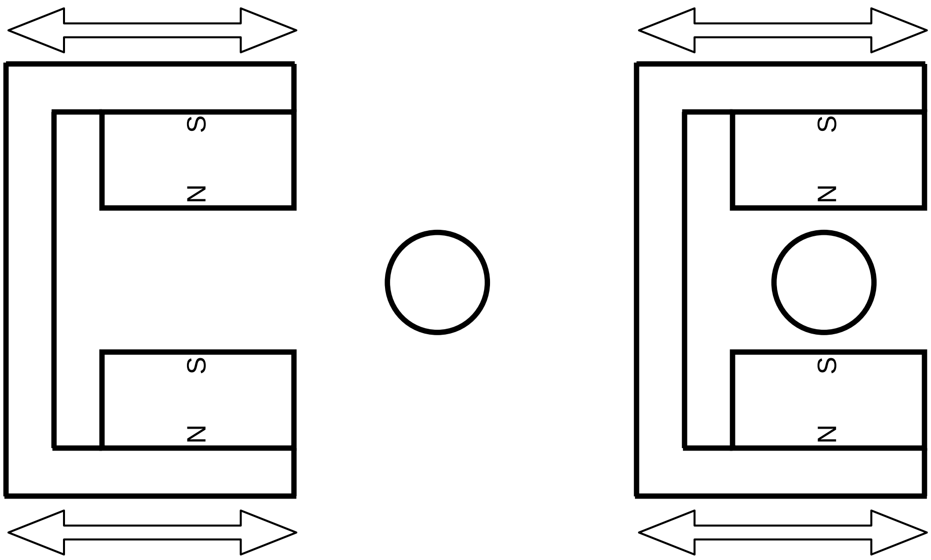


Fig. 7.20 Regulation of magnetic field exposition by positioning of permanent magnets; left – without magnetic field, right – under magnetic field

The tested heat pipe is schematically shown in the Fig. 7.21. It was longer compared to the previous experiment (length 470 mm, OD 8 mm, wall thickness 1 mm) and with the container made from brass with lower thermal conductance than those made from copper. This helped to eliminate residual heat flow through the container wall when the heat pipe operated under magnetic field exposure. The initial filling pressure was 8 MPa (at 297 K), but it was slowly decreasing due to some leakages in the container.

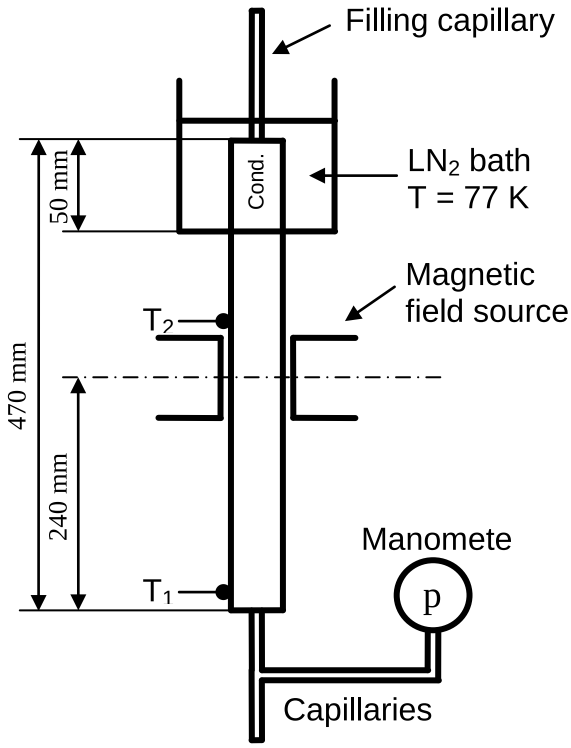


Fig. 7.21 Schema of the heat pipe

7.2.3.2 Measurement

The heat pipe started to be cooled by LN2 at the time T = 0. The heat pipe was exposed to the static magnetic field at the beginning and at the end of the experiment, in the meantime there was no exposure – see the Tab. 7.4.

Tab. 7.4 Definition of experiment periods

Time period	Magnetic field exposition
0 - 330 sec	B = 0,5 T
330 - 570 sec	B = 0 T
570 - 960 sec	B = 0,5 T

A series of identical experiments was repeated for three quantities of the liquid oxygen within the heat pipe (filling pressure resp.):

- 1,33 cm^3 (at 77 K), 8,0 MPa (at room temp.)
- 0,75 cm^3 (at 77 K), 4,5 MPa (at room temp.)
- 0,30 cm^3 (at 77 K), 1,8 MPa (at room temp.)

The magnetic field intensity varies between two states - maximal value 0,6 T (the heat pipe situated in the air gap of the magnetic circuit) and minimal value 0 T (the magnetic circuit moved away). Temperature characteristics of the heat pipe were measured and the internal pressure was monitored as well. (The pressure curves are not presented in the figures because of their similarity to the previous experiment).

7.2.3.3 Results and Discussion

The measured characteristics are illustrated in the following three figures, one for the each working fluid quantity. The temperature T_1 (red) belongs to the lower part of the heat pipe – below the magnetic field zone, T_2 (blue) belongs to the upper part – between the magnetic field zone and the LN_2 bath (see Fig. 7.21). The room temperature was 297 K. The time intervals with and without the magnetic field exposition are marked in the top of the figures and defined in the Tab. 7.4.

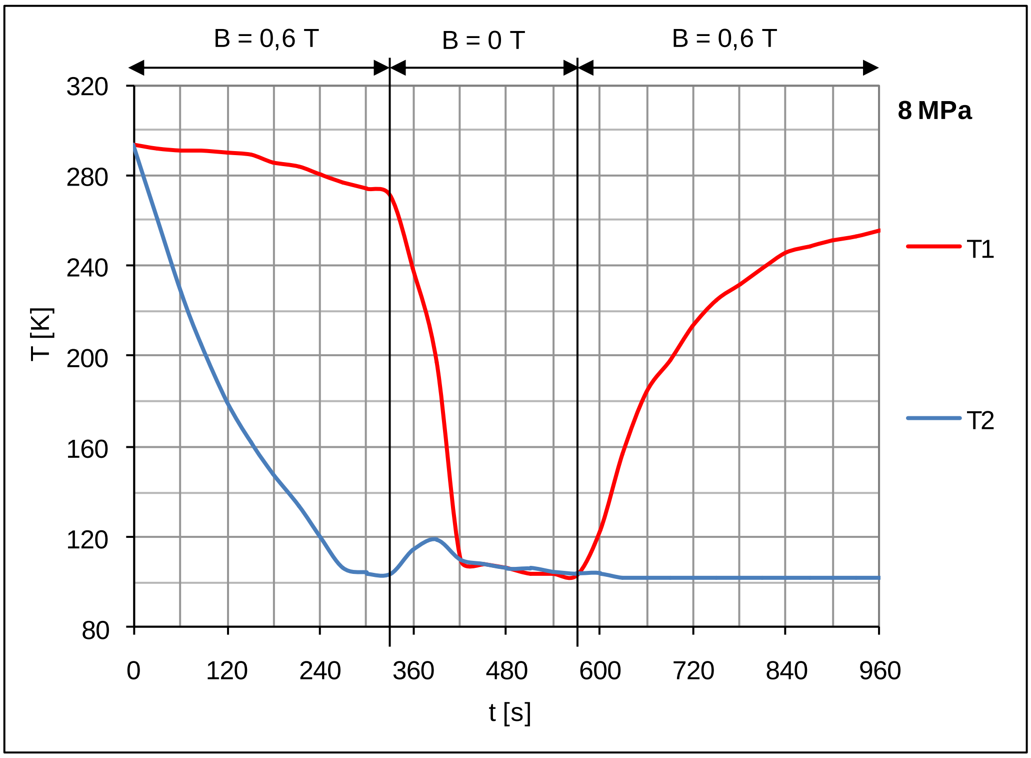


Fig. 7.22 Temperature characteristics of heat pipe with filling pressure 8 MPa

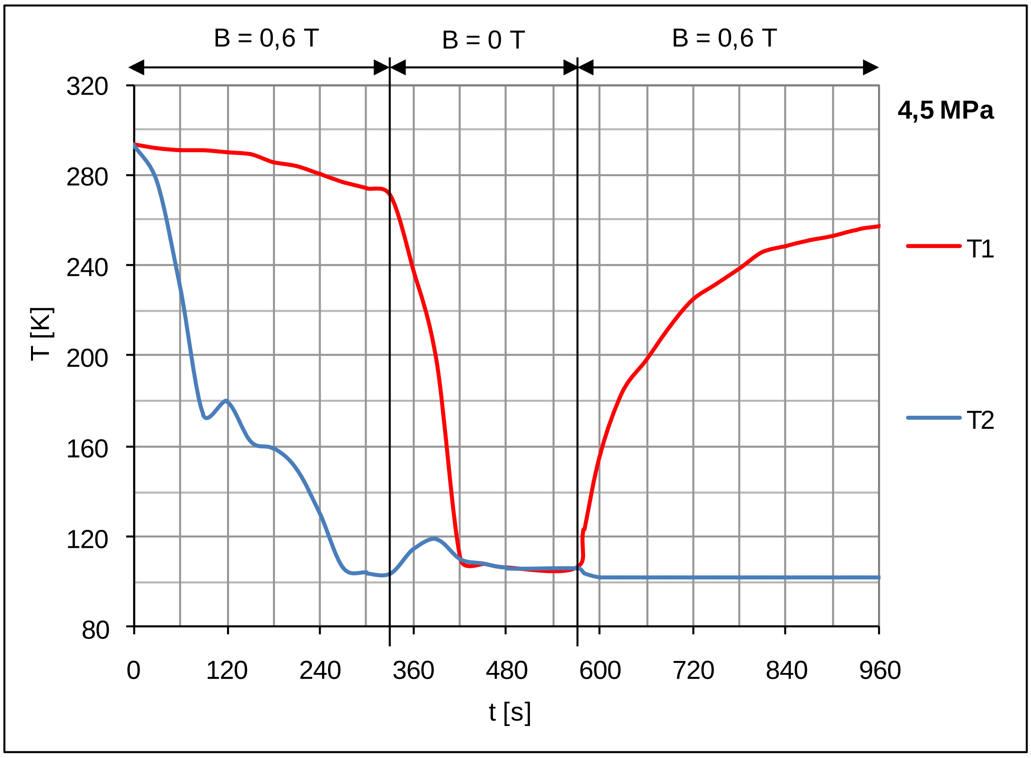


Fig. 7.23 Temperature characteristics of heat pipe with filling pressure 4,5 MPa

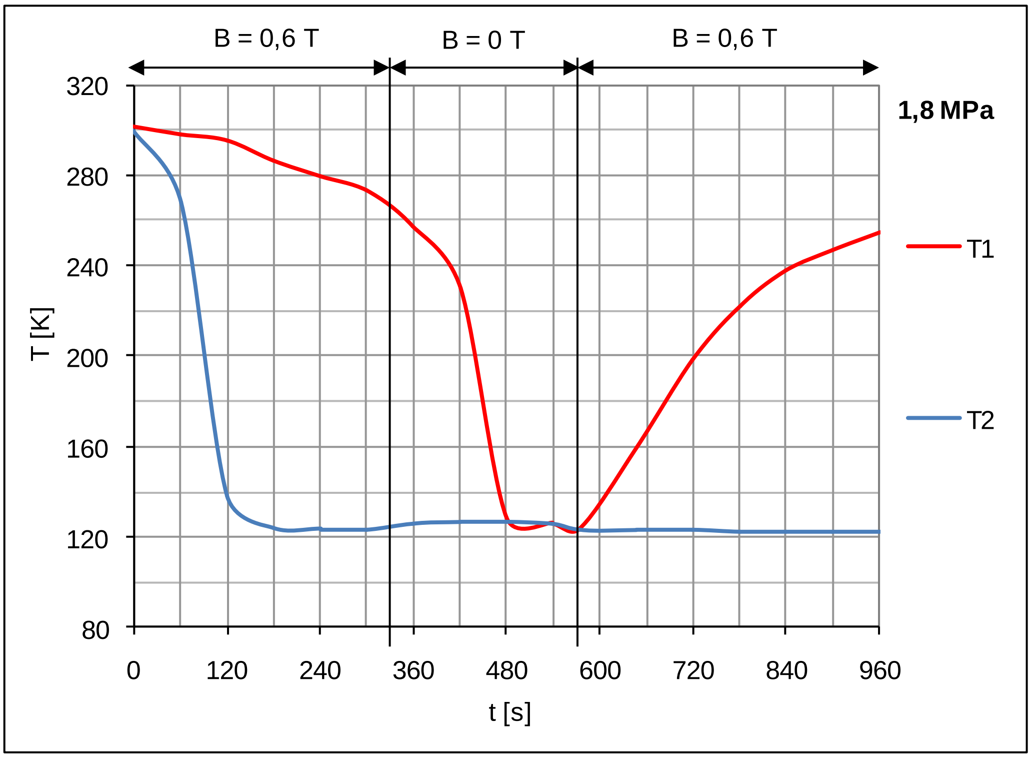


Fig. 7.24 Temperature characteristics of heat pipe with filling pressure 1,8 MPa

The performance of heat pipes working with various fluid inventories was very similar, as seen in the presented figures. The operation was satisfactory in the all cases and the heat pipe was always isothermal without the magnetic field exposition. However, for the 0,30 cm^3 (1,8 MPa) the isothermal temperature without magnetic field exposition was little bit higher, as seen in the Fig. 7.24. It might be caused by an insufficient fluid inventory negatively affecting the working cycle in the heat pipe.

The magnetic field influence on the heat transport was significant in the all cases. The temperature difference under the magnetic field exposition was up to 167 K. Obviously, the magnetic field of B = 0,6 T was large enough to caught most of working fluid in the magnetic trap and restrict the heat flow to the lower part of the heat pipe.

Tab. 7.5 Maximal temperature differences for each fluid inventory

Fluid inventory	**Temperature difference**
1,33 cm3 (8,0 MPa)	165 K
0,75 cm3 (4,5 MPa)	167 K
0,30 cm3 (1,8 MPa)	155 K

The efficiency of the magnetic trap was evaluated by a temperature drop at the time 330 sec, as presented in the Tab. 7.5. The highest value was achieved for the filling pressure 0,75 cm3 (4,5 MPa) – 167 K. For the 1,33 cm3 (8,0 MPa) it was very similar and the lowest value was obtained for the 0,30 cm3 (1,8 MPa). Heat pipe with the lowest fluid inventory had also a slower dynamic at the magnetic field changes.

7.2.4 O_2 Heat Pipe - Wick Type Experiment

All the experiments presented in the previous sections were based on gravitational heat pipes. This experiment deals first with wicked heat pipes operating under magnetic field exposition [1]. Magnetic Trap Method was applied on heat pipes with two different wick types - sintered and screen. The measurement was realized for variable heat pipe tilting and for variable working fluid quantity (filling pressure respectively).

Preliminary and testing processes had to be adapted to wicked heat pipes. It was decided to use oxygen as a working fluid because of its suitable behaviours approved in the previous experiments. It was practically impossible to find a supplier of an oxygen based heat pipe. Thus, we decided to modify construction of a standard water heat pipe and refill it with oxygen. Basic details of the experiment are briefly presented in the Tab. 7.6 and further discussed in the following text.

Tab. 7.6 Experiment specifications

Parameter	**Value**
Magnetic control method	Magnetic trap
Heat pipe	Wicked (sintered / screen)
Orientation	Variable
Working fluid	Oxygen
Filling pressure	8,7 / 12,2 - 12,4 MPa (at 298 K)
Operation temperatures	Cryogenic
Container (length x OD/ID)	Copper (380 mm x 10/8 mm)
Magnetic field	Permanent magnets, 0 / 0,6 T, max 100 T/m

7.2.4.1 Experimental Installation

The experimental installation is shown in the Fig. 7.25. The heat pipe was fixed in an arrangement with the tilt angle adjustment. The tilting feature was the main innovation of the arrangement. One end of the tested heat pipe was chilled by an LN_2 and the rest was exposed to forced air (about 10 m/s perpendicular to the heat pipe) of the room temperature (298 K). An LN_2 reservoir was coupled with the heat pipe by a flexible hose feeding the condenser by the LN_2. The magnetic field source of permanent magnets (B = 0,6 T, grad B = 100 T/m) was situated between the points T4 and T5, as seen in the Fig. 7.26. Its regulation was realized by mechanical positioning similar to the previous experiment shown in the Fig. 7.20. The temperature measurement was realized by K-type thermocouples fixed in five points along the heat pipe (see the Fig. 7.26). The pressure was measured by the digital manometer Greisinger coupled with the heat pipe by a copper capillary. All the measured values were continuously monitored and recorded by the data logger Comet MS5.

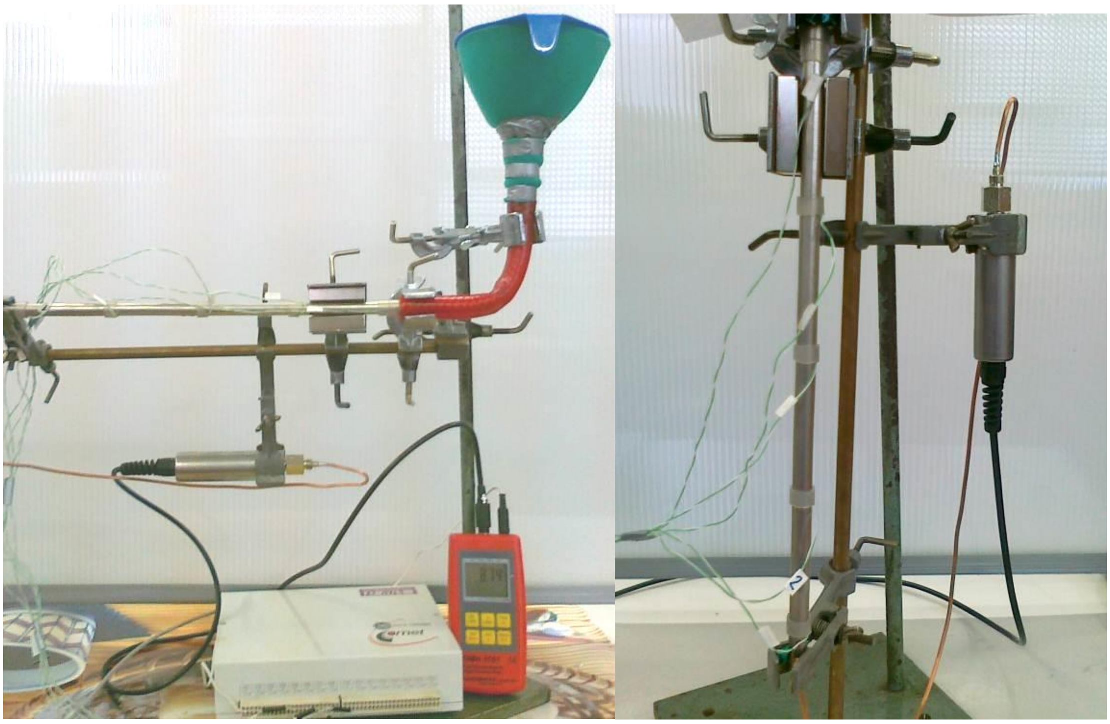
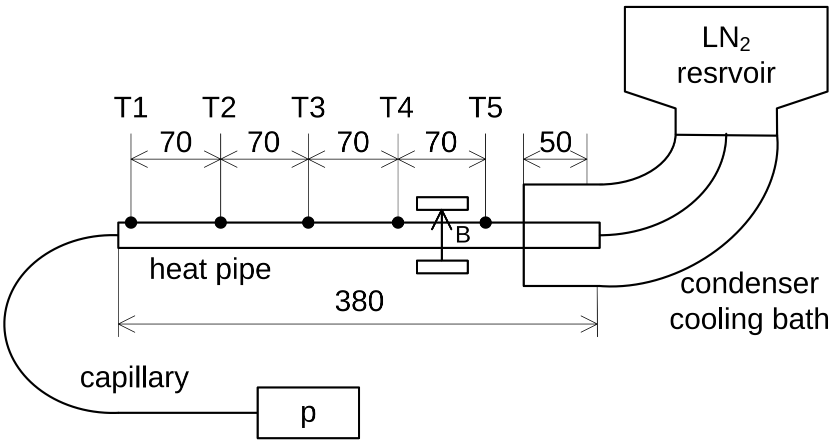


Fig. 7.25 Experimental installation in overview and detail

Two wicked heat pipes were tested in this experiment - sintered heat pipe and screen heat pipe. They were shape identical (380 mm long, OD 10 mm and wall thickness 1 mm), different in the wick type only. The both heat pipes were made by a modification of standard ambient temperature heat pipes with copper container and water as a working fluid. The container was open at the both ends and emptied. After cleaning it was re-closed by copper plugs with copper capillaries for connection with a filling device and a manometer. Finally, the heat pipes were filled with pure oxygen of a variable quantity:

- 1,45 cm^3 at 77 K, 8,7 MPa at 298 K (sintered heat pipe only)
- 2,03 cm^3 at 77 K, 12,2 MPa at 298 K (sintered heat pipe only)
- 2,06 cm^3 at 77 K, 12,4 MPa at 298 K (screen heat pipe only)



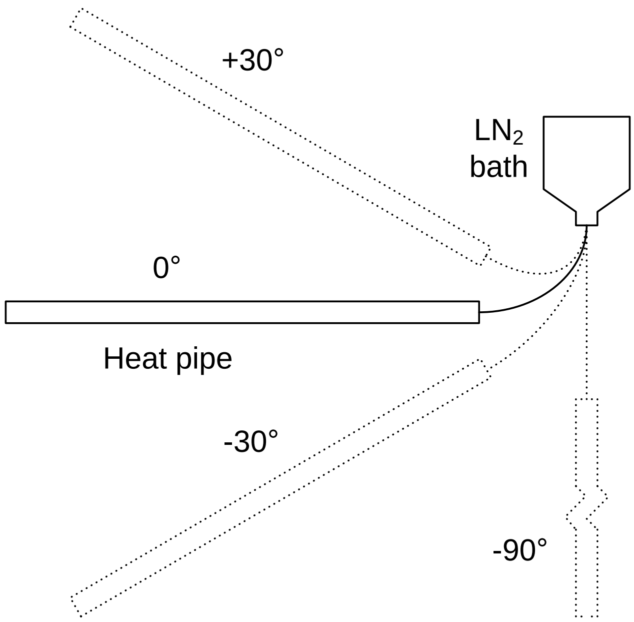


Fig. 7.26 Details of experimental arrangement and heat pipe positioning

7.2.4.2 Measurement

A series of identical experiments was realized for various tilt angles and different filling pressures. The measurement started at the time t = 0 when the LN_2 was filled into the reservoir. The total duration of each measurement was 25 minutes in which the heat pipe was intermittently exposed to the static magnetic field. There were four time periods - two with and two without the magnetic field exposition (marked in the each graph and specified in the Tab. 7.7). The heat pipe operation and magnetic field effects were evaluated by measurement of temperature in five points along the heat pipe.

Tab. 7.7 Definition of experiment periods

Time period	Magnetic field exposition
0 - 10 min	B = 0,5 T
10 - 15 min	B = 0 T
15 - 20 min	B = 0,5 T
20 - 25 min	B = 0 T

7.2.4.3 Results and Discussion

The heat pipe operation and the magnetic trap efficiency were tested on one sintered and one screen heat pipe operating under variable conditions (tilt angle, filling pressure). The results of the experiment presented in the following text and figures are sorted into the three groups:

- Tilt Angle Effect Comparison (screen heat pipe)
- Sintered vs. Screen Heat Pipe Comparison
- Filling Pressure Effect Comparison (sintered heat pipe)

In the figures there are temperature characteristics with curves from T_1 to T_5 corresponding to five points along the heat pipe (see the Fig. 7.26). In the top of the each figure duration of the magnetic field exposition is marked. Other information about tilt angle, filling pressure and the wick type are stated there as well. The tilt angle is related to the horizontal position, positive (+) means the evaporator above the condenser, negative (-) means the heat pipe operates in the gravity assisted mode.

Tilt Angle Effect Comparison (screen heat pipe)

Selected temperature characteristics for the screen heat pipe (working fluid quantity 2,06 cm^3, 12,4 MPa) operating at various tilt angles and including a comparison with the empty container are presented in the Fig. 7.27. At the positive tilt angle (+10°) and also in the horizontal position (0°) the heat pipe has never achieved the isothermal state which is typical for a standard operation mode. Obviously, the heat pipe could operate only partially in those positions. The heat pipe operated correctly in the gravity assisted mode only - when tilted down (-30°). In this position, the magnetic trap effect was significantly observed. Without any magnetic field exposition the heat pipe was able to achieve the isothermal state. With the magnetic field exposition the temperature difference Δ T1, T5 raised up to about 110 K. Because of the poor heat pipe operation observed in the +10° and 0° positions, the magnetic trap investigation was limited.

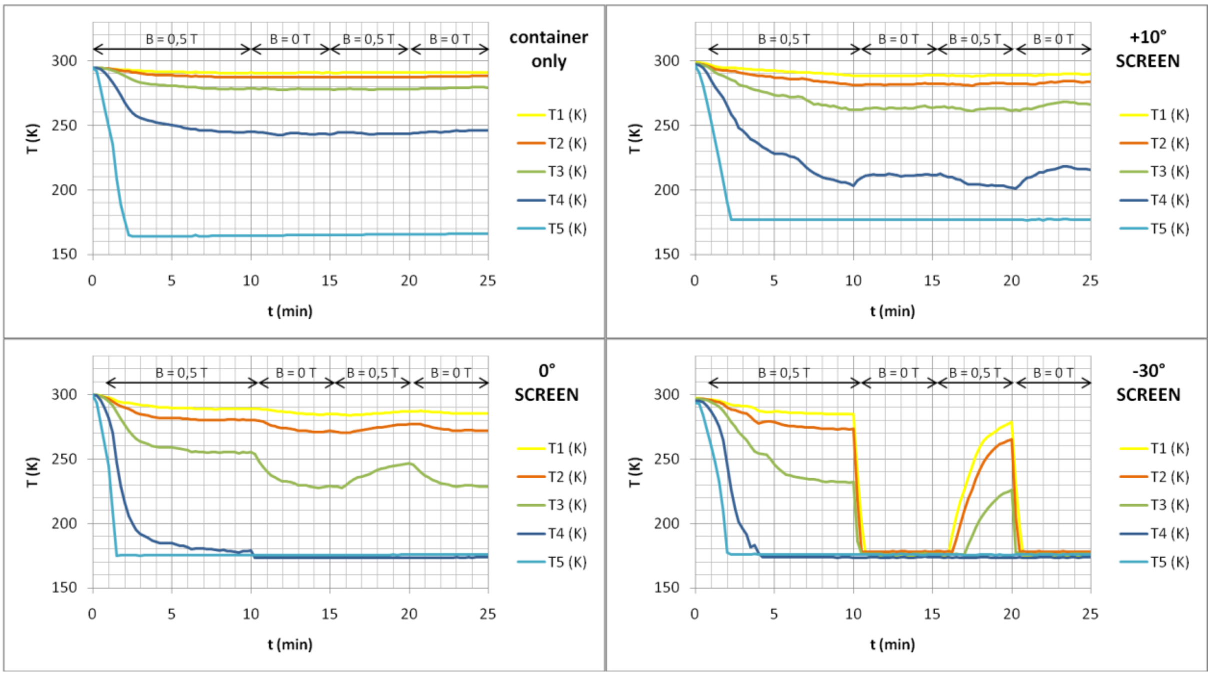


Fig. 7.27 Temperature characteristics of screen heat pipe operating at various tilt angles and of empty container (heat pipe without any working fluid)

Sintered vs. Screen Heat Pipe Comparison

The comparison between performance of the sintered heat pipe (2,03 cm^3, 12,2 MPa) and the screen heat pipe (2,06 cm^3, 12,4 MPa) operating at tilt angles 0° and -30° is presented in the Fig. 7.28. The operation without magnetic field in the horizontal position (0°) was very similar for the both heat pipes. In the gravity assisted mode (-30°), the screen heat pipe operated significantly better than the sintered one. The screen one was almost isothermal, in contrast to the temperature difference (Δ T1, T5) at the sintered one - about 95 K. Also the temperature of the cold end at the screen heat pipe (T_4, T_5) was higher than that of the sintered one. We assume that heat flow in the both heat pipes was limited mostly by the wick capability. From this perspective, the screen wick was significantly better. Hence, also the magnetic field influence on the heat pipe operation was significantly higher at the screen heat pipe than at the sintered one.

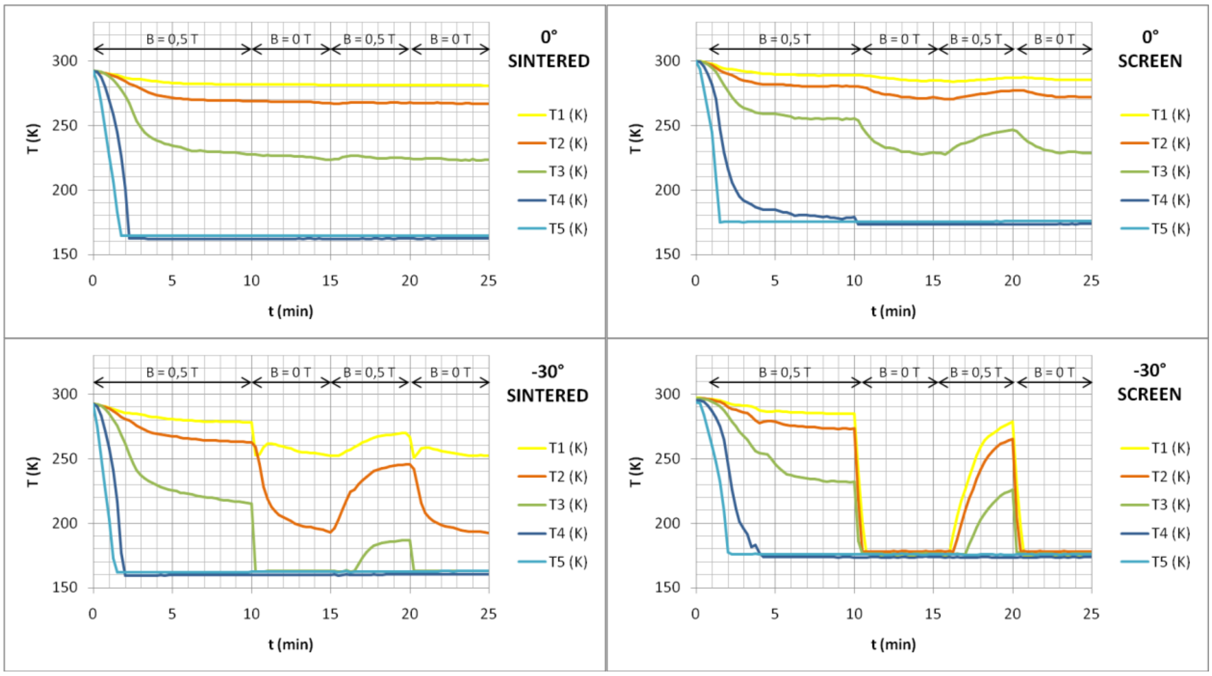


Fig. 7.28 Comparison of sintered and screen heat pipe characteristics

Filling Pressure Effect Comparison (sintered heat pipe)

The last group of graphs (Fig. 7.29) deals with the fluid inventory effect on the operation of the sintered heat pipe and Magnetic Trap performance. There are temperature characteristics for a heat pipe filled with two values of fluid inventory (1,45 cm^3, 8,7 MPa in the left column and 2,03 cm^3, 12,2 MPa in the right column) and operation under various tilt angles (+30°, 0°, -30°, -90°). The effect of the fluid inventory was significantly observed only at the gravity assisted modes (-30° and -90°). With more fluid the heat pipe achieved lower temperature drop compared to the lower fluid inventory.

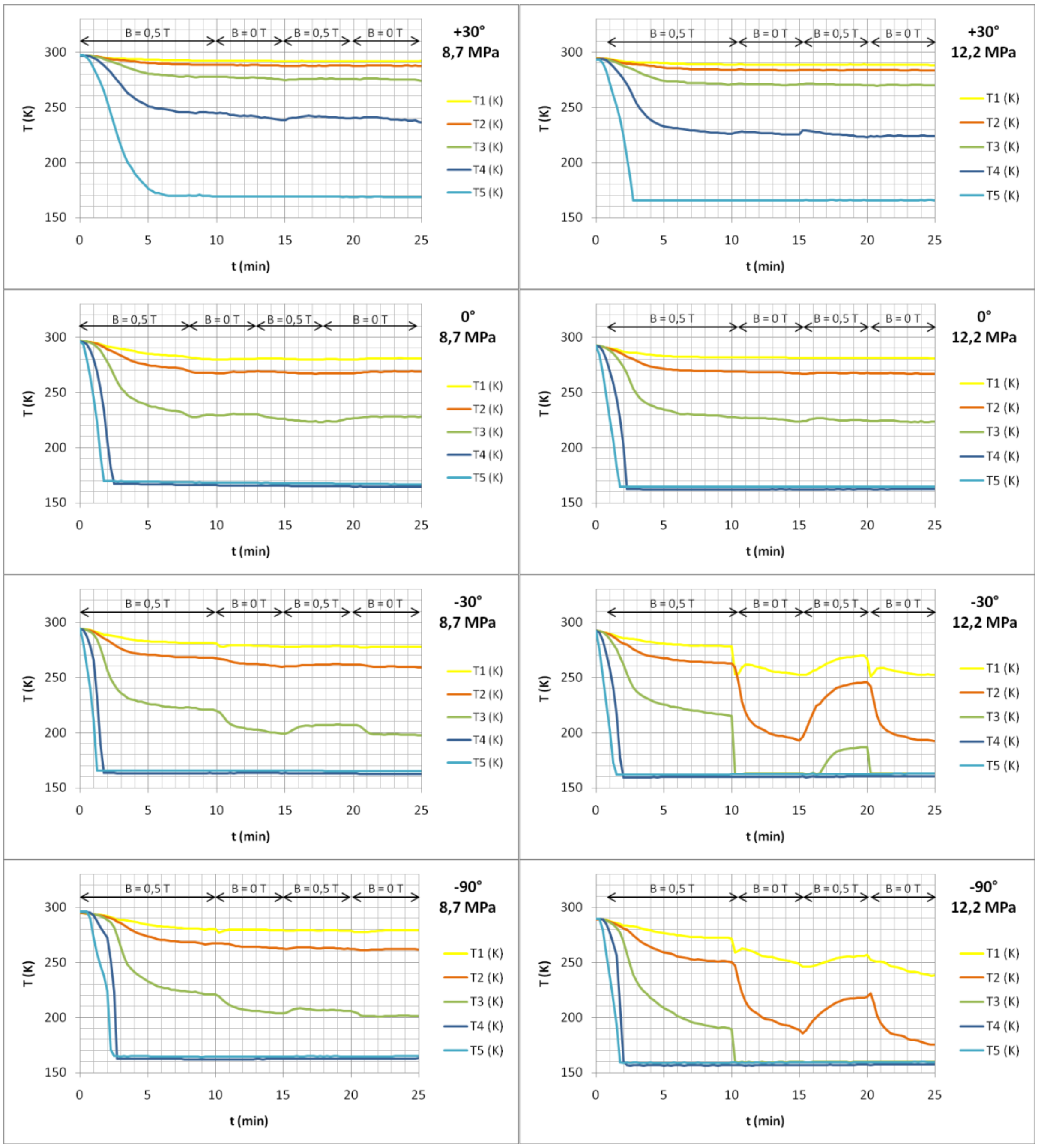


Fig. 7.29 Comparison of sintered heat pipe characteristics for different filling pressure

7.2.5 Ferrofluid Heat Pipe Experiment

This experiment deals with a gravitational heat pipe filled with a water based ferrofluid inside. Its performance under the Magnetic Trap Method was investigated. Magnetic field was generated by permanent magnets and the heat pipe construction was similar to the H_2O heat pipe, discussed in the section 7.2.1.

Tab. 7.8 Experiment specifications

Parameter	**Value**
Magnetic control method	Magnetic trap
Heat pipe	Gravitational
Orientation	Vertical
Working fluid	Water based ferrofluid
Operation temperatures	Ambient
Container (length x OD/ID)	Copper/glass (500 mm x 8/6 mm)
Magnetic field	Permanent magnets, 0 / 0,6 T, max 100 T/m

Magnetic particles contained in ferrofluids might separate from the liquid when it boils, as already discussed in the section 6.4.2. Thus, the original Magnetic Trap Method had to be adapted so that the magnetic trap was placed close above the evaporator for this experiment. This way it was able to catch the ferrofluid droplets streaming up.

7.2.5.1 Experimental Installation

The gravitational heat pipe was tested in a vertical position and magnetic field was applied on the adiabatic part very close above the evaporator (starting about 2 cm above the evaporator). Magnetic field was generated by permanent magnets and regulated by the magnets positioning between two states B = 0 T and B = 0,5 in the middle of the air gap. The temperature was measured by digital thermometers Greisinger with K-type thermocouples fixed in two points - at the copper evaporator (T_1) and at the copper condenser (T_2). A power supply Statron was used for feeding a heating wire on the heat pipe evaporator.

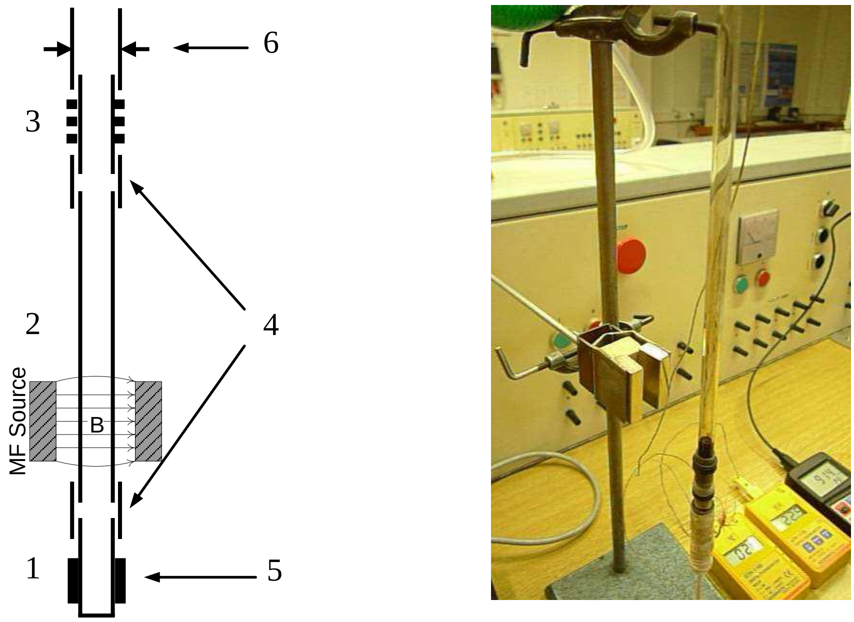


Fig. 7.30 Schema of the heat pipe and the arrangement illustration

The gravitational heat pipe tested in this experiment is shown in the Fig. 7.30. It consisted of three parts - copper evaporator (1), adiabatic section made of glass (2) and copper condenser (3). The sections were connected by rubber tubings together (4). Total length of the heat pipe was 350 mm, OD 10 mm and wall thickness 1 mm. The evaporator and the condenser were 75 mm long each. The heating wire (5) was wound directly on the evaporator and the condenser was equipped with fin radiators. A mechanic valve (6) at the condenser end allowed repeatable filling. The heat pipe was filled with a water-based ferrofluid Ferrotec of amount 2,5 ml.

7.2.5.2 Measurement

The evaporator was heated by the power of 10 W and the rest of the heat pipe was exposed to the natural convection of the ambient air (23 °C). The total duration of the each measurement was 25 minutes in which the heat pipe was intermittently exposed to the static magnetic field. There were four time periods - two with the magnetic field exposition and two without (marked in the figure and specified in the Tab. 7.9). After 25 minutes the heating was switched off. The heat pipe operation and magnetic field effects were evaluated by measurement of temperature in two points along the heat pipe.

Tab. 7.9 Definition of experiment periods

Time period	Magnetic field exposition
0 - 15 min	B = 0,5 T
15 - 18 min	B = 0 T
18 - 22 min	B = 0,5 T
22 - 25 min	B = 0 T

7.2.5.3 Results and Discussion

The temperature characteristics of the tested heat pipe are presented in the Fig. 7.31. The heat pipe started to operate after about 1 minute. Without magnetic field exposition the heat pipe operated in an almost isothermal mode with the maximum temperature drop up to 3 °C.

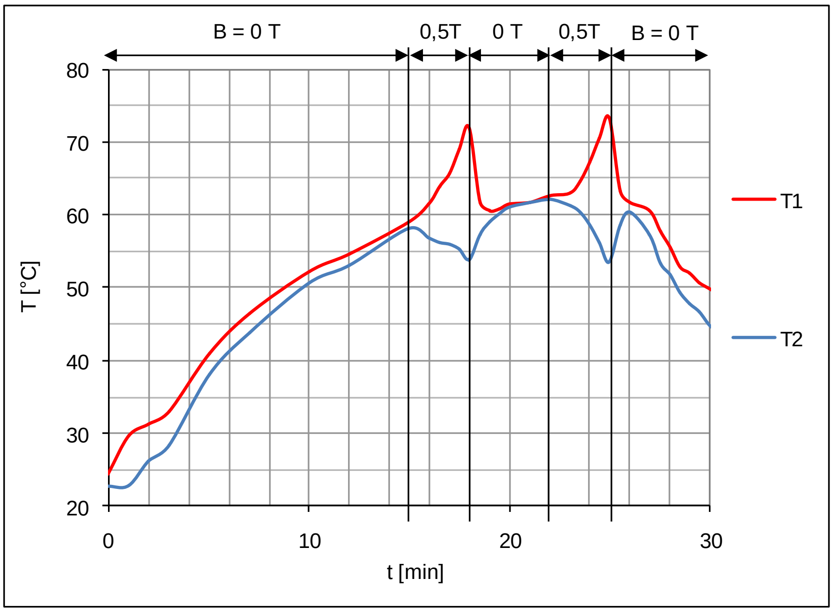


Fig. 7.31 Temperature characteristic of tested heat pipe under intermittent magnetic field exposition

When the magnetic field was applied on the heat pipe, droplets of the ferrofluid started to be collected at the magnets. After about one more minute most of the working fluid was caught in the adiabatic part between the permanent magnets, as seen in the Fig. 7.32. Insufficiency of the working fluid in the evaporator caused an increase of the temperature drop up to 20 °C. Dynamic of the control seemed to be slower compared to other experimental setups.

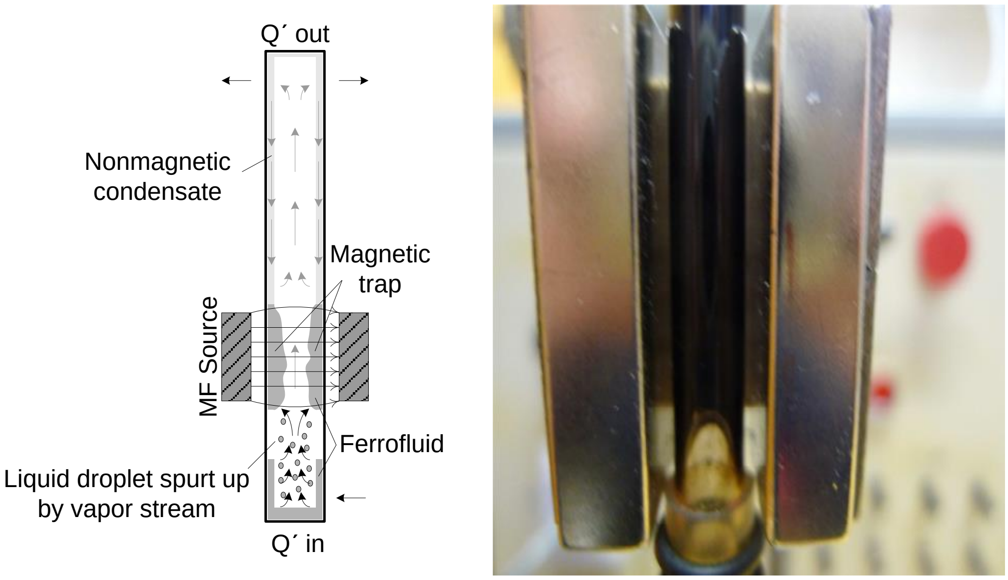


Fig. 7.32 Magnetic trap in schematic illustration and detail of magnetic fluid caught in trap between permanent magnets

7.3 Magnetic Plug Method Experiments

The Magnetic Plug Method, discussed in the chapter 6.2, has been developed as an alternative to the Magnetic Trap Method. It was designed especially for the heat pipes filled with ferrofluids. It represents an additional part of this work with a limited scope, outlining the possibilities of this alternative method only. An experimental investigation of the Magnetic Plug Method was realized and is presented in the following text.

Magnetic plug control is based on reduction of the active surface of the heat pipe evaporator. Inside the heat pipe is a movable plug consisting of a cylindrical permanent magnet covered by a ferrofluid around. The ferrofluid works here as a fluidal seal which stops the condensate flow. Thus, the heat pipe bellow the plug is cut off and the heat flow efficiency is reduced.

7.3.1 Water + Oil-Ferrofluid Heat pipe Experiment

This experiment was focused on ascertaining of the Magnetic Plug Method applied on a gravitational heat pipe. Water was used as a working fluid and an oil ferrofluid as a fluidal seal. In this system, there was no external magnetic field source, only the permanent magnet of the plug inside the heat pipe.

Tab. 7.10 Experiment specifications

Parameter	**Value**
Magnetic control method	Magnetic plug
Heat pipe	Gravitational
Orientation	Vertical
Fluid	Water + Oil ferrofluid
Operation temperatures	Ambient
Container (length x OD/ID)	Brass (500 mm x 10/8 mm)
Magnetic field	Permanent magnet - internal

7.3.1.1 Experimental Installation

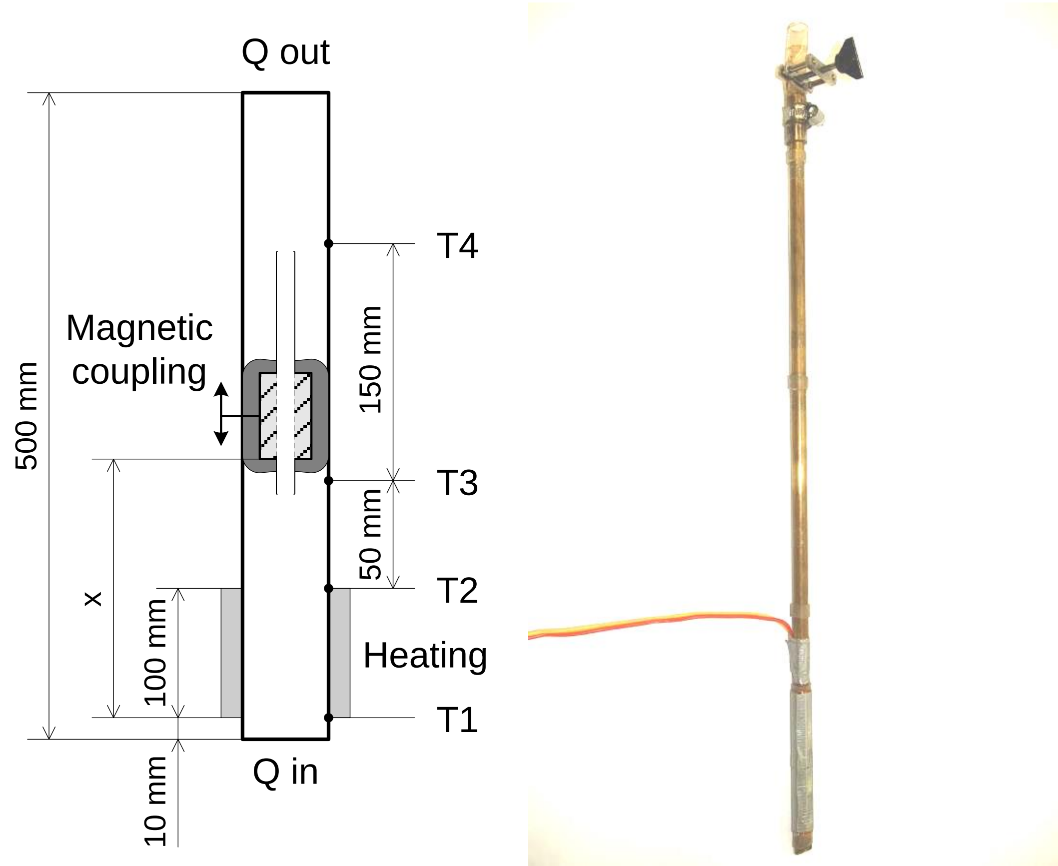


Fig. 7.33 Experimental heat pipe with magnetic plug inside

A schema of the tested gravitational heat pipe and its real form are presented in the Fig. 7.33. Water was used as a working fluid and an oil based ferrofluid formed a liquid seal around the plug. The heat pipe was positioned vertically during the experiment (evaporator on the bottom).

The heat pipe was made of a brassy tube 500 mm long, OD 10 mm and wall thickness 1 mm. The bottom end was compressed and soldered, the upper end was equipped with a rubber extension with a clamp on. A heating wire was wound on the heat pipe in the evaporator region. The temperature measurement was realized by K-type thermocouples fixed in four points along the heat pipe. All the measured data were continuously monitored and recorded by a data logger.

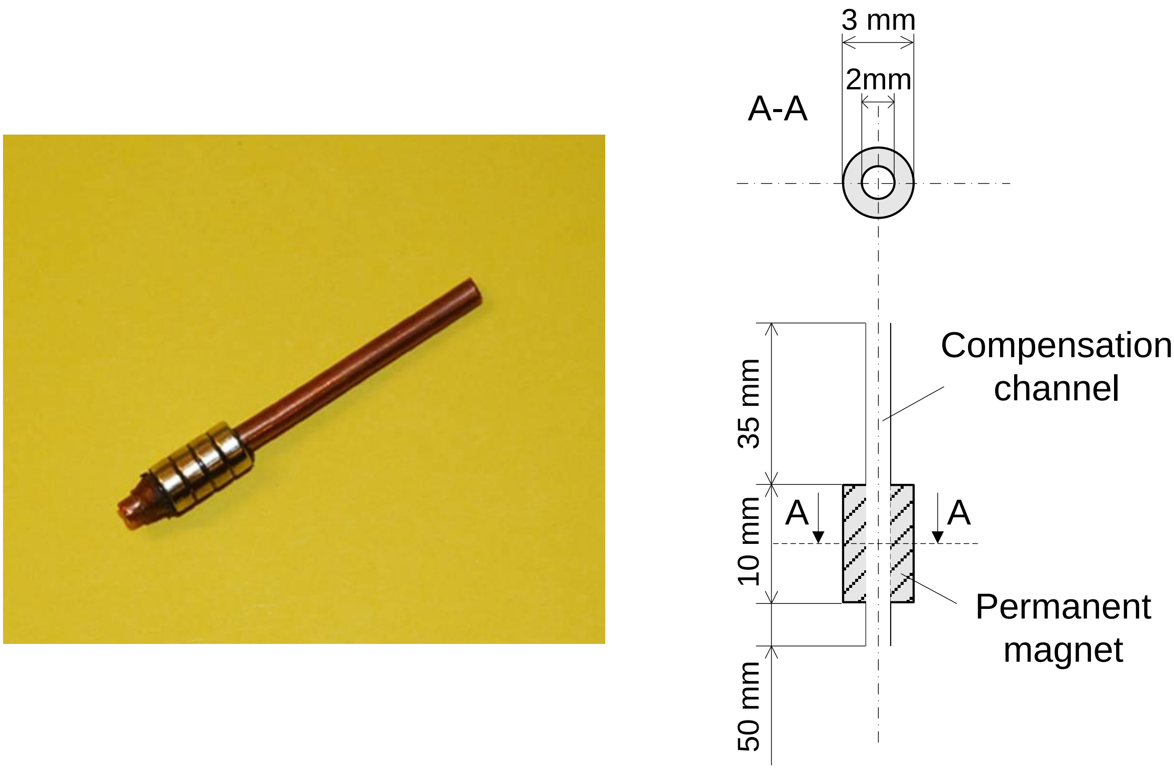


Fig. 7.34 Magnetic plug

Magnetic plug placed inside the heat pipe is shown in the Fig. 7.34. It consisted of 4 toroidal permanent magnets in the line and a small copper tube (capillary). The permanent magnets (each with dimensions: OD = 6 mm, ID = 3,5 mm, length = 2,5 mm) were made from Nd-Fe-B and achieved magnetic induction of 0,2 T in the hole through with the gradient max 100 T/m. The copper tube (dimensions: OD = 3 mm, ID = 2 mm, length = 50 mm) passed through the central hole of the magnets and was tightly glued there.

The plug was inserted into the open heat pipe and the oil ferrofluid of about 0,5 ml was filled inside. After that, the working fluid of about 1,5 ml was filled in the same way. The heat pipe was being evacuated by the vacuum pump for 5 minutes (degassing process) and then closed by the clamp on the rubber extension. The plug inside the heat pipe was positioned by a common ferrous nut being moved along the heat pipe surface from the outside.

7.3.1.2 Measurement

At the time t = 0 the evaporator started to be heated with the power of 5 W, constant over the whole experiment. The rest of the heat pipe was exposed to the natural convection of the room air (300 K). The plug was in the lowest position x = 0 at the beginning of the experiment. Then, the plug was moved up step by step higher according to the Tab. 7.11. The heat pipe was re-degassed (for about 5 sec) at the time t = 0:05 min and t = 0:50 min. The temperature characteristics of the heat pipe were measured and recorded.

Tab. 7.11 The plug positioning

Time (h:min)	**x (mm)**
0 : 00	0
0 : 20	50
0 : 55	75
1 : 25	100
1 : 40	150
2 : 05	200

7.3.1.3 Results and Discussion

The temperature characteristic of the tested heat pipe is presented in the Fig. 7.35. The curves in the figure correspond to the thermocouple points along the heat pipe, as shown in the Fig. 7.33. The position of the plug “x” is marked in the top of the figure.

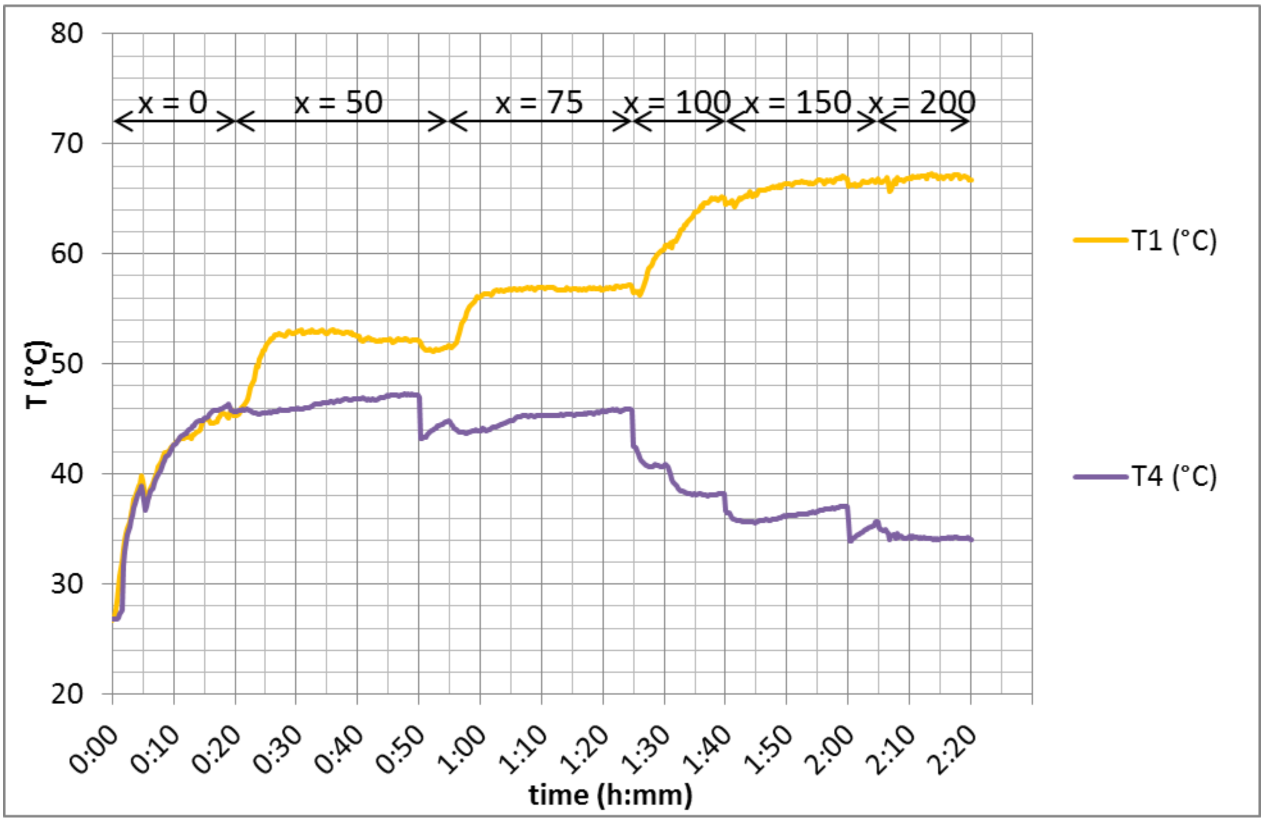


Fig. 7.35 Temperature characteristic of tested heat pipe with magnetic plug in variable position

At the beginning, the plug was in the lowest position and the whole evaporator was active. The heat pipe was almost isothermal along the whole length and it worked as usual for a standard operation mode. Then the plug was moved up in steps and the active surface of the evaporator was being appropriately restricted. The response on the each step is clearly seen in the Fig. 7.35. While the plug was being moved up, the temperature drop along the heat pipe was increasing. From the isothermal state it raised up to about 32 °C at the end of the measurement when the plug was in the highest position.

Obviously, it was possible to influence heat flow in the tested heat pipe by a magnetic field source placed inside. However, this is applicable only on systems utilizing strong magnetic liquids like ferrofluids. I that case, even a small permanent magnet is able to create a liquid formation around resulting into a barrier for the working fluid flow.

8 Conclusion and Further Work

8.1 Conclusion

This work describes a new approach to the heat transport control in heat pipes based on magnetic field exposition and it might be an alternative to several conventional methods. We have worked out two basic magnetic field based control approaches – Magnetic Trap Method and Magnetic Plug Method. Both are based on an interaction of static magnetic field with a fluid within a heat pipe, but with different arrangement and construction. Starting at the page 39 it represents original theories (chapter 6) and results of experimental research (chapter 7).

Applying the magnetic field control on heat pipe we are getting a very complex system with many variables related to magnetic field distribution, working fluid properties, heat pipe construction or its operation mode etc. Mathematic models and calculations are very complicated and less accurate because of extreme complexity of such systems. Hence, we decided to investigate this method by experimental ascertaining.

We have experimentally ascertained the magnetic field influence on heat pipes operation of various constructions and working fluids. The major focus was put on ascertaining the magnetic field influence on heat pipes operation, however, some related aspects were observed as well. There were no commercial heat pipes suitable for our aims available on the market. Hence, we had to design and create our own prototypes and also adapt or develop some manufacturing technologies, testing arrangements and procedures.

The experimental investigation is the most important part of this work and it also brings the major contribution to the improvement of the current state of knowledge. We have observed that it is possible to dramatically reduce the effective thermal conductance of a heat pipe and regulate the heat flow by this way. At specific conditions it was possible to catch or move the fluid by magnetic field or make a barrier for the fluid flow. Furthermore, using special magnetic fluids, so called ferrofluids, it is also possible to create a fluidal seal within the heat pipe. Additionally, we have successfully approved strong permanent magnets systems for these aims.

By this work we have experimentally approved that it is possible to significantly affect heat flow in specially constructed heat pipes by the both investigated approaches - Magnetic Trap Method and Magnetic Plug Method. The both methods were able to significantly reduce heat flow in selected heat pipes (increase of temperature drop of more than 10 K). The control effectiveness was affected especially by magnetic properties of working fluids and magnetic field intensity. Two types of working fluids were successfully approved for the magnetic field control - oxygen and ferrofluids. Best results were achieved with heat pipes filled with oxygen and exposed to magnetic field generated by permanent magnets. In that case the temperature drop increased from almost zero without magnetic field to more than 160 K with magnetic field.

The magnetic field control might be an alternative to conventional variable conductance heat pipes based on a noncondensable gas load. In some specific applications it may bring some desirable benefits like absence of a noncondensable gas (incompatibilities with other heat pipe components) or possible enhancement of heat exchange in the evaporator region.

Thesis and results based on this work have been published in several reviewed journals and presented at several international conferences and journals. Most of them have been high rated and also often awarded, including The Best Poster Award at the international conference ISSE 2009, the second place at the international conference POSTER 2009 or the first place at the CEZ Foundation Award Competition. Some of the prototypes and arrangements realized during this work were also registered as Utility Models at Czech Industrial Property Office in Prague and as Functional Models at Czech Technical University in Prague. They have been also utilized for educational aims at the Faculty of Electrical Engineering, Czech Technical University in Prague.

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8.2 Further Improvement or Applications

Further research work shall be focused especially on real applications of ascertained magnetic field control systems. Most of the potential applications are operating at ambient temperatures and hence this temperature range should be accented. For that purpose it is necessary to find a working fluid with suitable thermodynamic properties and magnetic behaviors. Perspective can be also further research of so called ferrofluids, already investigated and applied during this work. In this case would be necessary to solve their stability and degradation over longer use in heat pipes. It might be also useful to describe the mentioned effects theoretically and create a mathematical model for such systems.

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The contribution of authors was equal at all the above listed publications.