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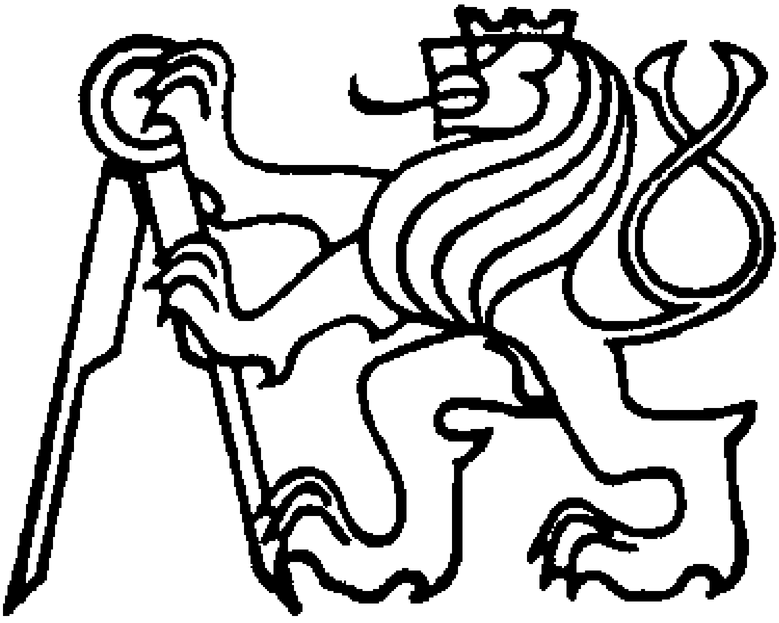

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Electrotechnology

Ing. Filip Cingroš

MAGNETIC FIELD CONTROL
OF HEAT TRANSPORT IN HEAT PIPES

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TABLE OF CONTENT

1 CURRENT SITUATION OF THE STUDIED PROBLEM

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 [9]. 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 [8]. 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.

There are known some methods of influencing 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. 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.

There are several 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 [6]. It has been observed that the fluid convection was reduced or stopped by interaction with external static magnetic field. Another one deals with a heat pipe filled with oxygen influenced by an electromagnet [7]. According to the presented results it was possible to significantly reduce heat flow in the heat pipe by static magnetic field.

2 AIMS OF THE DOCTORAL THESIS

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.

3 WORKING METHODS

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.

3.1 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.

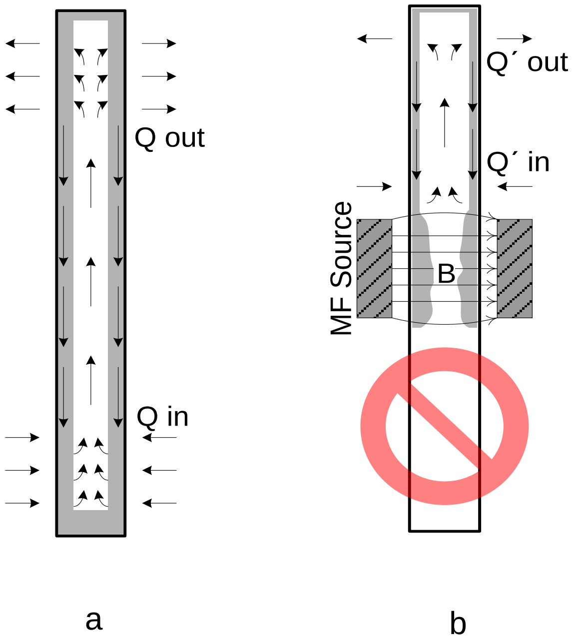

Fig. 3.1 Operation of heat pipe filled with pure oxygen;
a - standard operation, b - magnetic trap operation

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. 3.1a). When the heat pipe is exposed to the magnetic field (Fig. 3.1b), 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.

3.2 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.

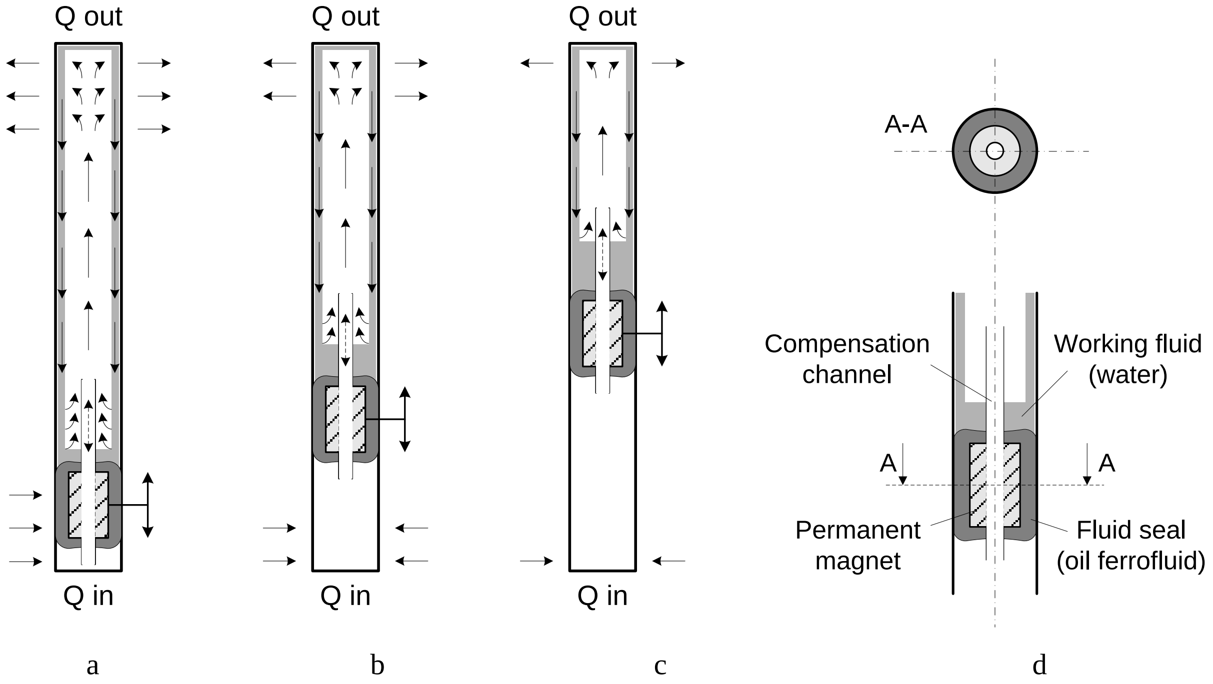

Fig. 3.2 Magnetic plug control system;
a - normal operation, b - reduced operation, c – heat flow cut off, d – plug in detail view

The magnetic plug control system has been also experimentally ascertained by this work. A heat pipe arrangement with this control system is presented in the Fig. 3.2. 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. 3.2 - d 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.

4 RESULTS

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.

4.1 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. 4.1. Magnetic field effects on heat transport in heat pipes were quantitatively evaluated by a comparison of heat pipe temperature drop with and without magnetic field exposition.

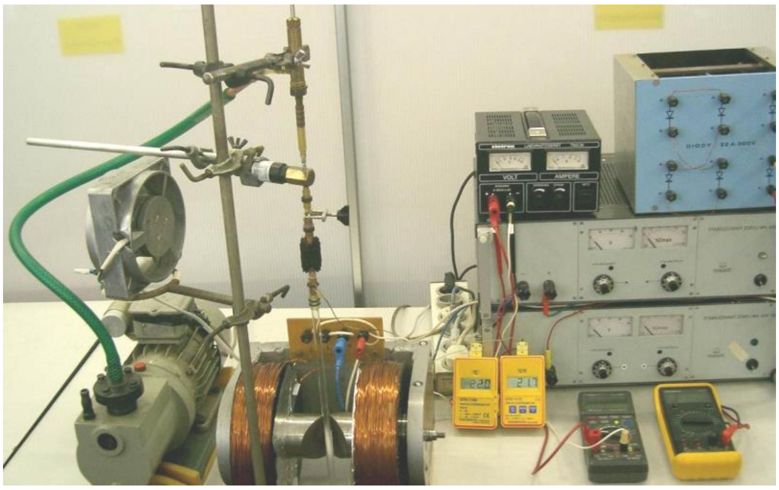

Fig. 4.1 Typical arrangement for ambient temperature experiments

A concept of an ambient temperature heat pipe in construction details see in the Fig. 4.2. 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.

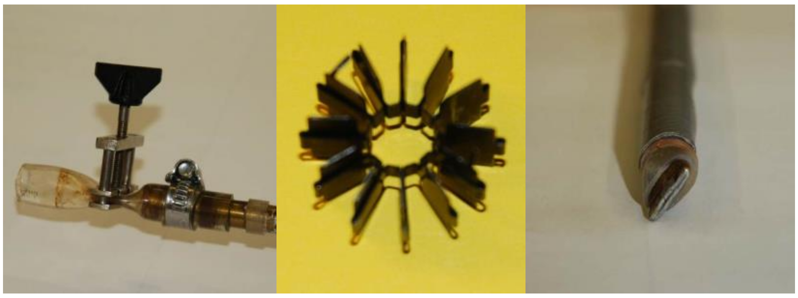

Fig. 4.2 The condenser end with a rubber extension and a clamp; fin radiator optionally placed on the condenser region; the evaporator end

An example of a cryogenic heat pipe with a wick utilized in our experiments is presented in the Fig. 4.3. In this case, it was made by refilling of a standard wicked heat pipe for ambient temperatures. Copper capillaries passing through the both plugs connected the heat pipe with a filling system and a manometer. Gravitational heat pipes were usually made of a standard tube made from copper or brass which are both compatible with oxygen.

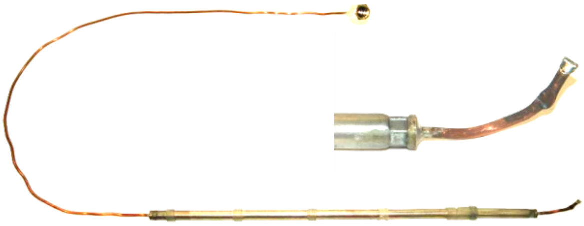

Fig. 4.3 Cryogenic heat pipe with capillary connections, heat pipe closure in detail

4.2 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.

4.2.1 Water and Ethanol Heat Pipes Experiment

In the early experiments gravitational heat pipes filled with deionized water or pure ethanol were tested [5]. The goal was investigation of heat pipes operation principles, including some start-up or other abnormalities. The magnetic field influence was insignificant because of weak magnetic properties of used working fluids (Water χ = -9,1·10-6, Ethanol χ = -7,9·10-6).

Tab. 4.1 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

For the overall installation see the Tab. 4.1 and Fig. 4.4. 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.

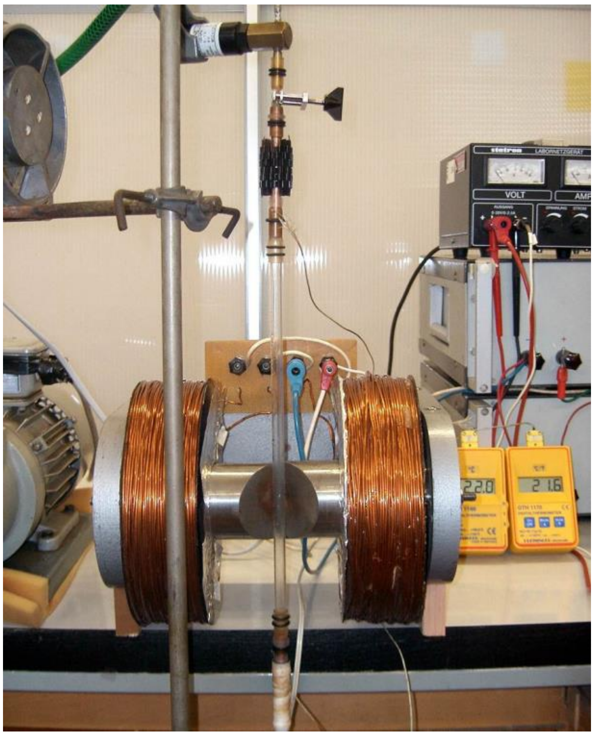

Fig. 4.4 Experimental heat pipe with transparent adiabatic section situated between the electromagnet poles

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.

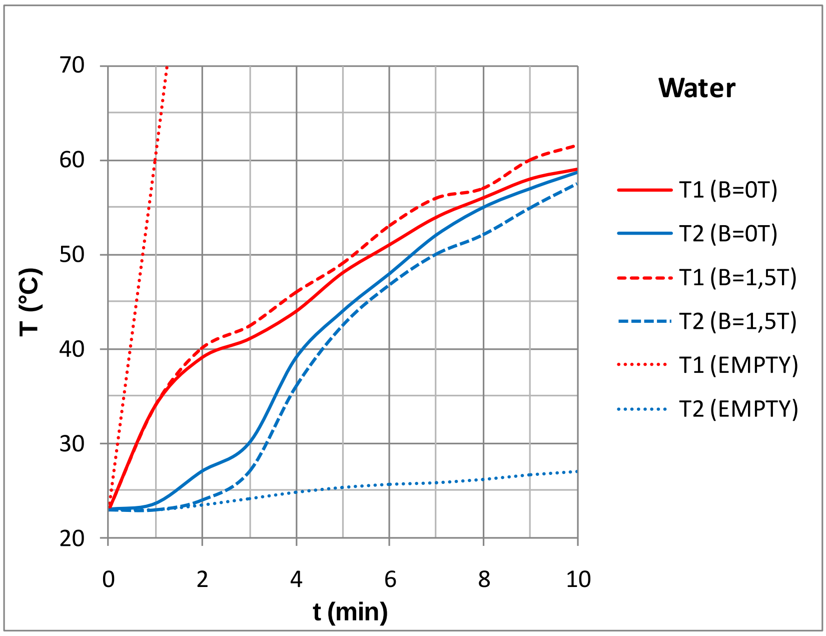

Fig. 4.5 Heat pipe with water as working fluid

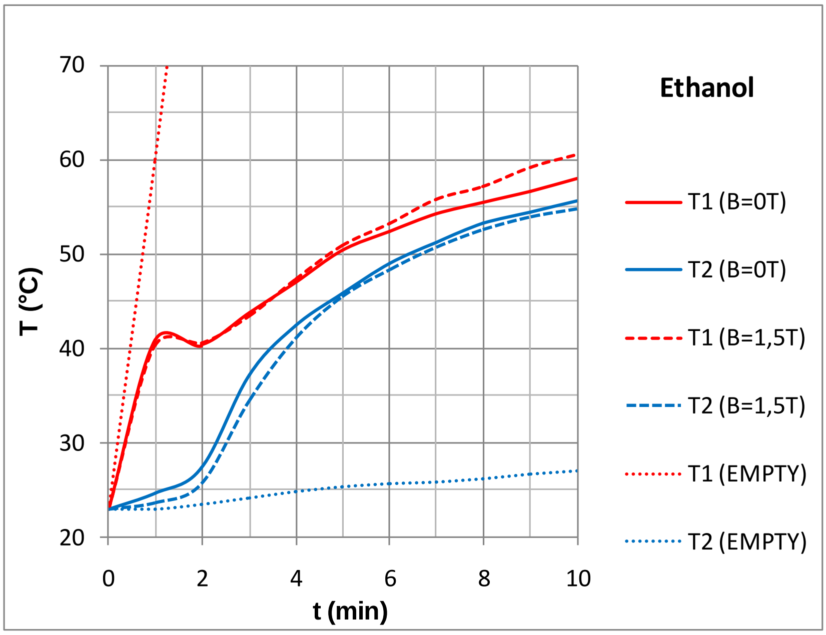

Fig. 4.6 Heat pipe with ethanol as working fluid

4.2.2 O_2 Heat Pipe with Electromagnet Experiment

In this experiment [3], possibilities of the Magnetic Trap Method utilizing a conventional electromagnet have been ascertained. An experimental gravitational heat pipe filled with pure oxygen was made for this purpose.

Tab. 4.2 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

For the experimental installation see the Tab. 4.2 and Fig. 4.7. 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 and the rest of the heat pipe (the whole evaporator) was exposed to the room temperature (295 K). The middle of the heat pipe was exposed to the static magnetic.

The measurement started with filling the LN_2 into the polystyrene vessel on the top of the heat pipe. 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.

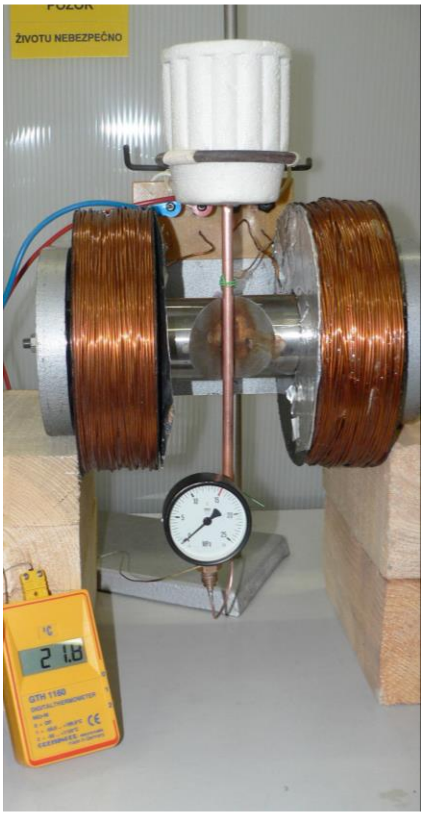

Fig. 4.7 Experimental installation of cryogenic heat pipe between electromagnet poles

Results and Discussion

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). The p - curve (black dash lines) represents the pressure inside the heat pipe.

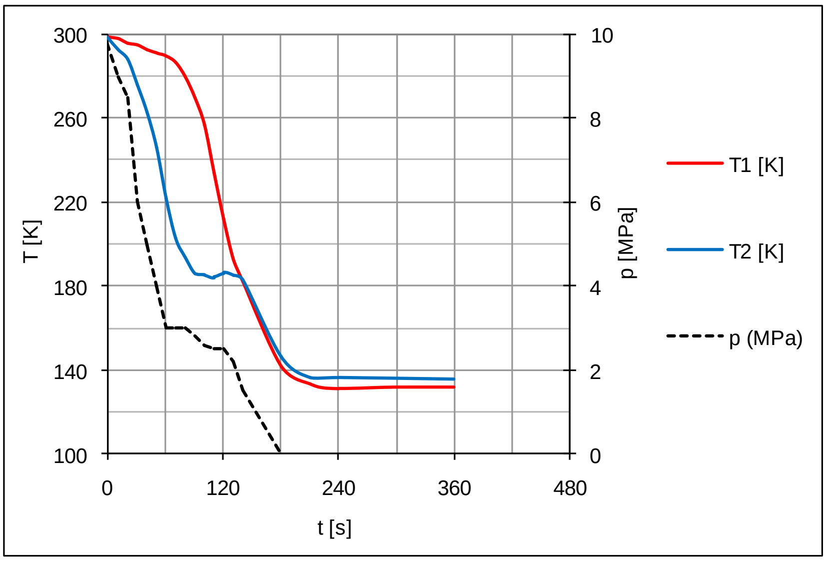

Fig. 4.8 Characteristics of standard heat pipe operation without any magnetic field exposure

Characteristics of the heat pipe without any magnetic field exposure are presented in the Fig. 4.8. 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.

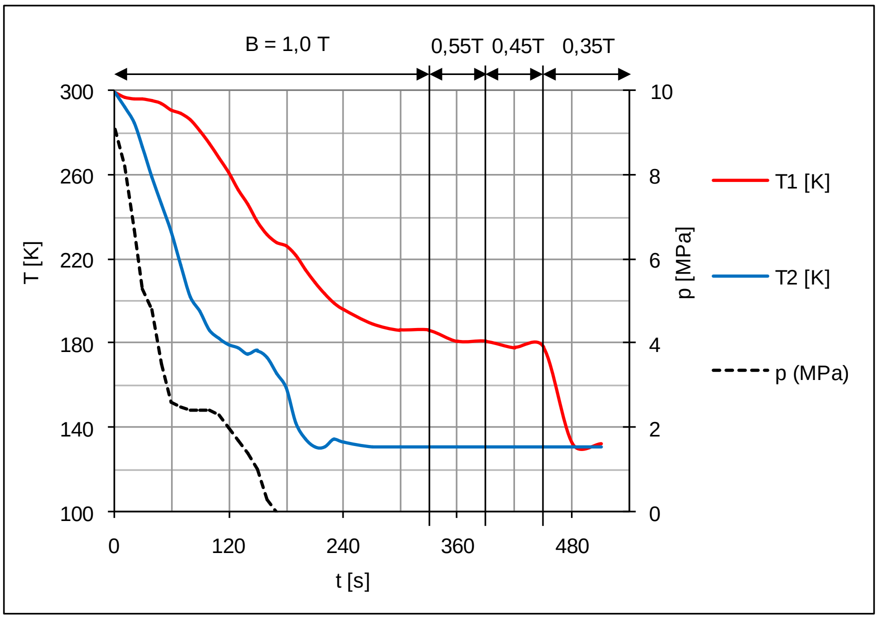

Fig. 4.9 Characteristics of heat pipe operating under variable magnetic field

Under the magnetic field exposition, the heat pipe operation was clearly different from the previous case, as seen in the Fig. 4.9. 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.

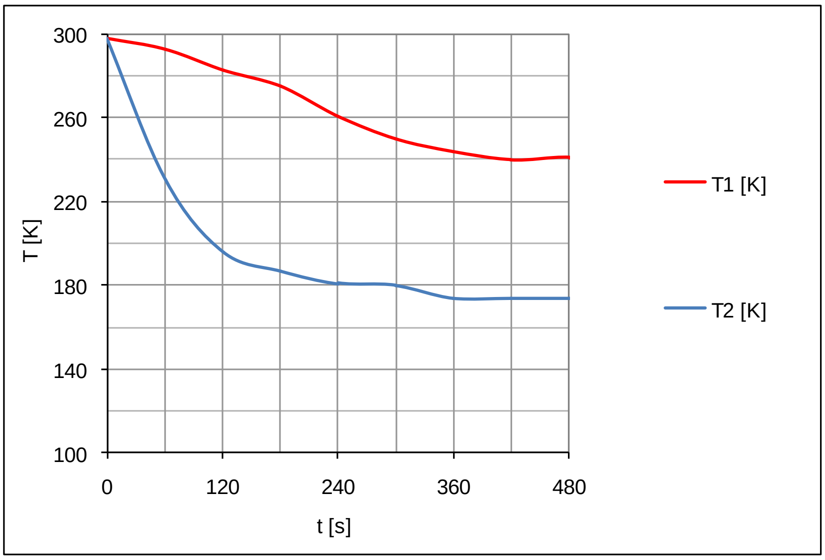

Fig. 4.10 Temperature characteristics for empty heat pipe

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. The measured temperature characteristics of an empty heat pipe are shown in the Fig. 4.10. The temperature difference 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.

4.2.3 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 [4]. 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 4.2.2. However, the heat pipe container was longer and made from brass with lower thermal conductance than that of copper, see the Tab. 4.3.

Tab. 4.3 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

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. 4.11. 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.

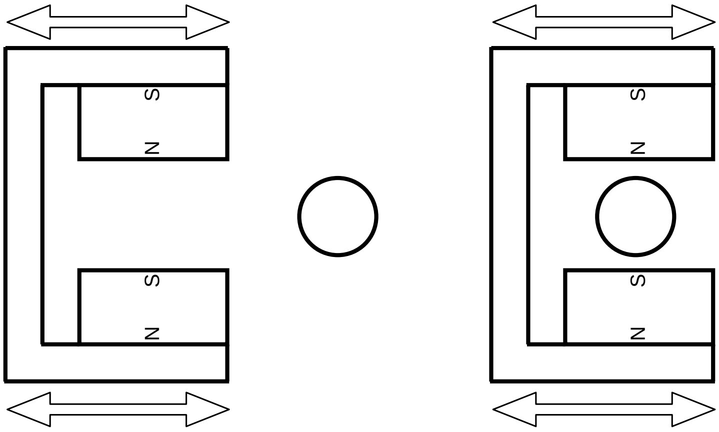

Fig. 4.11 Regulation of magnetic field exposition by positioning of permanent magnets; left – without magnetic field, right – under magnetic field

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. 4.4.

Tab. 4.4 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).

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. 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. 4.4.

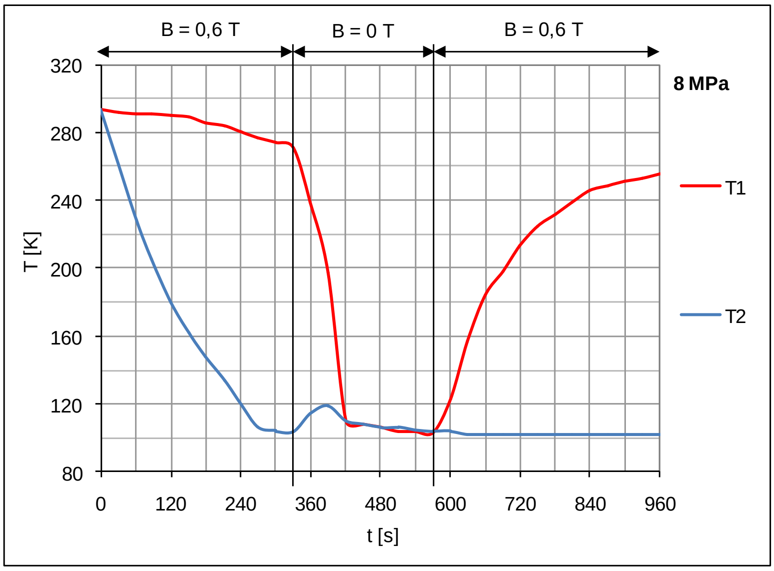

Fig. 4.12 Temperature characteristics of heat pipe with filling pressure 8 MPa

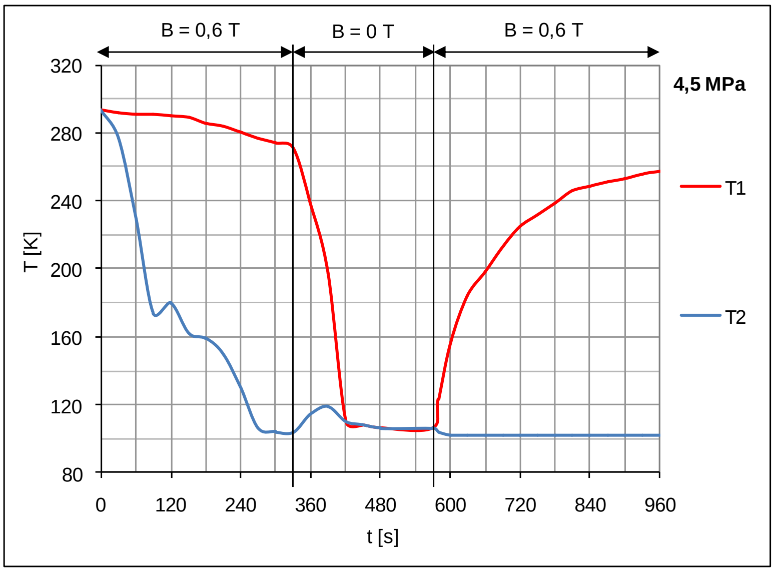

Fig. 4.13 Temperature characteristics of heat pipe with filling pressure 4,5 MPa

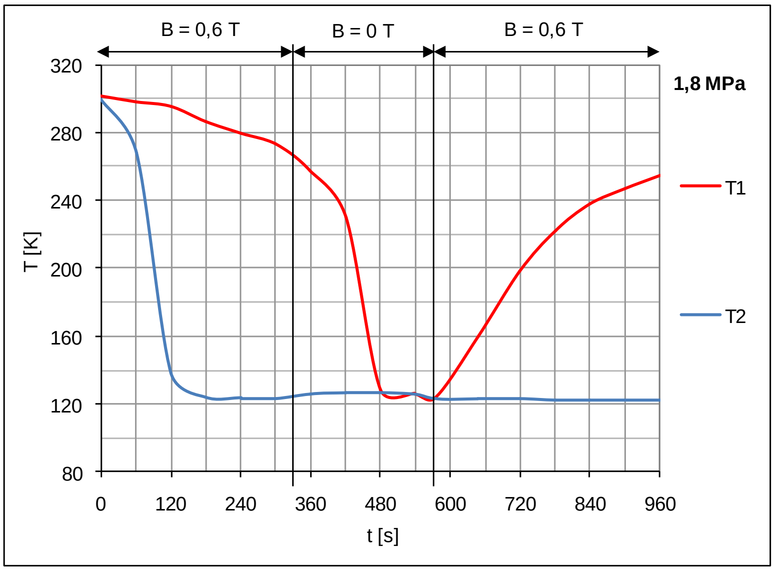

Fig. 4.14 Temperature characteristics of heat pipe with filling pressure 1,8 MPa

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. 4.14. It might be caused by an insufficient fluid inventory negatively affecting the working cycle in the heat pipe.

4.2.4 O_2 Heat Pipe - Wick Type Experiment

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). A standard water heat pipe was modified and refilled with oxygen. See more about installation in the Tab. 4.5 and Fig. 4.15.

Tab. 4.5 Experiment specifications

Parameter	**Value**
Magnetic control method	Magnetic trap
Heat pipe	Wicked (sintered / screen)
Orientation	Variable
Working fluid	Oxygen
Filling pressure	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

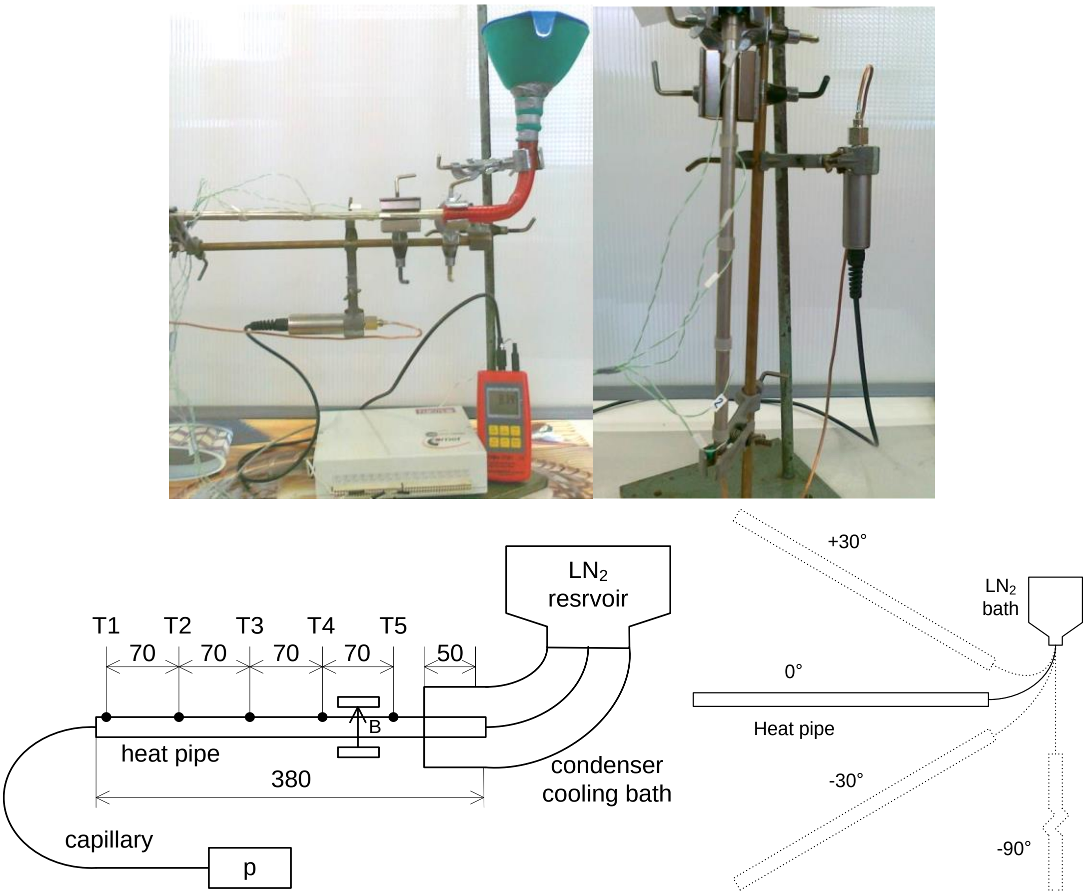

Fig. 4.15 Experimental installation in overview and detail

Two wicked heat pipes were tested in this experiment - sintered heat pipe and screen heat pipe filled with pure oxygen . 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. 4.6).

Tab. 4.6 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

Results and Discussion

Selected temperature characteristics for the screen heat pipe (working fluid quantity 2,06 cm^3, 12,4 MPa) are presented in the Fig. 4.16. 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.

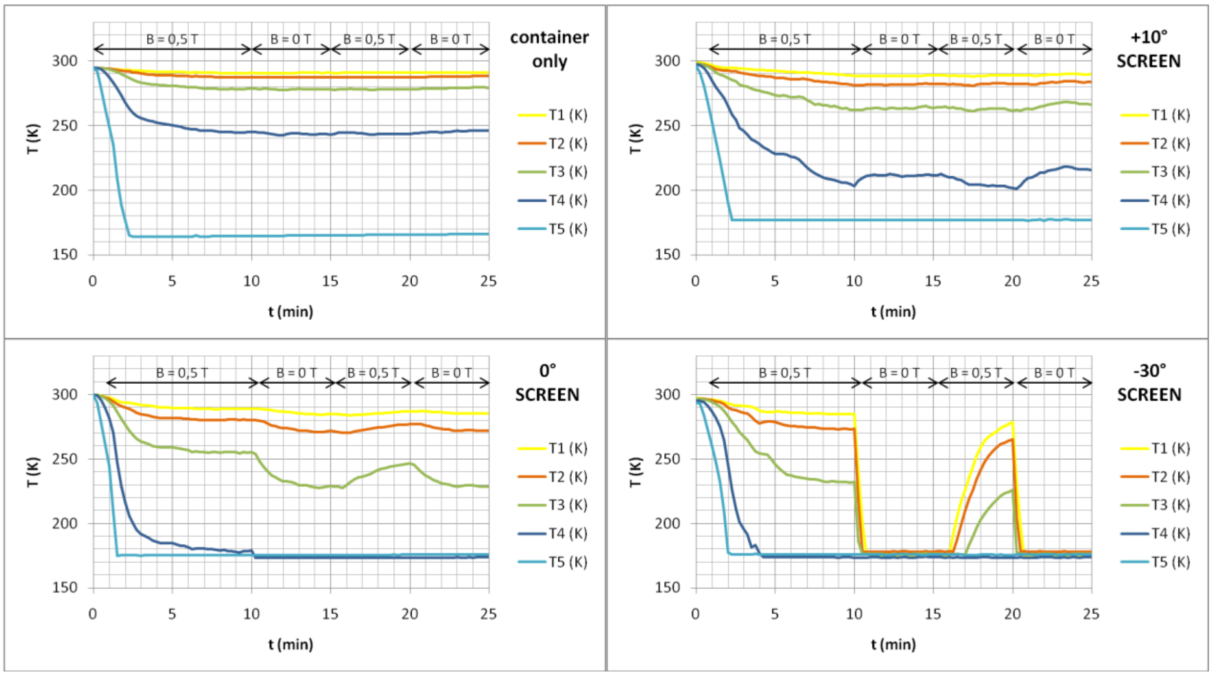

Fig. 4.16 Temperature characteristics of screen heat pipe operating at various tilt angles and of empty container (heat pipe without any working fluid)

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 is presented in the Fig. 4.17. 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.

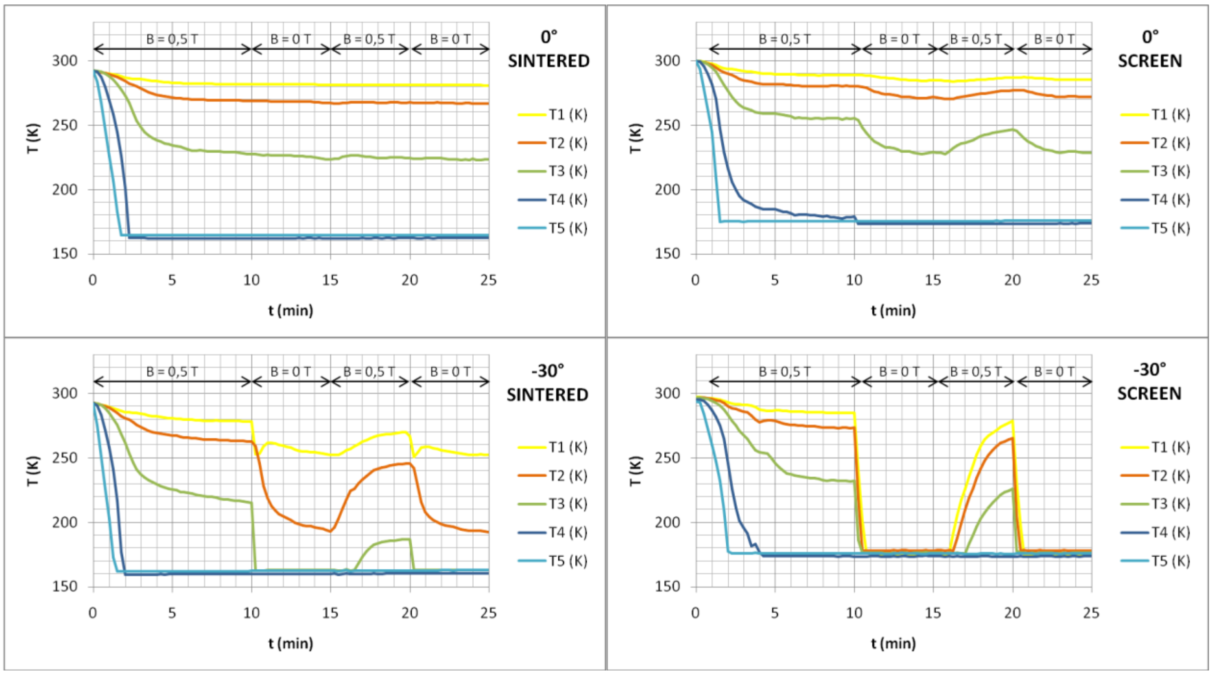

Fig. 4.17 Comparison of sintered and screen heat pipe characteristics

4.3 Magnetic Plug Method Experiments

The Magnetic Plug Method, discussed in the chapter 0, 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.

4.3.1 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 [2]. In this system, there was no external magnetic field source, only the permanent magnet of the plug inside the heat pipe.

Tab. 4.7 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

A schema of the tested gravitational heat pipe and its real form are presented in the Fig. 4.18. 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).

Magnetic 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.

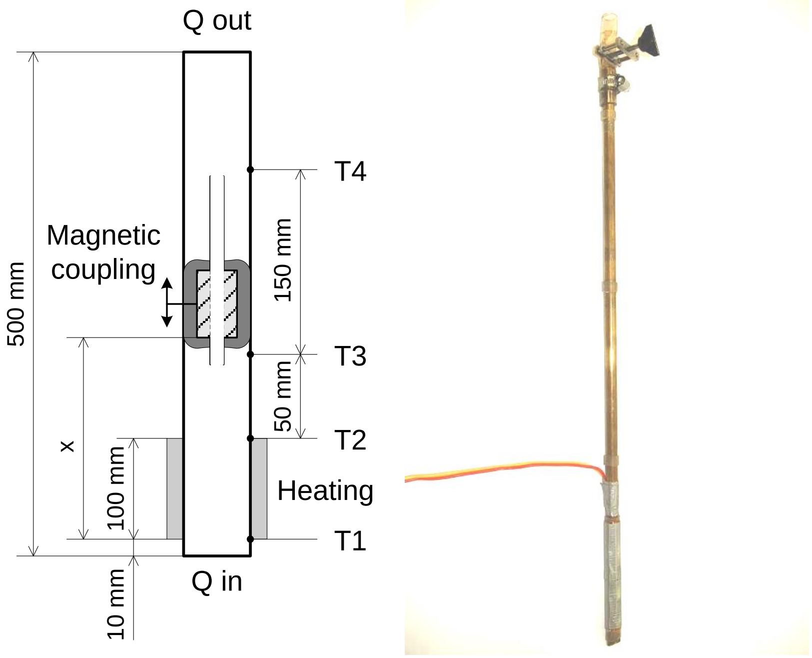

Fig. 4.18 Experimental heat pipe with magnetic plug inside

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. 4.8. 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. 4.8 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

Results and Discussion

The temperature characteristic of the tested heat pipe is presented in the Fig. 4.19. The curves in the figure correspond to the thermocouple points along the heat pipe, as shown in the Fig. 4.18. The position of the plug “x” is marked in the top of the figure.

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. 4.19. 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.

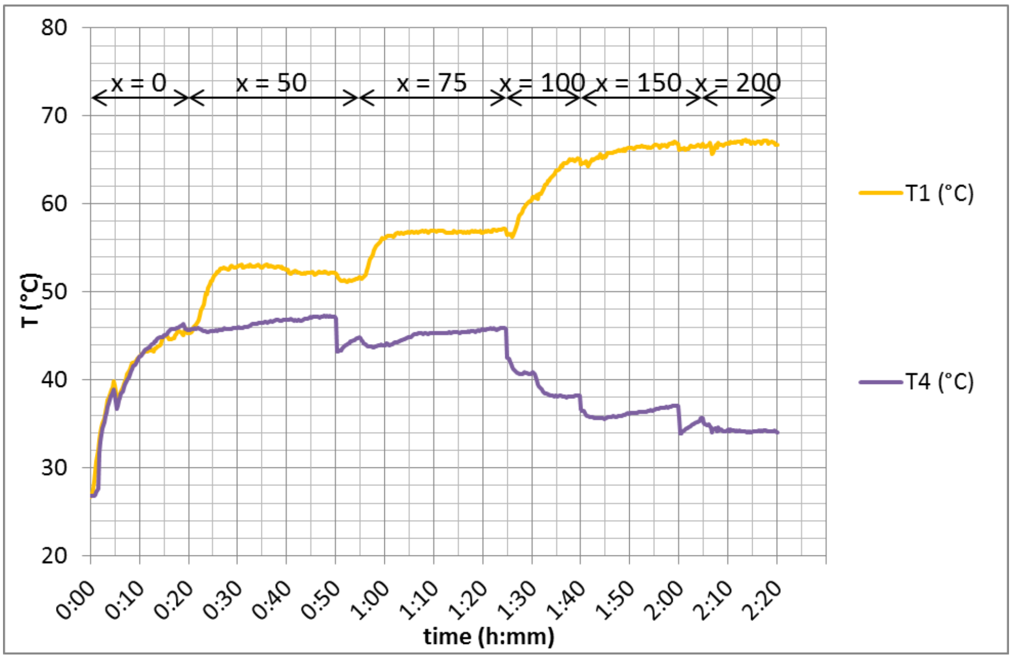

Fig. 4.19 Temperature characteristic of tested heat pipe with magnetic plug in variable position

5 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.

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.

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KUBA, J., CINGROŠ, F., HRON, T.: Interactive exposition demonstrating electromagnetic levitation system and heat transport by heat pipes, Functional model, CTU in Prague, Prague, 2008

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

RESPONSES

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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SUMMARY

In this work we have been ascertaining magnetic field effects on heat transport in heat pipes. We have proposed an alternative approach heat pipes regulation based on an interaction between a fluid contained within heat pipes and a static magnetic field. This method has not been applied in any commercial application yet and also related research activities are very limited. 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.

During this work we have designed and realized several experimental heat pipe systems utilizing magnetic field based regulation. 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 that it was also necessary to adapt or develop some manufacturing technologies and procedures. On the prototypes we have ascertain their behaviors and operation under magnetic field exposition.

We have observed that it is possible to dramatically reduce the effective thermal conductance of a heat pipe and regulate the heat flow by magnetic field exposition. 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 was also possible to create a fluidal seal within the heat pipe. We approved that it is possible to significantly affect heat flow in specially constructed heat pipes by the both proposed approaches - Magnetic Trap Method and Magnetic Plug Method.

RÉSUMÉ

V rámci této práce jsme se zabývali sledováním vlivů magnetického pole na transport tepla v tepelných trubicích. Byl navržen alternativní přístup k regulaci tepelných trubic založené na interakci statického magnetického pole a pracovní náplně tepelných trubic. Tento přístup dosud nebyl aplikován v žádném komerčně dostupném systému a také související výzkumné aktivity v této oblasti jsou omezené. Vypracovány byly dvě základní metody řízení transportu tepla – „Magnetic Trap Method“ a „Magnetic Plug Method“. Obě metody jsou založené na zmíněné interakci magnetického pole a pracovní náplně, obě ale s jiným uspořádáním a konstrukcí systému.

Během této práce navrhli a realizovali několik experimentálních systému tepelných trubic využívajících regulaci pomocí magnetického pole. Komerčně dostupné tepelné trubice nebyly pro naše účely vhodné, proto jsme museli z dostupných komponentů vyrobit vlastní prototypy. K tomu bylo také nutné zvládnout základní postupy a technologii výroby tepelných trubic. Na prototypech jsme pak provedli celou řadu experimentů zkoumajících zmíněné efekty.

Během experimentálního zkoumání jsme pozorovali že při splnění určitých podmínek je možné pomocí magnetického pole výrazně omezit efektivní tepelnou vodivost v některých sledovaných tepelných trubicích. V některých případech bylo možné vytvořit určitou formu bariéry pro transport tepla nebo vytvořit fluidní uzávěr uvnitř tepelné trubice taktéž zamezující transportu tepla. Provedenými experimenty jsme potvrdili, že obě navržené metody, tedy Magnetic Trap Method“ i „Magnetic Plug Method“ jsou schopné výrazně ovlivňovat transport tepla ve vybraných tepelných trubicích.