Project Report
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Heat pipes and its applications

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ABSTRACT

Heat pipes are one of the most effective procedures to transport thermal energy from one point to another, mostly used for cooling. It is based on a combination of conduction and convective heat transfer, what makes it to a complex heat transfer problem. In this report the main working principal and most important possibilities to calculate a heat pipe will be shown.

NOMENCLATURE

A	surface area, m^2
K	constant, -
R	radius, m
Q	energy flux, J/s
d	diameter, m
g	gravity, m/s^2
h	height, m
h_v	enthalpy of vaporization, J
p	pressure, Pa

Greek Symbols

λ	thermal conductivity, W/mK
σ	surface tension, N/mm
ρ	density, kg/m^3
ϑ	surface angle, rad
ν	kinematic viscosity, m^2/s

Subscripts

1	surface 1
2	surface 2
ad	adiabatic transport Zone
c	capillary
cond	condenser
eff	effective
evap	evaporator
g	gas
h	hydrostatic
i	capillary structure
l	liquid
ph	boundary layer at the outer wall
w	wall

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Superscripts

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INTRODUCTION

Heat pipes were developed especially for space applications during the early 60´ by the NASA. One main problem in space applications was to transport the temperature from the inside to the outside, because the heat conduction in a vacuum is very limited. Hence there was a necessity to develop a fast and effective way to transport heat, without having the effect of gravity force. The idea behind is to create a flow field which transports heat energy from one spot to another by means of convection, because convective heat transfer is much faster than heat transfer due to conduction.

Nowadays heat pipes are used in several applications, where one has limited space and the necessity of a high heat flux. Of course it is still in use in space applications, but it is also used in heat transfer systems, cooling of computers, cell phones and cooling of solar collectors.

Especially for micro applications there are micro heat pipes developed as for cooling the kernel of a cell phone down. Due to limited space in personal computers and the growing computational power it was necessary to find a new way to cool the processors down. By means of a heat pipe it is possible to connect the processor cooling unit to a bigger cooling unit fixed at the outside to cart of the energy.

Fig 1: Processor cooling

It is also used at the Alaska pipe line, where you use the low temperature of the ground to cool the transported fluid down.

Fig 2: Alaska pipeline with permafrost ground

The basic idea of heat pipes is based on an evaporation and condensation process. At the hot side, the working fluid is evaporated and at the cool side it condensates again. The transport idea will be explained in the next chapter.

LITERATURE SURVEY

The basic idea behind a heat pipe is the circular process shown.

in Fig. 1.

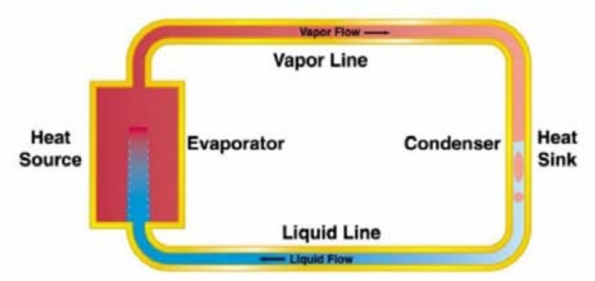

Fig 3: Circular process of a heat pipe

At the heat source the cold liquid is evaporated, the hot vapor flow is afterwards transported to the heat sink where the vapor condensates again and is transported back to the heat source. The problem of this process is the space consumption; hence it was necessary to develop a compacter way to transport the heat energy with the shown process.

The idea of a heat pipe is now to include the complete convective transport in one pipe, where the vapor flow is in the center of the pipe and the liquid flow takes place on the outside of the cylinder.

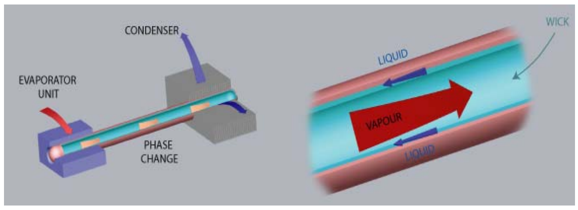

Fig 4: Concept of a heat pipe

Due to different properties of the materials it is necessary to choose the right materials for the given problem.

Figure 5 and Figure 6 show the application areas for different possible liquids.

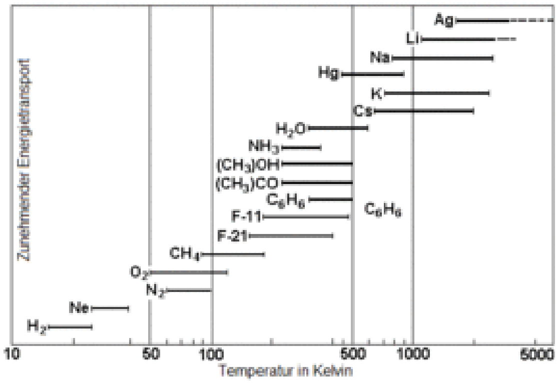

Fig 5: Working fluids of heat pipes

MEDIUM	MELTING PT. (°C)	BOILING PT. AT ATM. PRESSURE (°C)	USEFUL RANGE (°C)
Helium	- 271	- 261	-271 to -269
Nitrogen	- 210	- 196	-203 to -160
Ammonia	- 78	- 33	-60 to 100
Acetone	- 95	57	0 to 120
Methanol	- 98	64	10 to 130
Flutec PP2	- 50	76	10 to 160
Ethanol	- 112	78	0 to 130
Water	0	100	30 to 200
Toluene	- 95	110	50 to 200
Mercury	- 39	361	250 to 650
Sodium	98	892	600 to 1200
Lithium	179	1340	1000 to 1800
Silver	960	2212	1800 to 2300

Fig 6: Working area of the fluids

It also has to be discovered which fluid gets along with which wall material, there are a lot of possibilities well discovered and used:

- Acetone, methanol, water with copper
- Freon with high-grade steel, aluminum
- Ammonia with aluminum, nickel and steel
- Potassium with high-grade steel
- Sodium with high-grade steel, nickel and inconel
- Lithium with niobium, tantalum, tungsten and molybdenum
- Silver with tantalum and tungsten

To have a convective flow of the fluid it is a necessity to generate a pressure difference between the hot and the cold side of the pipe. If there is no gravity, electrical or other field forces appearing the pressure difference is mostly generated by a capillary pressure difference, due to evaporation on the hot side. The capillary pressure can be described by:

$$p_c = \sigma K = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right). \quad [1]$$

Due to this formula one needs a small radius of the capillary which transports the liquid from the cold to the hot side. But a very fine capillary structure causes very high pressure losses due to friction what works again a fast convection. A second problem of a very fine capillary structure is clogging of the capillary. It can occur when a vapor bubble is included in the liquid flow, that this bubble could close a capillary. And one also wants to have a high storage volume for the liquid.

Because of these issues different concepts how to design the capillary are developed, which are shown in Figure 7.

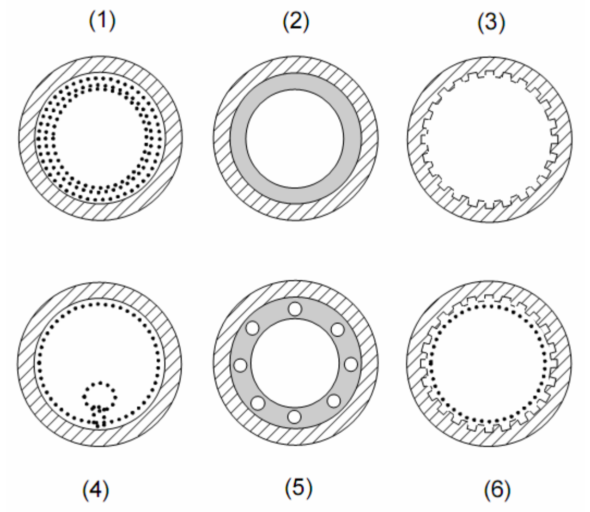

Fig 7: Different structures of the capillary layer

1. Net structure
2. Sinter structure
3. Open channel structure

4-6. Combined structures.

Sinter structures are very small, hence the capillary pressure is very high, but the risk to have bubbles which are closing the capillary is very high.

Open channel structures have very low pressure losses, but there is always the risk that the liquid leaves the channel before it reaches the hot side and gets carried away by the vapor.

Below a qualitative pressure diagram is shown in Figure 8.

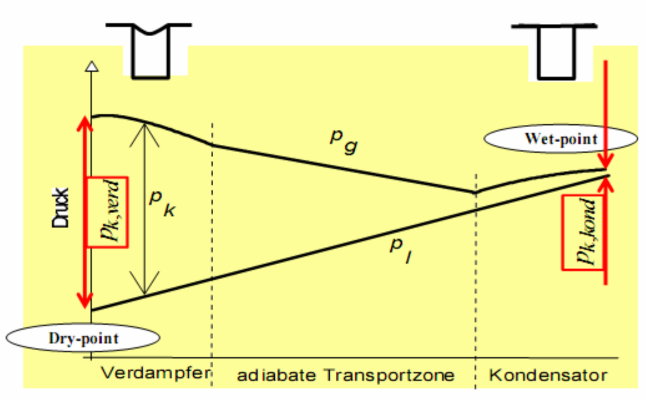

Fig 8: Pressure progression

The pressure as a driving force for the convection process can be shown on the basis of the equation:

[3]

If one wants to calculate a heat pipe, it is necessary to know the capillary pressure at the condenser and at the evaporator, which can be calculated with the formula. If one does not have a round capillary structure, or an open channel the concept of the effective radius of curvature by Chi. There the capillary pressure is described by $p_c = \frac{2\sigma}{R_{eff}} \cos\vartheta$, for example for an open rectangular channel, where R_{eff}=w and ϑ is the contact angle between the fluid and the solid.

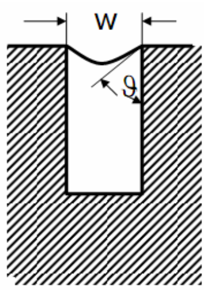

Fig 9: Nomenclature of an open channel

If one wants to find more effective R_{eff} one has to check the literature, there you can find R_{eff} for any geometry.

The pressure losses p_l of the channel can be divided into two parts: ($\Delta p_l = \Delta p_l(l,s) + \Delta p_l(l,I))$ 1. Flow pressure loss and 2. Hydrostatic pressure loss. The 2nd part is only a factor when there a gravity, or any other force field, exists.

The calculations of the pressure losses are based on a effective length l_{eff} as shown in Fig. 10. One uses ½ of the evaporator length and of the condenser length, because the mass flow decreases in both ends of the heat pipe nearly linearly.

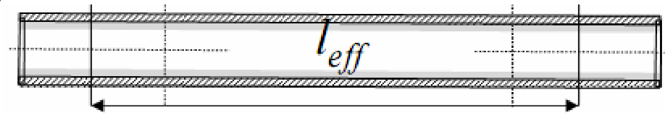

Fig 10: Definition of the effective length

$$l_{eff} = \frac{1}{2} l_{evap} + l_{ad} + \frac{1}{2} l_{cond} \qquad [3]$$

Usually it has to be taken care that the flow is not becoming turbulent, due to the high pressure losses of turbulent flows, there are several theories available to calculate the losses. Here will only two examples be shown:

1: laminar flow in capillary grooves, Hagen-Poisseulle law:

[4]

2: laminar flow in sinter structures, or net structures, Darcy law:

$$\Delta p_{l,s} = \left(\frac{\nu_l}{K A_l \Delta l_v} \right) Q l_{eff} \qquad [5]$$

The hydrostatic pressure loss is given by:

[6]

Pressure losses in the gas flow have to be divided into three sections: 1. Pressure loss in the evaporator $\Delta p_{g,evap}$ 2. Pressure loss in the condenser $\Delta p_{g,cond}$ 3. Pressure loss in $\Delta p_{g,ad}$.

the adiabatic transport zone

$$\Delta p_g = \Delta p_{g,evap} + \Delta p_{g,cond} + \Delta p_{g,ad} \qquad [7]$$

There are several theories available how to describe these losses based on laws as shown above (Hagen-Poisseulle, Darcy), for a laminar and turbulent flows. They will not be shown in this report.

It also has to be explained, why this way of heat transfer is so effective. Basically it is because of the low thermal resistance due to the convective flow, as mentioned before. This low thermal resistance is due to small length of heat transfer through solid walls as shown in Fig. … The entire problem can be reduced into a very small heat transfer problem.

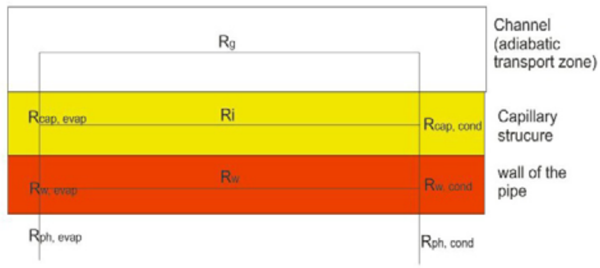

Fig 11: Thermal resistances in a heat pipe

There are several possibilities to transport energy through the heat pipe structure. Due to length properties nearly zero energy is transported from the hot side to the cold side by means of the pipe R_w and the capillary structure R_{cap} due to the high heat resistance (Table 1). It is also possible to neglect the resistance of the flow R_g, because it is very low.

Magnitude of thermal resistancy	K/W
$R_{w,evap}$, $R_{w,cond}$	10^{-1}
$R_{cap,\,evap}$, $R_{cap,\,cond}$	10^{+1}
$R_{ph,\,evap}$, $R_{ph,\,cond}$	10^{-5}
R_g	10^{-8}
R_i	10^{+4}
R_w	10^{+2}

Hence the entire thermal resistance can be described as:

$$R_{HP} = R_{w,evap} + R_{cap,evap} + R_{w,cond} + R_{cap,cond} \qquad [8]$$

The thermal resistance of the condenser and evaporator is very similar, the formula is based on the basic heat transfer formula for cylinders:

$$R_{k,evap(cond)} = \frac{\ln\left(\frac{d_{k,o}}{d_{k,i}}\right)}{2\pi l_{evap(cond)} \lambda_{eff}}, \qquad [9]$$

where λ_{eff} is the effective thermal conductivity, which varies for different structures. For example for a sinter structure:

[10]

To prosecute a heat pipe one has to take several limits into account, as shown in Fig. 12.

Melting temperature: One cannot use a heat pipe below the melting temperature of the fluid.

- Viscosity limit: The risk at low temperatures and low pressures, that the viscosity of the fluid is to high for being transported

- Speed of sound limit: It is important for high temperature heat pipes, where the vapor could possibly reach the speed of sound when leaving the evaporator
- Capillary force limit: When the capillary force is not satisfying the necessary force to transport the liquid
- Interaction limit: This limit is connected with open channels, where the vapor can be carried away by the vapor, due to high velocity differences
- Boiling limit: The liquid builds bubbles which close the capillary structures, is not a problem for open channel structures
- Critical temperature

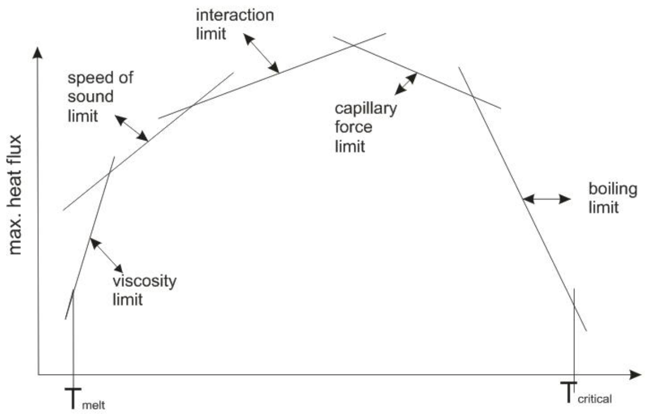

Fig 12: Usage limitations of a heat pipe

To judge about the efficiency of a heat pipe the Merit-number Me is introduced:

[11]

This number shows that the main influence factors for the heat pipe are the surface tension, evaporation enthalpy and the viscosity of the liquid, as higher Me as better is the heat pipe.

PROJECT DESCRIPTION

By means of knowledge about the theory of heat pipes, one is now able to carry out a basic calculation of a heat pipe. Beginning with a definition of the problem, including the temperature difference and the heat flow which has to be transported, one can define all the demands on a heat pipe.

Going through all the steps by an example (processor cooling) shows the major steps:

- Define the temperature working range (0°C-100°C).
- Choose a fluid based on Fig. 6 (Ammonia).
- Choose a material which works with Ammonia (aluminum, nickel, steel), depends also on economic or weight issues.
- Choose a structure of the capillary as shown in Fig. 7 (Open channel)
- Calculate the capillary pressure with $p_k = \frac{2\sigma}{R_{eff}} \cos\vartheta$,
- Estimate the heat resistance by formula [8]
- Estimate the necessary mass flow in the pipe and calculate its diameter
- Check if one does not reach any of the main limitations

Connected to the course heat and mass transfer there several different phenomena involved which are discussed in the course.
It is possible to define the complete process into a anisotropy heat transfer problem.
Furthermore one has mass transfer by vaporization and condensation through porous material (capillary) and also mass transport in porous material is involved, when the liquid flows through sintered structures. About all of these phenomena one could carry out a complete project, but here only the main working principal should be shown.

CONCLUSIONS

All in all it is necessary to understand all the basic theories of heat and mass transfer to understand the working principle of a heat pipe. On a first look a heat pipe seems to be a very easy tool to transport energy, but if one looks closer, it is a very complex heat and mass transfer process which takes place in a heat pipe. First of all one has convective heat transfer in the adiabatic transport range, and one has convection through porous materials also. The second major point is mass transfer due to vaporization and condensation, also through porous media. Furthermore there are capillary effects, pressure effects and heat conduction effects involved, which creates a complex structure of heat transfer, where a lot of knowledge is involved. And all of these points can be treated as a own problem, from this follows that a complete understanding of all involved processes needs more time and space than it is available for this project report.

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