Project Report
MVK160 Heat and Mass Transfer
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Heat Pipe, selection of working fluid

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Abstract

Heat pipes are common in many application fields for example cooling of electronics. The design of a heat pipe is rather complex with many things to consider. In this project the focus is the get knowledge about who to select the working fluid to be used.

Introduction

"A heat-transfer device consisting of a sealed metal tube with an inner lining of wicklike capillary material and a small amount of fluid in a partial vacuum; heat is absorbed at one end by vaporization of the fluid and is released at the other end by condensation of the vapor." *Definition by McGraw-Hill Dictionary of Scientific and Technical Terms.*

Heat Pipes are used in many applications all from cooling of the CPU in a computer, space application, energy storage for some solar thermal applications, air conditions etc. Micro heat pipes with diameters small as $100 \mu m$, high temperature heat pipes with silver as working fluid(temperature up to 2300°C) and low temperature heat pipes with helium(temperature down to -271°C). There are many different kinds of heat pipes but the working principle is similar. The design of a standard heat pipe are illustrated in figure 1. The liquid is evaporated at the hot end then transfered to the cool end and condensed to liquid again. The transfer back to the hot end is made by a capillary force with positive/negative contributions from gravity. The capillary force makes it possible to transfer liquid against the gravity field.

When you design a heat pipe there are three main selection to do, working fluid, case material and wick. These are closely linked to each other to achieve best conditions. In this project the main purpose is to select the working fluid but case and wick is also briefly described to get better knowledge of a heat pipe.

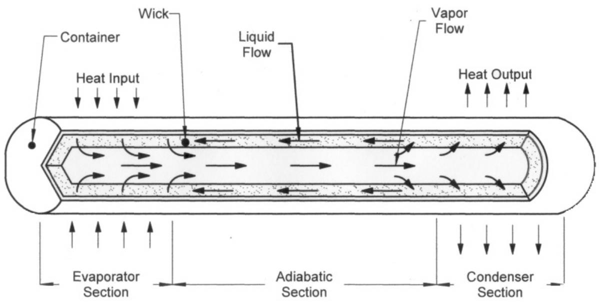

Figure 1: Standard Heat Pipe

Problem Statement

Selection of working fluid in a heat pipe

Theory

Working fluid

Selection of working fluid is directly linked to the properties of the fluid. The properties is going to both affect the ability to transfer heat and the comparability with the case and wick material. Below is some things to consider when you choose the working fluid.

- Compatibility with wick and wall materials

- Good thermal stability
- Wettability of wick and wall materials
- Vapor pressures not too high or low over the operating temperature range
- High latent heat
- High thermal conductivity
- Low liquid and vapor viscosities
- High surface tension

Table 1: Working fluids

Medium	Melting point (°C)	Boiling point at atmos. press. (°C)	Useful range (°C)
Helium	−271	−261	−271 to −269
Nitrogen	−210	−196	−203 to −160
Ammonia	−78	−33	−60 to 100
Pentane	−130	28	−20 to 120
Acetone	−95	57	0 to 120
Methanol	−98	64	10 to 130
Flutec PP2[1]	−50	76	10 to 160
Ethanol	−112	78	0 to 130
Heptane	−90	98	0 to 150
Water	0	100	30 to 200
Toluene	−95	110	50 to 200
Flutec PP9[1]	−70	160	0 to 225
Thermex[2]	12	257	150 to 350
Mercury	−39	361	250 to 650
Caesium	29	670	450 to 900
Potassium	62	774	500 to 1000
Sodium	98	892	600 to 1200
Lithium	179	1340	1000 to 1800
Silver	960	2212	1800 to 2300

Operation Limits

To be able to choose right material, it is important to understand the operation limitations. Figure 2 show the different limitations to be considered. The limitations must be fulfilled both during design conditions and during start up. The figure is for a specific condition and and going to change depending on fluid and wick.

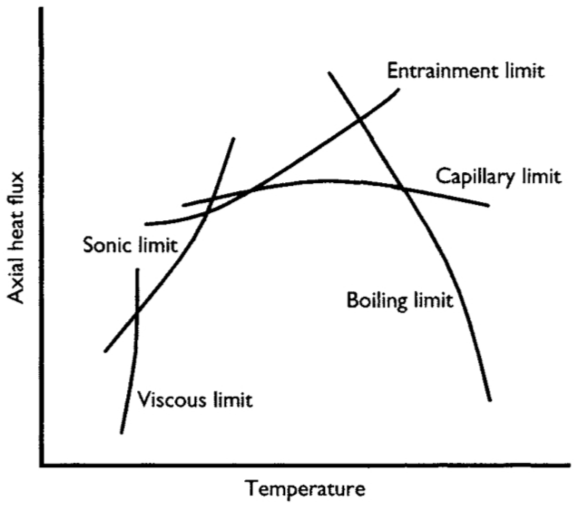

Figure 2: Operation Limitations

The viscous limit

At very low temperature the vapor pressure difference between the closed end of the evaporator and the closed end of the condenser may be very small. Viscous forces can then be dominant and limit the operation of the heat pipe. Low temperature in the working fluid is most common at startup and makes the possibility to reach the viscous limit most possible at startup. Expression below is a criterion for when the viscous limit has to be considered

$$\frac{\Delta P_v}{P_v} < 0.1 \quad (1)$$

derived by Dunn and Reay. The concern of this limit depend on the temperature and is of little important in design of heat pipes for room temperature applications according to Handbook of heat transfer.

The sonic limit

The vapor velocity may reach sonic values. As velocity approaching sonic there is going to compressibility effects that affect pressure. It makes it therefore desirable to have maximum velocity below sonic, which give the maximum heat flux as equation below.

$$\dot{q}_s = \rho_v L \sqrt{\frac{\gamma_v R T_v}{2(\gamma_v + 1)}} \tag{2}$$

The entrainment limit

The liquid and vapor flows in different directions in the heat pipe. When the vapor reach the condenser it is going to affect the liquid in the inside of the wick. If the shear force because of the vapor is big compared to the surface tension in the liquid there is likelihood of entrainment of liquid drops in the condenser. The Weber number is the ratio between inertial vapor forces and liquid surface tension fores and is defined as,

$$We = \frac{\rho_v v_v^2 z}{2\pi\sigma_l} \tag{3}$$

where index v relate to vapor, σ_l is the surface tension and z is a dimensions characterizing the vapor-liquid surface. In a wicked heat pipe, z is related to the wick spacing. Experiment have proved that entrainment may occur when Weber number is of order of one. The maximum velocity because of entrainment is then

$$v_c = \sqrt{\frac{2\pi\sigma_l}{\rho_v z}} \tag{4}$$

which do that the maximum heat flux is

$$\dot{q} = \rho_v L v = \sqrt{\frac{2\pi\rho_v L^2 \sigma_l}{z}} \tag{5}$$

From equation 5 it can be seen that just some of the properties depend on the working fluid. These properties can be used to form a expression of entrainment for the working fluids.

$$\rho_v L^2 \sigma_l \tag{6}$$

The capillary limit

$$\Delta P_c \leq \Delta P_l + \Delta P_v + \Delta P_g \tag{7}$$

where indexes c,l,v,g refers to capillary, liquid, vapor and gravity. If this condition is not met, the wick will dry out in the evaporator region and the heat pipe will not operate. An expression for the maximum flow rate may be obtained if it is assumed that

- the liquid properties do not vary along the pipe
- the wick is uniform along the pipe
- the pressure drop due to vapor flow can be neglected

$$\dot{m}_{max} = \left[\frac{\rho_l \sigma_l}{\mu_l}\right] \left[\frac{KA}{l}\right] \left[\frac{2}{r_e} - \frac{\rho_l g l}{\sigma_l} sin(\phi)\right] \tag{8}$$

The maximum allowed heat flux can den be specified as

$$\dot{Q} = \dot{m}_{max} L = \left[\frac{\rho_l \sigma_l L}{\mu_l}\right] \left[\frac{KA}{l}\right] \left[\frac{2}{r_e} - \frac{\rho_l g l}{\sigma_l} sin(\phi)\right] \tag{9}$$

The first group depends only on the properties of the working fluid and is called Merit number.

$$M = \frac{\rho_l \sigma_l L}{\mu_l} \tag{10}$$

The capillary limit is the above limit of the heat flux for a big part of the temperature region. The Merit number can therefore be used to evaluate the performance of the heat pipe depending on working fluid.

The boiling limit

At high temperature and heat flux there is going to be nucleate boiling in the wick of the evaporator. Vapor may then block the liquid to be supplied to all parts of the evaporator. It is desirable to reduce the chance of nucleation. A working fluid degree of superheat to cause nucleation is given by

$$\Delta T = \frac{3.06 \sigma_l T_{sat}}{\rho_v L \delta} \tag{11}$$

where δ is the thermal layer thickness and is taken as a representative value of $25\mu m$ to compare working fluids. It is desirable to have a working fluid with high value of superheat, ΔT.The expression comes from analysis by Hsu.

Compatibility with wick and case materials

Compatibility between the working fluid and material of the wick is important for the heat pipe to work work good and have a desired service life. Problem because of non compatibility are decreased performance,failure or corrosion. Decomposition of the working fluid can lead to corrosion and formation of non condensible gases through chemical reactions between the working fluid and material, can cause problem with the operation of the heat pipe. Compatibility test by Basiulis and Busse have been made which the result is showed in table 2.

Table 2: Compatibility data

Wick material	Working fluids					
	Water	Acetone	Ammonia	Methanol	Dow-A	Dow-E
Copper	RU	RU	NU	RU	RU	RU
Aluminium	GNC	RL	RU	NR	UK	NR
Stainless steel	GNT	PC	RU	GNT	RU	RU
Nickel	PC	PC	RU	RL	RU	RL
Refrasil fibre	RU	RU	RU	RU	RU	RU

RU, recommended by past successful usage; RL, recommended by literature; PC, probably compatible; NR, not recommended; UK, unknown; GNC, generation of gas at all temperatures; GNT, generation of gas at elevated temperatures, when oxide present.

Case material

The case is the heat pipes connection to the outside environment. Heat has to be able to transfer through the case to and from the working fluid in the evaporator and condenser. At the same time it is desirable to have no heat transfer in the adiabatic area and to maintain pressure differential across the walls. Selection of the case material depends on the following factors

- Compatibility (both with working fluid and the external environment)
- Strength-to-weight ratio
- Thermal conductivity
- Ease of fabrication, including weldability, machineability and ductility.

Wick material

The main functions of the wick is to generate capillary pressure and to distribute the liquid around the evaporator area. If the heat pipe has to return the liquid over a distance against the gravity field there is big requirement of the wick. Therefor there are many different forms of wick depending of the heat pipe and it's location to be able to satisfy the two main functions. Some forms of wicks are showed in figure below.

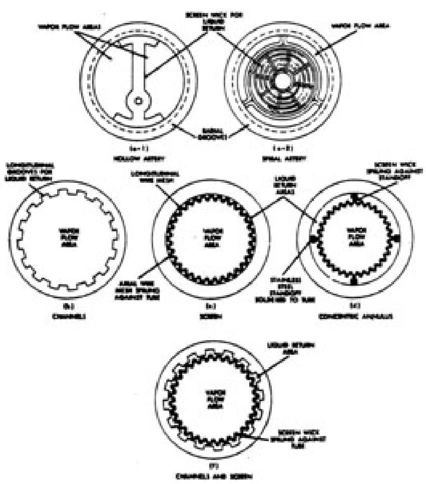

Figure 3: Wick Structure

Problem description

A heat pipe with minimum heat transport of 25 W is going to be used for cooling electronic components. Vapor temperatures are in region 40°C - 120°C. The inner diameter is 3 mm and wick and case is made of copper. Select a working fluid.

Result

Working fluids that can operate in the specified temperature range and are compatible with copper according to the known theory is acetone, methanol and water.

Satisfaction of operation limits

The operation temperature is not considered for very low temperatures and therefore you don't have to consider the viscous limit. The four remaining limits are sonic limit, entrainment limit, boiling limit and capillary limit.

Sonic Limit

The sonic limitations has to be considered at the minimum temperature, 30°C. Equation 2 is used to evaluate the fluids. The heat capacity ratio and gas constant for the fluids are in table below

Table 3: Fluid Properties

	λ	R[J/kgK]
Acetone	1.11	150
Methanol	1.26	390
Water	1.32	460

This give that the maximum heat flux because of the sonic limit is

Table 4: Sonic Limit

	Heat flux
Acetone	6.3 kW/cm^2
Methanol	$11.3kW/cm^2$
Water	$2.4kW/cm^2$

The heat pipe have a circular cross section and are required to transport minimum of 25 W $\Rightarrow$ $25/0.15^2\pi W/cm^2 = 0.35kW/cm^2$. Comparison with the sonic limitations, you can see that limit is not going to be reach for the fluids.

Boiling limit

ΔT is evaluated at 120 °C, as the lowest permissible degree of superheat will occur at the maximum operating temperature.

Table 5: Boiling Limit

	ΔT
Acetone	0.11K
Methanol	0.09K
Water	1.07K

Entrainment Limit

The entrainment limit is evaluated for the temperature interval and are showed in figure 4. Values for the fluids are taken from appendix.

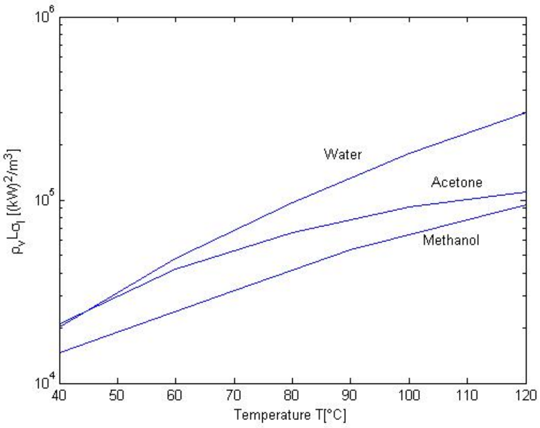

Figure 4: Entrainment Limit

Capillary Limit

The performance of the working fluids can be evaluated by the Merit Number. The Merit number for the different fluids are showed in figure below. Values for the fluids are taken from appendix.

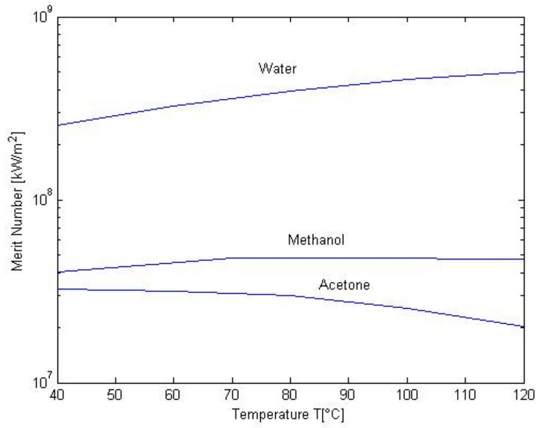

Figure 5: Capillary Limit

Conclusions

The three working fluids have been evaluated with regard to the operation limitations. Water are best for most of the limits compared to methanol and acetone. Especially the capillary limit that is a measurement for the performance is water superior. The choice is therefore water as working fluid.

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Appendix

Heptane

Temp °C	Latent heat kJ/kg	Liquid density kg/m³	Vapour density kg/m³	Liquid thermal conductivity W/m °C	Liquid viscos. cP	Vapour viscos. cP × 10²	Vapour press. Bar	Vapour specific heat kJ/kg °C	Liquid surface tension N/m × 10²
−20	384.0	715.5	0.01	0.143	0.69	0.57	0.01	0.83	2.42
0	372.6	699.0	0.17	0.141	0.53	0.60	0.02	0.87	2.21
20	362.2	683.0	0.49	0.140	0.43	0.63	0.08	0.92	2.01
40	351.8	667.0	0.97	0.139	0.34	0.66	0.20	0.97	1.81
60	341.5	649.0	1.45	0.137	0.29	0.70	0.32	1.02	1.62
80	331.2	631.0	2.31	0.135	0.24	0.74	0.62	1.05	1.43
100	319.6	612.0	3.71	0.133	0.21	0.77	1.10	1.09	1.28
120	305.0	592.0	6.08	0.132	0.18	0.82	1.85	1.16	1.10

Water

Temp °C	Latent heat kJ/kg	Liquid density kg/m³	Vapour density kg/m³	Liquid thermal conductivity W/m °C	Liquid viscos. cP	Vapour viscos. cP × 10²	Vapour press. Bar	Vapour specific heat kJ/kg °C	Liquid surface tension N/m × 10²
20	2448	998.2	0.02	0.603	1.00	0.96	0.02	1.81	7.28
40	2402	992.3	0.05	0.630	0.65	1.04	0.07	1.89	6.96
60	2359	983.0	0.13	0.649	0.47	1.12	0.20	1.91	6.62
80	2309	972.0	0.29	0.668	0.36	1.19	0.47	1.95	6.26
100	2258	958.0	0.60	0.680	0.28	1.27	1.01	2.01	5.89
120	2200	945.0	1.12	0.682	0.23	1.34	2.02	2.09	5.50
140	2139	928.0	1.99	0.683	0.20	1.41	3.90	2.21	5.06
160	2074	909.0	3.27	0.679	0.17	1.49	6.44	2.38	4.66
180	2003	888.0	5.16	0.669	0.15	1.57	10.04	2.62	4.29
200	1967	865.0	7.87	0.659	0.14	1.65	16.19	2.91	3.89

Acetone

Temp °C	Latent heat kJ/kg	Liquid density kg/m³	Vapour density kg/m³	Liquid thermal conductivity W/m °C	Liquid viscos. cP	Vapour viscos. cP × 10²	Vapour press. Bar	Vapour specific heat kJ/kg °C	Liquid surface tension N/m × 10²
−40	660.0	860.0	0.03	0.200	0.800	0.68	0.01	2.00	3.10
−20	615.6	845.0	0.10	0.189	0.500	0.73	0.03	2.06	2.76
0	564.0	812.0	0.26	0.183	0.395	0.78	0.10	2.11	2.62
20	552.0	790.0	0.64	0.181	0.323	0.82	0.27	2.16	2.37
40	536.0	768.0	1.05	0.175	0.269	0.86	0.60	2.22	2.12
60	517.0	744.0	2.37	0.168	0.226	0.90	1.15	2.28	1.86
80	495.0	719.0	4.30	0.160	0.192	0.95	2.15	2.34	1.62
100	472.0	689.6	6.94	0.148	0.170	0.98	4.43	2.39	1.34
120	426.1	660.3	11.02	0.135	0.148	0.99	6.70	2.45	1.07
140	394.4	631.8	18.61	0.126	0.132	1.03	10.49	2.50	0.81

Methanol

Temp °C	Latent heat kJ/kg	Liquid density kg/m³	Vapour density kg/m³	Liquid thermal conductivity W/m °C	Liquid viscos. cP	Vapour viscos. cP × 10²	Vapour press. Bar	Vapour specific heat kJ/kg °C	Liquid surface tension N/m × 10²
−50	1194	843.5	0.01	0.210	1.700	0.72	0.01	1.20	3.26
−30	1187	833.5	0.01	0.208	1.300	0.78	0.02	1.27	2.95
−10	1182	818.7	0.04	0.206	0.945	0.85	0.04	1.34	2.63
10	1175	800.5	0.12	0.204	0.701	0.91	0.10	1.40	2.36
30	1155	782.0	0.31	0.203	0.521	0.98	0.25	1.47	2.18
50	1125	764.1	0.77	0.202	0.399	1.04	0.55	1.54	2.01
70	1085	746.2	1.47	0.201	0.314	1.11	1.31	1.61	1.85
90	1035	724.4	3.01	0.199	0.259	1.19	2.69	1.79	1.66
110	980	703.6	5.64	0.197	0.211	1.26	4.98	1.92	1.46
130	920	685.2	9.81	0.195	0.166	1.31	7.86	1.92	1.25
150	850	653.2	15.90	0.193	0.138	1.38	8.94	1.92	1.04