MATHEMATICAL CALCULATION OF TOTAL HEAT POWER OF THE SODIUM HEAT PIPE

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Abstract

Article deal about heat pipe, their basic principles and operating limits. High temperature heat pipes are being evaluated for use in energy conversion applications such as fuel cells, gas turbine re-combustors, and Stirling cycle heat sources, with the resurgence of space nuclear power, additional applications include reactor heat removal elements and radiator elements. In the temperature range between 500 and 1000 °C, heat pipes can offer the favourable features of passive, reliable operation, effective thermal coupling between non-contacting fluid streams, and modest cost. Long operating life and reliable performance are critical requirements for these applications.

Key words

Heat pipe, sodium, heat power, heat transfer limitations, mathematical calculation

Introduction

The heat pipe is a vapor-liquid phase change device that transfers heat from evaporator to the condensator using capillary forces generated by a wick or porous material and a working fluid. Capillary-driven two-phase systems offer significant advantages over traditional single-phase systems. The best known capillary-driven two-phase system is the heat pipe, where a schematic of conventional heat pipe is shown in Fig. 1. Heat pipes are passive devices that transport heat over relatively long distances via the latent heat of vaporization of a working fluid. As shown, a heat pipe generally has three sections: an evaporator section, an adiabatic section, and a condenser section.

Due to the two-phase characteristic, the heat pipe is deal for transferring heat over long distances with a very small temperature drop and for creating a nearly isothermal surface for temperature stabilization. The amount of heat that can be transported through the use of latent heat is typically several orders of magnitude greater than transported by sensible heat for a geometrically equivalent system. Additionally, no mechanical pumping systems are required due to the capillary-driven working fluids. Given the wide range of operating temperatures for working fluids, the high efficiencies, the low relative weights, and the absence of external pumps in heat pipes, these systems are seen as attractive options in a wide range of heat transfer applications.

Theoretically, heat pipe operation is possible at any temperature between the triple state and the critical point of the working fluid utilized, albeit at significantly reduced transport capabilities near the two extremes due to the fluid property characteristic of surface tension and viscosity.

Each heat pipe application has a temperature range in which the heat pipe is intended to operate. Therefore, the working fluid must be chosen to take into account this operating temperature, but also its chemical compatibility with the container and wick materials [2].

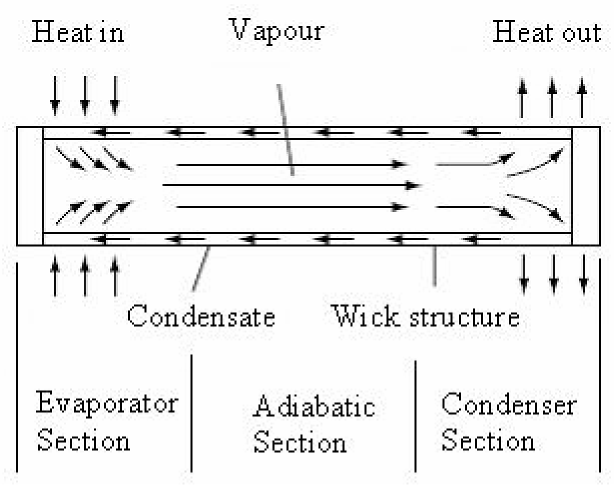

Fig. 1 *Wick heat pipe*

Heat pipe construction

The major components of a heat pipe are a sealed container, a wick structure, and a working fluid. The wick structure is placed on the inner surface of the heat pipe wall and is saturated with the liquid working and provides the structure to develop the capillary action for liquid returning from the condenser to the evaporator. Return of the liquid to the evaporator from the condenser is provided by wick structure. Pressure difference drives the liquid from the condenser through the wick structure to the evaporator region, thus allowing the overall process to be continuous.

Wick structure

The wick structure and working fluid generate the capillary forces required to pump liquid from the condenser to the evaporator and keep liquid evenly distributed in the wicking material. Heat pipe wicks can be classified as either homogeneous wicks or composite wicks. Homogeneous wicks are composed of a single material and configuration. The most common types of homogeneous wicks include wrapped screen, sintered metal, axial groove, annular, crescent, and arterial. Composite wicks are composed of two or more materials and configurations. The most common types of composite wicks include variable screen mesh, screen-covered groove, screen slab with grooves, and screen tunnel with grooves. Regardless of the wick configuration, the desired material properties and structural characteristics of heat pipe wick structures are a high thermal conductivity, high wick porosity, small capillary radius, and high wick permeability [1].

Working fluid

The working fluid must have good thermal stability properties at the specified operational temperature and pressure. Working fluid must have high wettability, surface tension and other desirable thermo-physical properties include a high liquid thermal conductivity, high latent heat of vaporization, low liquid viscosity, and a low vapor viscosity. Therefore, the working fluid must be chosen to take into account this operating temperature, but also its chemical compatibility with the container and wick materials.

Heat transport limitation

Heat pipes undergo various heat transfer limitations depending on the working fluid, the wick structure, the dimensions of the heat pipe, and the heat pipe operational temperature.

Viscous limitation

The viscous limit occurs at low operating temperatures, where the saturation vapor pressure may be of the same order of magnitude as the pressure drop required to drive the vapor flow in the heat pipe. This results in an insufficient pressure available to drive the vapor. The viscous limit is sometimes called the vapor pressure limit.

$$Q_{vp} = \frac{\pi . r_v^4 . h_{fg} . \rho_{v,e} . P_{v,e}}{12 . \mu_{v,e} . l_{eff}} \text{ [3].} \tag{1}$$

Sonic limitation

The sonic limit is due to the fact that at low vapor densities, the corresponding mass flow rate in the heat pipe may result in very high vapor velocities, and the occurrence of choked flow in the vapor passage may be possible.

$$Q_s = 0{,}474 . A_v . h_{fg} . (\rho_v . P_v)^{0{,}5} \text{ [3].} \tag{2}$$

Entrainment limitation

The entrainment limit refers to the case of high shear forces developed as the vapor passes in the counterflow direction over the liquid saturated wick, where the liquid may be entrained by the vapor and returned to the condenser. This results in insufficient liquid flow of the wick structure.

$$Q_e = A_v . h_{fg} . \left(\frac{\rho_v . \delta_l}{2 . r_{c,ave}} \right)^{0.5} \text{ [3].} \tag{3}$$

Capillary limitation

The capillary limit relates to the fundamental phenomenon governing heat pipe operation which is development of capillary pressure differences across the liquid-vapour interfaces in the evaporator and condenser. When the driving capillary pressure is insufficient to provide adequate liquid flow from the condenser to the evaporator, dryout of the evaporator wick will occur.

$$\dot{Q}_c = \frac{\sigma_l . \rho_l . h_{fg}}{\mu_l} . \frac{K . A_v}{l_{ef}} . \left(\frac{2}{r_{c,e}} - \frac{\rho_l . g . l_t . \cos \Psi}{\sigma_l} \right) \text{ [3].} \tag{4}$$

Boiling limitation

The boiling limit occurs when the applied evaporator heat flux is sufficient to cause nucleate boiling in the evaporator wick. This creates vapor bubbles that partially block the liquid return and can lead to evaporator wick dryout. The boiling limit is sometimes referred to as the heat flux limit.

$$\dot{Q}_b = \frac{4\pi . l_{eff} . \lambda_{ef} . T_v . \sigma_v}{h_{fg} . \rho_v . \ln \frac{r_i}{r_e}} . \left(\frac{1}{r_n} - \frac{1}{r_{c,e}} \right) \text{ [3].} \tag{5}$$

Experiment

The heat transport limitation equations in previous paragraph are equations to define of total heat power of heat pipe. The heat pipe power is depending from operating temperature. For solution we must find appertaining thermo-physical values to operating temperature. Thermo-physical parameters for sodium are in table 3. Sodium heat pipe operate at high temperatures around 500 and 1000 °C. Following this thermo-physical parameters, heat pipe and wick structure parameters was create in excel dependencies and equations for solution heat transfer limitations.

HEAT PIPE PARAMETERS Table 1

evaporator length	l_e	0.15	[m]
adiabatic length	l_{ad}	0.2	[m]
condenser length	l_c	0.15	[m]
total length	l_t	0.5	[m]
effective length	l_{ef}	0.35	[m]
inner radius	r_i	0.0075	[m]
cross - sectional area	A	0.000132	[m^2]
axial angle	Ψ	90	[°]
thermal conductivity	λ_m	30	[W.m^{-1}.K^{-1}]
cross - sectional area of wick structure	A_k	0.0000168	[m^2]
vapor core radius	r_v	0.0065	[m]

Experimental calculation of total heat power of wick heat pipe is developed for horizontal orientation heat pipe made from steal, sodium as a working fluid and parameters from table 1. Main from them are total length 0.5 m, inner radius 7.5 mm and thermal conductivity of steal is 30 is W.m^{-1}.K^{-1}. From many types of wick structures we choose groove wick structure for your simple manufactured, because we will this type of groove wick structure with parameters of groove high 0.4 mm, groove width 0.4 mm and groove pitch 0.4 mm made in future.

WICK STRUCTURE PARAMETERS Table 2

grooves wick structure	groove high	h	0.0004	[m]
	groove width	b	0.0004	[m]
	groove pitch	e	0.0004	[m]
	permeability	K	0.0000000114	[m^2]
	effective radius wick structure	r_{ef}	0.0004	[m]
	effective thermal conductivity	λ_{ef}	1.897	[W.m^{-1}.K^{-1}]

The geometry of wick structure is the most influencing on permeability (in our case it is 1,14 . 10^{-8}), which make capillary effect in wick heat pipe. Others parameters of wick structure are in table 2.

THERMO-PHYSICAL PROPERTIES OF SODIUM FOR WIDE OPERATING TEMPERATURE RANGE

Table 3

t	**ρ_L**	**σ_L**	**λ_L**	**μ_l**	**l_v**	**p_v**	**ρ_v**	**μ_v**
[°C]	[$kg.m^{-3}$]	[$N.m^{-1}$]	[$W.m^{-1}.K^{-1}$]	[$N.s.m^{-2}$]	[$J.kg^{-1}$]	[Pa]	[$kg.m^{-3}$]	[$N.s.m^{-2}$]
500	828.1	0.01510	70.080	0.00024	4,370,000.0	1000.0	0.003	0.000018
600	805.4	0.01420	64.620	0.00021	4,243,000.0	4000.0	0.013	0.000019
700	763.5	0.01330	60.810	0.00019	4,090,000.0	15000.0	0.050	0.00002
800	757.3	0.01230	57.810	0.00018	3,977,000.0	47000.0	0.134	0.000022
900	745.4	0.01130	53.350	0.00017	3,913,000.0	125000.0	0.306	0.000023
1000	725.4	0.01040	49.080	0.00016	3,827,000.0	281000.0	0.667	0.000024
1100	690.8	0.00950	45.080	0.00016	3,690,000.0	549000.0	1.306	0.000025
1200	669.0	0.00860	41.080	0.00015	3,577,000.0	959000.0	2.303	0.000026
1300	654.0	0.00770	37.080	0.00015	3,477,000.0	1591000.0	3.622	0.000027

t – temperature, ρ_L - density (liquid), σ_L - surface tension (liquid), λ_L - thermal conductivity (liquid), μ_l - viscosity (liquid), l_v - latent heat , p_v - pressure (vapour), ρ_v – density (vapour), μ_v – viscosity (vapour).

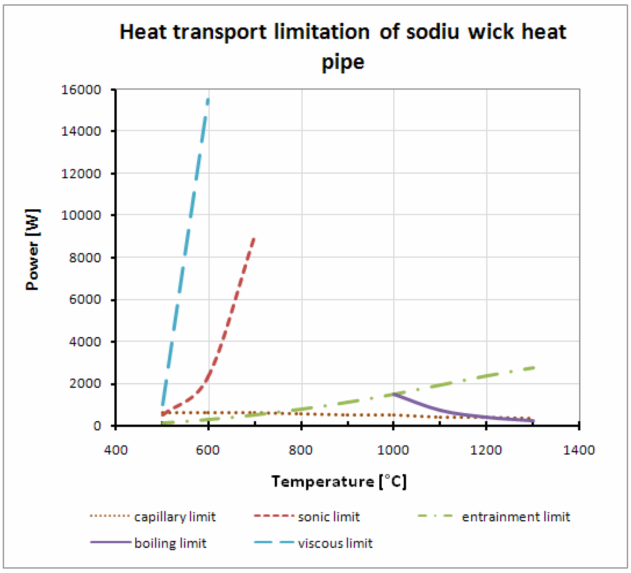

Fig. 2 *Graphic dependencies heat transport limitation of sodium wick heat pipe*

Graphic dependencies expressly define, who limiting performance influencing total cooling performance of heat pipe. Generally limit values depend to heat pipes parameters, wick structure parameters and thermo-physical properties of working fluid. The most highly values reach viscous limitation and sonic limitation. These limitations reach so high values that are not important for influence total heat pipe performance. Critical values influencing to heat pipe performance are values entrainment limitation, capillary limitation and boiling limitation. The capillary limitation cover the most of operating temperature region, therefore we can say, that the capillary limit is the primary maximum heat transport limitation of heat pipe.

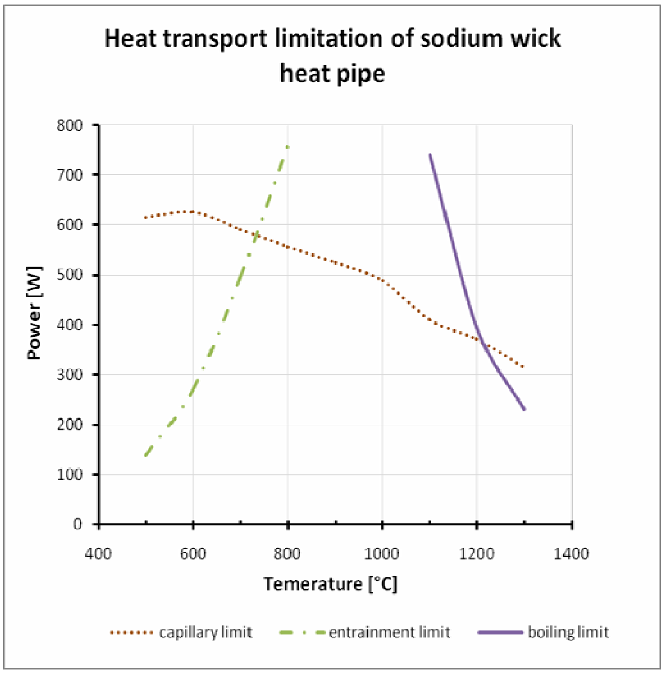

Fig. 3 *Graphic dependencies failure heat transport limitation of sodium wick heat pipe*

Conclusion

Using the analysis techniques for each limitation independently, the heat transport capacity as a function of the mean operating temperature can be determined. This procedure yields a heat pipe performance region that is shown on graph 1 and graph 2. As shown, the separate performance limits define an operational range represented by the region bounded by the combination of the individual limits. In effect, this operational range defines the region or combination of temperatures and maximum transport capacities at which the heat pipe will function. Limitations of the maximum heat input that may be transported by a heat pipe can be divided in two primary categories: limits that result in heat pipe and limits that do not. For the limitations resulting in heat pipe failure, all are characterized by insufficient liquid flow to the evaporator for a given heat input, thus resulting in dryout of the evaporator wick structure. However, limitations not resulting in heat pipe failure that the heat pipe operating at temperature for an increase in heat input.

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