OPERATING TEMPERATURE OF A LOOP HEAT PIPE

M. A. Chernysheva, Yu. F. Maydanik
Institute of Thermal Physics, Ural Branch of the Russian Academy of Sciences,
Amundsena St., 106, Ekaterinburg, 620016, Russia
Tel: (7-343) 2678-791, Fax: (7-343) 2678-799,
E-mail: maidanik@etel.ru

Abstract

The vapor temperature of a loop heat pipe is an important parameter which characterizes the device serviceable condition. The LHP temperature level is influenced by both external and internal factors, and also by the geometrical parameters of the device itself. For this reason different values of the vapor temperature may correspond to the same value of the heat load supplied to the evaporator. The paper presents a classification of the parameters and conditions forming the LHP operating temperature for regimes of variable and constant conductance.

KEYWORDS

Loop heat pipe, LHP, heat-transfer device, operating temperature, evaporator, condenser, heat exchange.

INTRODUCTION

A loop heat pipe (LHP) is a highly efficient heat-transfer device. One of the parameters that characterize the LHP serviceable condition is the vapor temperature, which is usually called the operating temperature. The paper [1] gives a detailed consideration of the loop principle, which is at the basis of the LHP operation. Among the characteristic features resulting from the LHP physical conception the authors designate the ability of the device to operate in the regime of constant and variable conductance, and also the possibility of active control over the operating temperature. The authors of the paper [2] also point to these peculiarities in the LHP operation on the basis of analysis of experimental curves obtained in testing a heat-transfer device under different conditions. The paper [3] is devoted to the problem of choosing a working fluid for an LHP. It is mentioned that the thermophysical properties of a working fluid have a considerable effect on the LHP operating characteristics, and first of all on the vapor temperature. This paper examines various conditions determining the LHP operating temperature for regimes with variable and constant conductance.

1. LOOP HEAT PIPE OPERATING TEMPERATURE AND THE CHOICE OF A WORKING FLUID

As shown by numerous investigations, loop heat pipes are capable of operating in a wide temperature range, from cryogenic temperatures to values of the order of 200°C. Unfortunately, in nature there is no "universal" liquid embracing such a considerable temperature range. Nevertheless, possessing a wide variety of working fluids for LHPs, it is possible to satisfy practically any service requirements concerning the provision of the necessary temperature level or regime for a thermostatted object. In principle, any fluid compatible with structural materials whose temperature range of LHP operation is between the temperatures of the triple and the critical point may serve as a working fluid for LHPs. The problems of choosing a working fluid are discussed in detail in [4]. Ibidem one can find the main requirements imposed on working fluids and an analysis of the totality of their properties. In this paper the choice of a working fluid is considered only from the viewpoint of its thermodynamic properties and their effect on the operating characteristics of a heat-transfer device, and primarily leans upon a thermodynamic approach. For a certain given temperature range there may exist several acceptable liquids. Thus, for instance, for operation in the temperature range from -10°C to 70°C potential working fluids may be ammonia, acetone, methanol, Freon 152, etc. The main decisive criterion for the choice in this case may become the fact that the LHP operating characteristics, such as the device maximum heat-

transfer capacity Q_{max} and its thermal resistance R, depend considerably on the thermophysical properties of the working fluid in use.

On the other hand, if a liquid used as a working fluid for an LHP is known, one can speak unambiguously about the values of minimum and maximum admissible operating temperatures for the heat-transfer device in question. Thereby one can determine in a first approximation the range of operating temperatures for this device.

2. FORMATION OF THE LHP OPERATING TEMPERATURE

One of the LHP main peculiarities is its capacity for self-regulation of the operating temperature, which adjusts itself to changes in the external conditions, such as the heat load supplied to the evaporator, conditions of heat removal in the condenser, changes in the ambient temperature and also in the device orientation in the gravity field. An LHP reacts to external changes by passing automatically to the corresponding temperature level. This happens, in the main, owing to a possibility to redistribute the liquid inside an LHP between the condenser and the compensation chamber (CC), which is joined to the evaporator. The function of the compensation chamber is to accumulate a liquid allowing it to form in the condenser the required surface for vapor condensation. Investigations show that an LHP possesses a capacity to function in two qualitatively different regimes determined by the situation in the compensation chamber: the regime of constant conductance, when the CC is fully filled with a liquid, and the regime of variable conductance, when the CC is filled with a liquid partially. Depending on the conductance regime the formation of the LHP temperature level will be different.

Regime of constant conductance

In the regime of constant conductance the condensation surface S_{cond} is fixed and depends on the amount of a working fluid in the device, or in other words on the charge volume. In this case the temperature of condensing vapor T_c in the condenser at a given heat load Q is determined by the intensity of heat exchange α_{sink} and depends on the temperature of the heat sink T_{sink}.

$$T_c = T_{sink} + \frac{Q}{\alpha_{sink} \cdot S_{cond}} \tag{1}$$

If the vapor line is not heat insulated, in this case one should take into account the heat exchange with the outside medium, then in Equation (1) instead of Q one should write Q′, which in a first approximation takes the form:

$$Q' = Q - \alpha_{amb} \cdot (\overline{T}_{ev} - T_{amb}) \cdot \pi \cdot d_{vl} \cdot l_{vl} \ . \tag{2}$$

Since both in the condenser and in the evaporator there are interfaces between liquid and vapor, it is possible to write an equation which relates the temperature T_c and the pressure P_c of the vapor in the condenser to the temperature T_{ev} and the pressure P_{ev} of the vapor in the evaporation zone of the evaporator:

$$P^s_{ev}(T_{ev}) - P^s_c(T_c) = \Delta P_{ev-c} \tag{3}$$

or

$$\left.\frac{dP}{dT}\right|_{\overline{T}} \cdot (T_{ev} - T_c) \approx \Delta P_{ev-c} \quad , \tag{4}$$

where $\left.\frac{dP}{dT}\right|_{\overline{T}}$ is the derivative that characterizes the slope of the saturation line at the temperature $\overline{T}$ ($\overline{T}$ may be the average temperature between T_{ev} and T_c), ΔP_{ev-c} stands for the pressure losses during the vapor motion from the evaporator into the condenser. For the

traditional design of the LHP evaporator these losses are formed by the pressure drop ΔP_i in each i-th section of the transportation lines along which the vapor moves:

$$\Delta P_{ev-c} = \sum_i \Delta P_i \tag{5}$$

Or, writing Equation (5) in a more expanded form, we have:

$$\Delta P_{ev-c} = \Delta P_{cvc} + \Delta P_{lvc} + \Delta P_{vl} + \Delta P_{v\_cond} + \Delta P^{v}_{iner}, \tag{6}$$

where the first four terms allow for the viscosity components of the pressure drop, namely, the pressure drop in the azimuthal vapor-removal channels, in the longitudinal vapor-removal channels, in the vapor line and in the vapor section of the condenser, respectively. The last term in Equation (6) ΔP_{iner} is the inertial component of the pressure drop in the vapor motion, which allows for the effect of the vapor injection, the local resistances of bends and turns on the transportation line. Since ΔP_i depends on many parameters, in the general form this dependence may be presented as:

$$\Delta P_i = f(Q, F_{ht}, F_{gp}), \tag{7}$$

where F_{ht} is the complex that takes into account the thermophysical properties of a working fluid, F_{gr} is the complex that account for the geometrical parameters of the transportation section.

With allowance for (1), (4) and (5) the expression for T_{ev} will look like:

$$T_{ev} = \left(\left. \frac{dP}{dT} \right|_{\bar{T}} \right)^{-1} \sum_i \Delta P_i + \frac{Q'}{\alpha_{\sin k} \cdot S_{cond}} + T_{\sin k} \tag{8}$$

The factors and the parameters which form the LHP operating temperature and in an explicit or an implicit form are present in (8) may be grouped as follows:

Table 1.

	Governing factors and parameters
Conditions external with respect to the LHP	Q, T_{sink}, T_{amb}
Heat-exchange characteristics	α_{sink}, α_{amb}, α_{ev}
LHP geometrical parameters	S_{cond}, l_{con_v}, l_{vl}, l_{lvc}, l_{cvc}, d_{vl}, d_{vl_ext}, d_{lvc}, d_{cvc}, N_{lvc}, N_{cvc}
Thermophysical parameters of the working fluid	μ_v, ρ_v, h_{hv}, P'_T

According to Equation (8) the reference point in the determination of the operating temperature should be considered the temperature of the heat sink T_{sink}. The lower this temperature, the lower the operating temperature of the LHP. The efficiency of the heat-transfer device is determined by the value of thermal resistance:

$$R = \frac{T_{ev} - T_{sink}}{Q} \tag{9}$$

Since at a given temperature of the heat sink T_{sink} and the value of heat load Q the thermal resistance is a function of T_{ev}, one can determine possible means of decreasing the thermal resistance on the basis of analysis of Equation (8). First, this is the intensification of heat-exchange processes in the condenser. Second, the choice of the most promising working fluids. Among these are working fluids with the most optimal thermophysical parameters, and first of all a low value of dT/dP. And, third, almost always there is a possibility to vary within admissible limits the geometrical parameters of vapor transportation lines with the aim of decreasing ΣP_i.

To the regime of constant conductance corresponds the minimum vapor operating temperature possible at the heat load and the cooling conditions in question. The operating curve for this regime has the form of an almost straight line. This regime can take place in two cases:

1. For the LHP orientation φ=90° and φ=0° at sufficiently high heat loads, when the CC is already completely filled with a liquid (see Fig.1: curve 1 and curve 2).
2. For the LHP orientation φ=-90° for heat loads beginning with the minimum ones (see Fig. 1: curve 3).

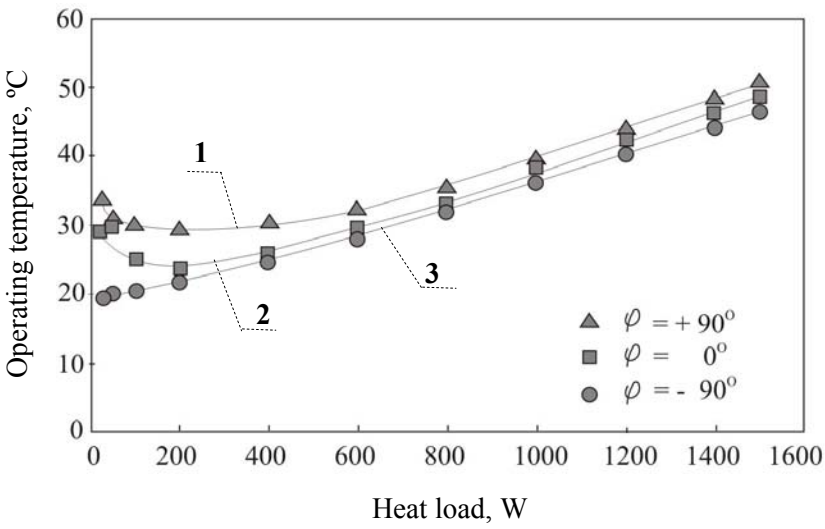

Fig.1. Typical appearance of LHP performance curves for different orientations φ

Regime of variable conductance

In the regime of variable conductance the compensation chamber is partially filled with a liquid, and over its interface there is saturated vapor. For the circulation of a working fluid it is necessary to fulfill the condition:

$$P^s_{ev}(T_{ev}) - P^s_{cc}(T_{cc}) = \Delta P_{ext} \tag{10}$$

This condition is specific to the LHP. It relates the vapor pressure, and accordingly its temperature in the evaporation zone, to the vapor pressure in the CC through the pressure drop in the transportation sections of the circulation loop external with respect to the capillary structure ΔP_{ext}. We can write the condition of serviceability as:

$$\left.\frac{dP}{dT}\right|_{\bar{T}} (T_{ev} - T_{cc}) \approx \Delta P_{ext} \quad , \tag{11}$$

and also express ΔP_{ext} in terms of the sum of the hydrostatic pressure ΔP_g, the pressure losses in the transportation sections along which vapor moves ΔP_v and along which a liquid moves ΔP_l:

$$\Delta P_{ext} = \Delta P_l + \Delta P_v + \Delta P_g \ , \tag{12}$$

$$\Delta P_v = \Delta P_{cvc} + \Delta P_{lvc} + \Delta P_{vl} + \Delta P_{v\_cond} + \Delta P^v_{iner} \ , \tag{13}$$

$$\Delta P_l = \Delta P_{l\_cond} + \Delta P_{ll} + \Delta P^l_{iner} \quad , \tag{14}$$

$$\Delta P_g = \rho_l g l_{ll} \sin\varphi \quad . \tag{15}$$

It is convenient to present the dependence of ΔP_{ext} on many parameters as follows:

$$\Delta P_{ext} = f(Q, F_{ht}, F_{gp}, \varphi) \quad , \tag{16}$$

where F_{ht} is the complex that takes into account the thermophysical properties of a working fluid, F_{gp} is the complex that allows for geometrical parameters of the transportation sections. By rearranging Equation (11) we can get an expression for the vapor temperature:

$$T_{ev} = \left(\left. \frac{dP}{dT} \right|_{\bar{T}} \right)^{-1} \Delta P_{ext} + T_{cc} \tag{17}$$

It is seen that T_{ev} is directly related to the temperature in the compensation chamber. There are some advantages and disadvantages in it. Among the main advantages one should mention the possibility of active control over the LHP temperature level. For instance, with an additional thermal action on the CC, for a certain range of heat loads, the LHP operating temperature may be fixed at a certain temperature level [5]. Let us examine the factors and the conditions that have an effect on the temperature formation in the CC, and consequently on the LHP operating temperature during an independent operation of a heat-transport device.

Let a liquid leave the condenser with the temperature T_{out_cond}. With allowance for the heat exchange with the medium, at the evaporator inlet it will have the temperature T_{in_cc}:

$$T_{in\_cc} = T_{amb} + (T_{out\_cond} - T_{amb}) \cdot e^{-A}, \tag{18}$$

where

$$A = \frac{\pi \cdot d_{ll} \cdot \alpha_{amb} \cdot h_{hv} \cdot l_{ll}}{c_l \cdot Q}. \tag{19}$$

T_{sink} may be taken as T_{out_cond}, which holds quite true for intense heat-exchange processes in the condenser. The temperature in the compensation chamber T_{cc} is established from the balance of heat flows:

$$Q_{cc} = Q_{liq} + Q_{wick} + Q_{wall} + Q_{amb} \cdot \tag{20}$$

where Q_{cc} is the resultant heat flow, Q_{liq} is the heat arriving at the CC with the liquid flow returning from the condenser, Q_{wick} is the heat flow through the wick, Q_{wall} is the heat flow over the evaporator wall, Q_{amb} is the heat flow at the expense of heat exchange between the CC external surface and the medium. One can exclude the thermal action of the outside medium on the CC by means of thermal insulation of its external surface. At the same time it is practically impossible to get rid of parasitic heat flows into the compensation chamber through the wick Q_{wick} and over the evaporator body Q_{wall}. Therefore, it is precisely they that finally the temperature, and consequently the vapor-processes in the CC. The value of these heat flows depends on the intensity of heat-exchange processes in the evaporation zone, and also the evaporator geometrical parameters and the relation between them [6].

Thus, the factors and the parameters which form the LHP operating temperature in the regime of variable conductance and in an explicit or an implicit form are present in Equations (11) – (20) may be grouped as follows:

Table 2.

		Governing parameters
Thermophysical parameters of the working fluid		μ_v, ρ_v, c_v, μ_l, ρ_l, c_l, h_{hv}, P'_T
Heat-exchange characteristics		α_{sink}, α_{amb}, α_{ev}
Conditions external with respect to the LHP		Q, T_{sink}, T_{amb}, $g \cdot \sin\varphi$
LHP geometrical parameters and characteristics	Parameters external with respect to the evaporator	d_{cond}, l_{cond}, l_{vl}, d_{vl_ext}, d_{vl_int}, l_{ll}, d_{ll_ext}, d_{ll_int}
	Evaporator parameters	d_{ev}, δ_{wall}, l_{ev}, l_q, δ_{wick}, l_{wick}, l_{lvc}, l_{cvc}, d_{lvc}, d_{cvc}, N_{lvc}, N_{cvc}, k_{wall}
	Wick characteristics	k_{wick}, ε, K_p
	Charge volume	V_{ch}

When comparing the content of Table 1 with that of Table 2, one can say that the regime of variable conductance is characterized by a much larger number of factors and conditions that influence the LHP operating temperature than the regime of constant conductance. Moreover, a correct prediction of the temperature level for a heat-transfer device becomes possible only in the event that the whole complex of conditions and parameters contained in Table 2 is taken into account. In practice this influence manifests itself in the fact that different values of the vapor temperature may correspond to the same value of the heat load supplied to the evaporator. The self-regulation property of operating characteristics for the regime of variable conductance is expressed in the nonlinear character of variation of T_{ev} under changes in the value of the heat load supplied. The shapes of the temperature curves presented in Fig.1 show that the LHP operated in the regime of variable conductance at low heat loads with device operations φ=90° and φ=0° (see Fig.1: curve 1 and curve 2).

CONCLUSION

1. A characteristic feature of an LHP is its ability to operate in two regimes: in the regime of variable conductance or in the regime of constant conductance.
2. The LHP operating temperature depends on many factors, parameters and conditions. The paper gives their classification for both conductance regimes.
3. In the regime of constant conductance the number of factors, parameters and conditions that have an effect on the LHP temperature level is much smaller than in the regime of variable conductance. Therefore, the operating characteristics for the regime of constant conductance are easier to predict.

NOMENCLATURE

c	specific heat at constant pressure, J/(kg·K)
d	diameter, m
g	gravitational acceleration, m/c^2
k	thermal conductivity, W/(m·K)
K_p	permeability, m^2
h_{hv}	latent heat of vaporization, J/kg
P'_T	dP/dT at temperature T, Pa/K
l_{cond_v}	length of condensation zone, m
l	length, m
N_{lvc}	quantity of longitudinal vapor grooves
N_{cvc}	quantity of azimuthal vapor channels
P	pressure, Pa
Q	heat load, W
R	thermal resistance, K/W
S_{cond}	condensation surface, m^2
V_{ch}	charge volume, m^3
α_{ev}	coefficient of heat exchange in evaporation zone, W/(m^2·K)
α_{sink}	coefficient of heat exchange between the vapor and heat sink, W/(m^2·K)
α_{amb}	coefficient of heat exchange with ambient, W/(m^2·K)
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
φ	angle of LHP slope, °
ε	porosity
δ	thickness, m

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amb	ambient (outside medium)
c	condenser

cc	compensation chamber
cond	condensation
cvc	azimuthal vapor channels
ev	evaporator
ext	external
ht	heat transfer liquid
int	internal
iner	inertial
gp	geometrical parameters
liq	liquid
ll	liquid line
lvc	longitudinal vapor grooves
max	maximum
min	minimum
q	active zone (heat input zone)
s	saturation
vl	vapor line
v	vapor
v_cond	vapor occupied part of condenser
wick	wick
wall	evaporator body

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