THE HEAT-TRANSFER CRISIS IN A CLOSED EVAPORATION THERMOSIPHON

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We determine the factors and conditions resulting in pronounced impairment of heat transfer through the cavity of a closed evaporation thermosiphon during the heat-transfer process. We have established the optimum conditions for the utilization of the heat-transfer elements.

Closed evaporation thermosiphons are used as the heat-transfer elements in baking furnaces [1, 2] and in the air heaters of boiler installations [3, 4]. The high heat-transmission capacity of the closed channel, partially filled with a liquid intermediate heat carrier, makes it possible to use the thermosiphon element for the cooling of blades in high-temperature gas and steam turbines [5-7].

An analysis of the literature devoted to the use of thermosiphons shows that the extent to which the cavity of the element should be filled with the heat carrier (primarily water) is determined empirically. The recommendations most frequently call for 1/3 of the volume of a closed evaporation thermosiphon to be filled [1, 2]. It is indicated in [2] that the filling of the cavity with a liquid level above or below 1/3 of the volume may lead to the rupture of the heat-transmission tube.

Experiments on fixed and rotating thermosiphons showed that there is a minimum permissible extent to which the cavity of the element can be filled with the intermediate heat carrier. When the cavity is filled to levels below the limit, the heat flows through the closed evaporation thermosiphon are markedly reduced. The reason for this phenomenon, according to the hypotheses of [5, 6], is a unique heat-transfer "crisis" that is associated with an inadequate amount of liquid to ensure complete wetting of the inside walls of the element cavity.

The few data on the minimum amounts for the filling of the cavity in a closed evaporation thermosiphon with the intermediate heat carriers differ substantially from each other in terms of quantity. Thus, for a fixed thermosiphon element the fill factor is given as 0.172% in [6], and 0.38 and 0.48% in [7]; for a rotating element the corresponding figures are 1.5% in [6] and 15% in [5].

In the literature with which we are familiar there are no theoretical recommendations for the determination of the minimum permissible fill factor for the cavity of a closed thermosiphon.

Here we make an attempt experimentally and theoretically to determine the factors responsible for the heat-transfer crisis in the cavity of a closed thermosiphon, as well as to establish the theoretical relationship for the determination of the fill factors for the cavity of the element with an intermediate heat carrier, from the standpoint of achieving maximum heat loads.

We use the installation described in [8] to solve the formulated problems experimentally.

The test stand is based on a thermosiphon element fashioned from 1Kh18N9T steel in the form of a tube with an inside diameter of 30 mm and a cavity volume of 165 cm^3. The heat is fed in and removed through the ends of the element. The thermodynamic state of the heat carrier within the cavity was determined from the averaged readings of three Chromel–Alumel thermocouples positioned at the surface of the element at the middle cross section of the cavity. Adjustment tests demonstrated excellent agreement between the saturation temperature determined by this method and the saturation pressure for the intermediate heat carrier within the cavity of the thermosiphon element.

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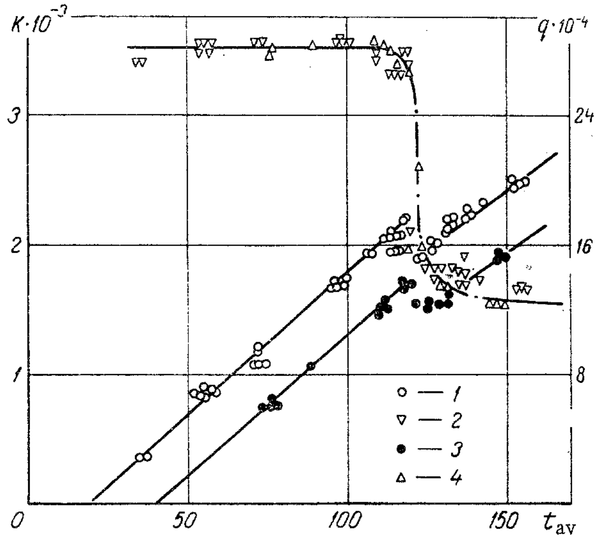

Fig. 1. Specific heat flow (q, W/m^2) and heat-transfer coefficients (K, W/m^2·deg) as functions of the average temperature (t_{av}, °C) of the heat carrier: 1, 2) specific heat flow and heat-transfer coefficient for $t_W = 19°C$; 3, 4) the same, for $t_W = 40°C$ (the heat carrier is ammonia, and fill factor is $\Omega_{20} = 64.8\%$, $\varphi = 90°$).

During the main test, the manometer was not connected to the element cavity. This made it possible to eliminate those errors associated with the effect of the additional volume of the manometer tube and the connecting lines.

The quantity of the heat carrier in the cavity was determined by weighing the element prior to and following the filling operation. The weighing operation was correct to 0.05 g. To ensure the required heat-carrier weight and to eliminate the air from the cavity, a special filling procedure was developed, and this was based on the complete filling of the element cavity with liquid subsequently evaporating the excess substance.

Liquid ammonia was used as the intermediate heat carrier in the basic experiment. The control tests designed to test the theoretical method were performed with the cavity of the thermosiphon element filled with 96% ethyl alcohol.

These experiments showed that the saturation temperature for the heat carrier within the cavity increases in conjunction with a rise in the heat load through an element partially filled with liquid.

The characteristic relationships between the specific heat loads transmitted through the element and the heat-transfer coefficient for one of the liquids filling the cavity (industrial ammonia) and for two temperatures of the cooling water are shown in Fig. 1.

As we can see from the figure, at a certain saturation temperature for the intermediate heat carrier the heat transfer in the cavity element is markedly impaired and the heat-transfer coefficient is reduced. A heat-transfer "crisis" occurs. We will subsequently refer to this as the "crisis" temperature.

At average temperatures for the intermediate heat carrier above the crisis level, the heat-transfer coefficient diminishes subsequently tending toward a constant value. In the crisis temperature region we note a disruption of the monotonicity for the specific heat flow transmitted through the thermosiphon element as it relates to the average temperature of the intermediate heat carrier. As we can see from Fig. 1, the crisis temperature region extends from 10 to 15°C.

For more exact determination of the crisis temperature, we utilized graphs showing the temperature head over the entire length of the element cavity as a function of the temperature at the midsection of the cavity (Fig. 2). The construction of such graphs made it possible to determine the crisis temperatures with an accuracy with up to 1-2°C. The nature of the relationship between the temperature differences across the remaining segments of the cavity in the thermosiphon element (the heating side, the cooling side,

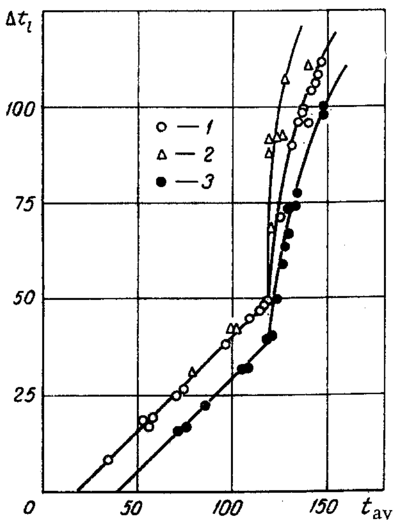

Fig. 2

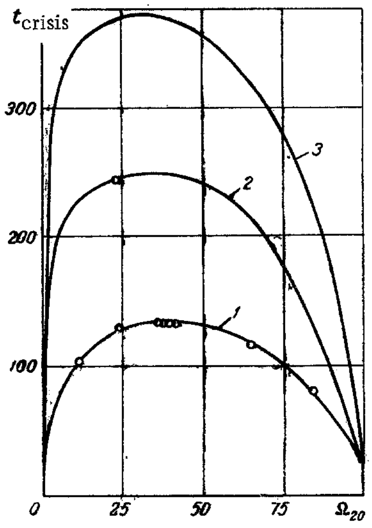

Fig. 3

Fig. 2. Determination of heat-transfer crisis temperature (ammonia, = 64.8%; Δt_l, t_{av} °C): 1, 2) $t_w = 19$ and 40°C for $\varphi = 90°$; 3) $t_w = 19°$C for $\varphi = 0$.

Fig. 3. Crisis temperature as a function of the fill factor for the cavity of a thermosiphon element with an intermediate heat carrier; 1) ammonia; 2) 96% ethyl alcohol; 3) water; the curves denote theory; the points denote experiments.

the middle portion) and the average temperature for the intermediate heat carrier is similar to that shown in Fig. 2.

The experiments to determine the crisis temperatures were performed with the cavity of the thermosiphon element filled 11 times with ammonia, at various cooling-water temperatures (12°, 19°, 30°, and 40°C), as well as at various angles of inclination toward the horizontal on the part of the thermosiphon element (90, 59, 45, 30, 15, 5, and 0°).

According to the experiment (Fig. 2), the change in the temperature of the cooling water and in the angle of element inclination from the vertical as the heat is supplied from below ($\varphi = 90°$) to the horizontal ($\varphi = 0°$) has no effect on the magnitude of the crisis temperature. Its value is found in direct relation to the extent to which the element cavity is filled with the intermediate heat carrier.

The absolute value of the crisis value for the specific heat flow depends substantially on the temperature of the cooling water and may vary for the same filling level (Fig. 1).

Higher values for the limit heat loads correspond to lower temperatures for the cooling water, given an identical level of filling. With a constant temperature for the cooling water the magnitude of the maximum specific flow transmitted through the element depends significantly on the extent to which the cavity is filled with the intermediate heat carrier.

The observations cited above indicate that the fill hypothesis cannot completely explain the factors for the crisis in heat transfer in a closed evaporation thermosiphon. Indeed, according to calculations the quantity of heat carrier in the form of a film on the inside walls of the channels makes up an insignificant fraction of the total quantity of material in the cavity.

Calculations of the thermodynamic state of the heat carrier in the cavity demonstrated that the basic factor responsible for the crisis is the transition from heat transfer in a two-phase medium with a change in the aggregate state to the transfer of heat in a single-phase liquid or vapor medium.

The theoretical values for the crisis temperature were determined on the basis of the specific volume for the intermediate heat carrier at the heat-transfer crisis, i.e.,

$$v_{\text{crisis}} = \frac{V_0}{G}. \tag{1}$$

From the derived values for the specific volumes, the crisis temperatures were determined as points located at the upper or lower boundary curves of the diagrams of state for the intermediate heat carriers.

The fill factor for the cavity of the thermosiphon element was determined from the equation

$$\Omega_{20} = \frac{G}{G_{20}^{\max}} \, 100\% . \tag{2}$$

The maximum quantity of heat carrier in the element cavity was determined from the relationship

$$G_{20}^{\max} = \frac{V_0}{v'_{20}} . \tag{3}$$

The theoretical and experimental values of the crisis temperatures, depending on the extent to which the thermosiphon element cavity is filled with ammonia, are shown in Fig. 3 (curve 1). The theoretical and experimental quantities are in good agreement.

The greatest magnitude for the crisis temperature is noted at a critical fill factor. In this case the critical quantity of heat carrier can be calculated from the equation

$$G_{\mathrm{cr}} = \frac{V_0}{v'_{\mathrm{cr}}} . \tag{4}$$

Under the above-indicated conditions, the crisis temperature coincides with the temperature that is critical for the heat carrier under consideration. In the case of ammonia, the theoretical critical fill factor amounts to 38.4%.

Figure 3 also makes it possible for us to establish the region of optimum fill factors for the cavity of the evaporation thermosiphon element when liquid industrial ammonia is used as the intermediate heat carrier. This region covers fill factors from 25 to 50%.

Since we note a linear relationship between the specific heat flow and the saturation temperature at a constant cooling-water temperature, the maximum magnitude of the specific heat flow will occur when the cavity is filled to the critical level with the intermediate heat carrier.

The theoretical values of the crisis temperatures for the various fill factors of the cavity in the case of 96% ethyl alcohol are shown in Fig. 3 (curve 2). Here we also find the magnitude of the crisis temperature determined experimentally for a fill factor of 21.8%.

Where the cavity is filled with the heat carrier to a factor of the critical – determined from (4) – the transition through the crisis temperature leads to the filling of the cavity with the liquid phase at a comparatively low coefficient of compressibility, which results in a pronounced increase in the pressure within the cavity of the thermosiphon element. This phenomenon may be responsible for the rupture of the heat-transmission tube.

Transition through the crisis temperature when the fill factor is below the critical causes the cavity to be filled with the heat carrier in a vapor state, and the carrier is subsequently heated. Since the gas and vapor compression ratio is high, the pressure rise within the cavity will be insignificant and it is only the pronounced increase in the temperature in the wall on the heating side that represents a danger to the thermosiphon element.

The theoretical critical fill factors are 33.4% for ethyl alcohol and 31.5% for water. Thus the recommendations in the literature which call for the filling of 1/3 of the volume of the thermosiphon element cavity with water are within the limits of the optimum fill factors, but slightly above the critical values.

When the cavity of the heat-transmission tube is filled with a "margin," the element may rupture when the temperature of the tube rises above the crisis level. According to Fig. 3, the greater this "margin," the lower the value of the crisis temperature and, consequently, the lower the magnitude of the permissible working temperature for the operation of thermosiphon elements.

In connection with the above, the recommended cofactors for the element cavities in the case of intermediate heat carriers must be from 2 to 10% below the critical. For water this amounts to 20-30% (Fig. 3, curve 3).

NOTATION

v_{crisis}	is the specific volume of the intermediate heat carrier at the heat-transfer crisis;
V_0	is the physical volume of the thermosiphon element cavity;
G	is the weight of the intermediate heat carrier in the element cavity;
G_{20}^{max}	is the maximum possible quantity of heat carrier in the element cavity at 20° C;
v_{20}'	is the specific volume of the liquid intermediate heat carrier at 20° C;
v_{cr}	is the specific heat-carrier volume at the critical point.

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