HEAT TRANSFER AND HYDRODYNAMIC CHARACTERISTICS AT EVAPORATION OF LIQUID FILM IRRIGATING A HORIZONTAL BUNDLE OF FINNED TUBES

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Abstract. The paper presents experimental results on heat transfer during evaporation of an R21 freon film that irrigates a packing of horizontal finned tubes. It is shown that heat transfer on the finned tubes is noticeably more intense even with respect to the full surface of the finned tube.

Introduction

The finning of tubes is a well-proven method of heat transfer enhancement at evaporation and boiling. Unfortunately, experimental data on heat transfer at evaporation and boiling of film irrigating a horizontal bundle of finned tubes are very few [1, 2]. Below there are heat transfer experimental results at the evaporation of Freon R21 irrigating a bundle of horizontal finned tubes. The experiments are carried out on an installation with forced circulation of the working substance.

Measurement technique

The temperature of the water heating experimental section is measured by semiconductor temperature sensors as well as controlled by multi-junction differential thermocouples. The sensors are calibrated with the accuracy of not less than 0.02°C.

The wall temperature is calculated from the heat transfer coefficient.

The heat flux density on the experimental sections is calculated according to:

\[ q = \frac{m \cdot C_p \cdot \Delta T}{F} \]  

(1)

The heating water flow rate is determined on the readings of rotameters as well as flowmeters with the accuracy rating 0.5. The rotameters installed in every section are calibrated individually.

The experiments are carried out at irrigation of the bundle with Freon R21 at \( t_s = 40°C \). Reynolds number of the film irrigating the tube bundle is changed within the range of \( 380 \leq Re \leq 1500 \). The bundle consists of 12 tubes arranged in a vertical row. Experimental tubes are placed in the bottom part of the bundle. The second from the bottom tube was a plain copper (M-1) tube with technical surface finish \( R_s \approx 2.5 \text{ microns} \), the wall thickness \( \delta_{w} = 2 \text{ mm} \), and \( D = 10 \text{ mm} \). The third from the bottom copper (M-1) tube is a finned tube with the pitch of helical finning 1.07 mm and the finning factor 1.46.

**Figure 1.** Dimensions (in mm) of the helical groove threaded on the outer surface of the 3rd copper experimental tube.
In Fig. 1 the dimensions of the finned tube are given. According to the investigation results published in [3], the distance between ribs is sufficient to hold the minimal liquid amount within a groove between ribs.

Measurement results

In Fig. 2 heat transfer experimental results are presented both for the plain and the finned tube in coordinates $q - \Delta T$. It is seen that boiling on the plain copper tube took place at $\Delta T = 4.5 - 5^\circ C (q \approx 10^4 \text{ W/m}^2)$. The value of heat flux density on the finned tube is here conditional because it is calculated relative to the surface area of a plain tube with the outer diameter 10 mm. The experimental results on the finned tubes appeared to be non-traditional. Usually boiling on finned tubes takes place at considerably lower temperature drops than on plain tubes. In these experiments, there is no boiling within the whole investigated range of heat fluxes.

**Figure 2.** Experimental results for plain and finned copper tubes in coordinates $q - \Delta T$.

It is especially distinctly clear in the Fig. 3 showing that $\alpha \approx \text{const}$ within the whole range of parameters. In Fig. 3 the heat flux density is calculated relative to the whole surface area of the finned tube. It follows from the Fig. 3 that evaporation heat transfer is considerably higher on the finned tube than on the plain tube even if the heat flux density is calculated relative to the full surface of the finned tube.

**Figure 3.** Experimental results for plain and finned copper tubes in coordinates $\alpha - q$ where the heat flux density is calculated relative to the whole surface area of the finned tube.
In Fig. 4 a physical model of film flow on a finned tube is presented. Supposed that surface tension force considerably exceeds gravitational force at film flow through the area between fins. Both visual observations and analysis of video films investigating hydrodynamics of film irrigating finned tube bundle justify this supposition. Micro-bubbles escaping at ethanol irrigation of finned tubes show the liquid motion trajectory along the lateral rib surface quite distinctly. A diagram of this movement is shown in Fig. 4.

Our visual observation, as well as video films, showed that under the force of surface tension liquid flows from a rib apex on the lateral rib surface to the groove bottom along the trajectory shown in Fig. 4. A thin film on the lateral area of the rib wets its surface and evaporates intensively.

It means that at liquid film irrigation of a finned tube the rib height becomes a characteristic linear dimension. Besides, the copper finned tube could be considered as an isothermal surface because the rib efficiency for this tube is determined according to the following dependency (4)

$$E = \frac{\frac{1}{2} \alpha \delta}{\sqrt{2 \alpha \delta^2}}$$

and close to 1. Here $l = h/\delta$; $\delta$ is the rib thickness near its base; $h$ is a height of the rib.

![Diagram of liquid movement along the rib.](image)

1 – the base of the finned tube, 2 – liquid film, 3 – liquid layer held between ribs, 4 – the direction of liquid movement along the rib. $H$ – the average height of the held liquid layer.

Calculation of heat transfer at the evaporation of film irrigating a bundle of finned tubes is difficult because of very complicated hydrodynamics at the irrigation of each rib.

The lateral rib surface is irrigated in its upper part with thin liquid laminar film flowing down from the rib edge.

The bottom part of the rib within the groove between ribs is irrigated with the main liquid flow that flows along the groove between ribs and is turbulent.

The boundary between laminar and turbulent flows cannot be determined correctly. It can be estimated at a first approximation.

Heat transfer coefficient at film evaporation from different rib surfaces can be calculated only approximately taking into account the following assumptions:
a) Surface tension force exceeds considerably the force of gravity. The upper part of the lateral rib surface is irrigated with liquid flowing from the edge rib surface to the groove along the trajectory shown in Fig. 4. 
b) Heat transfer both on the edge part of a rib and within the groove between ribs takes place like on a smooth tube [5].
c) The mass flow rate irrigating the rib edge is determined from the balance dependencies.
d) He rib is within the initial section of the thermal boundary layer with the rib height as a characteristic linear dimension.
e) A copper finned tube can be considered as isothermal surface so the rib efficiency is close to 1.
f) The film thickness in the groove is calculated on the Dukler – Bergelin dependence [6]:

\[
\delta = \frac{Re_{cr}^{0.2} \left( \frac{3 \nu^2}{\mu} \right)^{1/3}}{Re^{8/15}}
\]  

The critical Reynolds number is determined here according to the Brauer dependence [7]:

\[
Re_{cr} = 35 K a^{1/6}
\]

The film thickness calculated on (2) is close to a film thickness determined according to the dependency from [8] and to the experimental results presented in [9].

The irrigation density of the upper rib part is calculated according to the dependence:

\[
G_T = \frac{m_T}{2 \pi R} \text{[kg/m s]},
\]

where \( m_T \text{[kg]} \) is a mass flow rate of the liquid flowing along the rib edge. The film Reynolds number \( Re_2 \) on the lateral rib surface is determined on the dependence \( Re_2 = G_2 / \mu \).

The heat transfer on the initial section of the thermal boundary layer (the upper part of the lateral rib surface) is determined on the dependence:

\[
Nu_2^* = 0.6 Pr^{1/3} \left( \frac{Re_2}{h} \right)^{1/9}
\]  

Dependence (4) is an empirical one. It is recorded by analogy with the analytical formula from [1] obtained to describe heat transfer on the initial section of a vertical wall. In the dependence (4) the Galileo number is replaced by a dimensionless rib height:

\[
\bar{h} = \frac{h}{\sigma} \sqrt{\frac{\rho_L - \rho_V}{g}}
\]

To determine heat transfer coefficients both on the edge part of the rib and within the groove at turbulent film flow we can use the three-layer model described in [11], where turbulent viscosity is piecewise approximated by corresponding dependencies. In [11] a Table of numeral computation results of Nusselt number via film Reynolds number for some integer values of Prandtl number is presented.

Calculating film thickness in the groove according to (5) and considering that the groove has a trapezoidal shape, we can approximately determine areas of the lateral rib part streamlined by turbulent or laminar liquid flows. Using experimental data on \( \Delta T = T_w - T_i \) we can calculate specific heat fluxes on each part of a finned tube. The total heat removal consists of the following components:
\[ \Sigma Q = (Q_{\text{edge}} + Q_{\text{groove}} + 2Q_{\text{lam}} + 2Q_{\text{turb}})n \]  

(5)

Here \( n \) is the number of fins on the experimental tube surface; \( Q_{\text{edge}} \), \( Q_{\text{groove}} \), \( 2Q_{\text{lam}} \), \( 2Q_{\text{turb}} \) – heat removals from the tube edge, from the horizontal groove part between ribs, from the lateral rib part streamlined by laminar flow, by turbulent flow, \( n \) is a number of ribs on an experimental tube.

The calculated on (5) values of heat removals agree with experimental value with an error \( \pm 15\% \) within the whole parameter range of the experimental investigation.

Conclusion

The heat transfer at evaporation on finned tubes is so intense that excludes conditions which are necessary for vapor bubble origin. It should be noted that at the maximum heat flux value on the finned tube \( \Delta T_w \) was always \(< 5^\circ\text{C} \) (i.e. the temperature head of the boiling inception on the smooth tube).

The presented calculation algorithm describes the experimental results satisfactorily.

Acknowledgements

The study was performed at the Institute of Thermophysics (SB RAS) with the support of the BSI SAS Program for 2017-2020 (project III.18.2.3, reg. no. AAAA-17-117030310025-3)

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