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On Experimental Study of Heat Transfer in Gravity Driven Water Film

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Abstract: The object of this study was to throw more light on the heat transfer developments in the entrance region of a falling liquid film. The topic is also of importance because it aids the understanding and design of heat exchangers, turbines, refrigeration and air conditioning systems and etc. In many applications an estimation of the entrance region is often required. Velocity profiles predictions for the falling down film in the entrance region are given in the paper. Experimental investigation of heat transfer in the entrance region for the turbulent film was performed. The description of experimental set-up is presented. The research has been carried out with water film falling down a surface of vertical tube as Reynolds number ranged from $9.2 \cdot 10^3$ to $10.5 \cdot 10^3$. The results of experiments are discussed with the respect to the local heat transfer coefficient dependence upon Reynolds number and initial velocity of the film. Heat transfer stabilization length was established experimentally. Evaluation of heat losses in the test section is presented.

Key-Words: Heat transfer, entrance region, turbulent film, vertical tube, stabilization length

1 Introduction

Heat transfer has a very wide application from our everyday activities to various food processing equipments, to advanced nuclear and electronic processing facilities. It also has economical and environmental importance as sources of energy are valuable commodities and therefore various processes involving energy transport must to be optimized to meet future demands. Some of processes that involve the application of heat transfer are energy generation, separation technology, drying processes, storage and disposal of hazardous waste.

Falling liquid films are often used in many technological processes, during which heat and mass transfer exchange takes place. Gravity driven water films are very frequent in thermal energy systems where evaporation processes occurs in boilers or nuclear reactors or vapor condenses in condensers [1]. They are also widely spread in chemical industry. In recent years, heat and mass transfer equipment operating with the falling films on their external or internal surfaces have found a wide application in the food industry [2-4].

The intensity of evaporation, condensation, absorption, adsorption, burning and other technological processes depends upon ability to form and maintain a stable smooth film of uniform thickness on the wetted surface [5]. It is difficult to obtain the uniform liquid film distribution in the feed inlet. Specially designed liquid distributors at the feed inlet permit to explore more thin liquids films in the strict temperature regime.

The most of the film apparatus for the thermal treatment of liquid products consists of vertical tubes with falling films on their external surfaces [6-10]. In the case when liquid film flows down a vertical tube the curvature of its surface and the film itself effects heat transfer characteristics on the surface and correspondingly thickness of the liquid film [11-13]. The cases that deal with vertical plane film flow are investigated in [14-16]. The results of experimental research regarding the local heat transfer at liquid film flow on the horizontal tubes are presented in papers [17-19]. The questions as how the hydromechanics parameters of gravitational turbulent liquid film are affected by initial velocity of the film have been investigated in [20].

Although many experimental methods has been used to determine film parameters on the wetted surface, most investigations have been done in the stabilized flow region. Few works considered the entrance region both theoretically and experimentally. In fact, the entrance region deals much more often with the turbulent flow than with the laminar flow.

2 Experimental Set-up

The physical situation is considered here for a falling liquid film emerging from a ring-shape slot and flowing down an external surface of vertical tube.

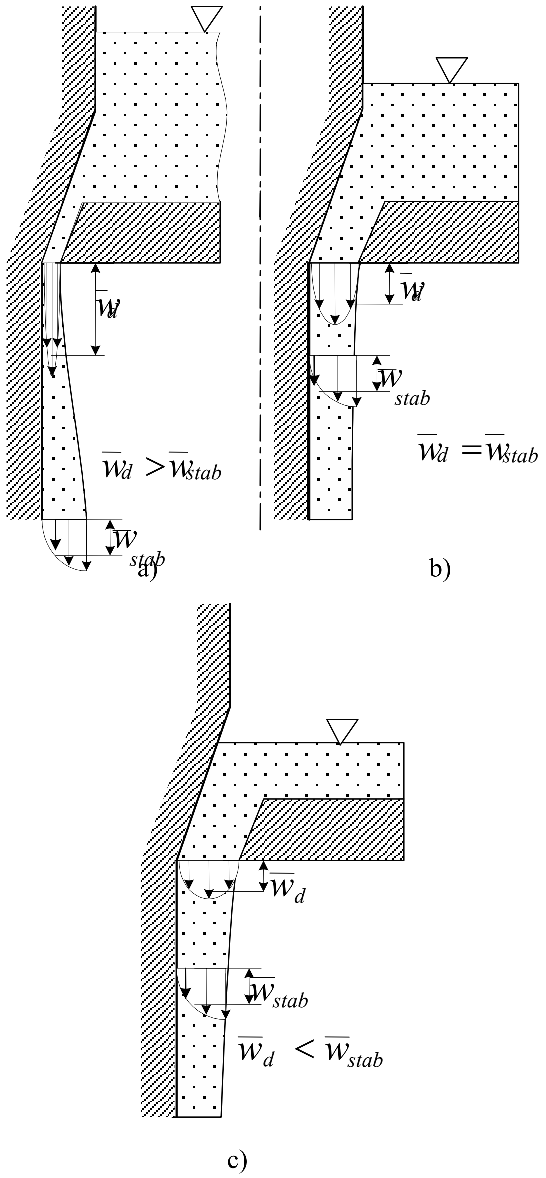

Fig. 1 Velocity profiles predictions for the falling down film in the entrance region at *Re = const*

Fig. 1 illustrates the assumed entrance region scheme. Let us consider the entrance region model as *Re = const*. Reynolds number defines the character of the velocity profile in the slot. In real situation considered here the liquid film accelerates or decelerates to the limiting semi-parabolic velocity profile. The flow decelerates (case a) when initial average velocity of the film exceeds an average velocity of stabilized flow while the thickness of the film increases until stabilization takes place. And otherwise, the film accelerates and gets thinner when initial average velocity of the film in the slot is less than an average velocity of stabilized flow (case c). No doubt, something kind of the film thickness decrease is predictable even when initial average velocity of the film is equal to an average velocity of stabilized flow (case b).

In order to generate the liquid film flow the experimental arrangement (Fig. 2) was applied.

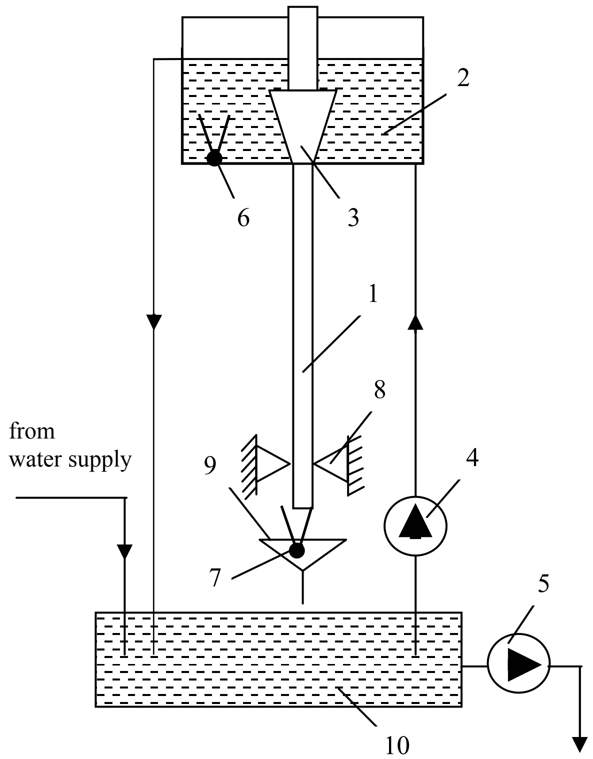

Fig. 2 Schematic diagram of experimental set-up: *1* - calorimeter; *2* - liquid distributor; *3* - slot distributive mechanism; *4* - feed-pump; *5* - exhaust-pump; *6* - inlet thermocouple; *7* - outlet thermocouple; *8* - centering bolts; *9* - gutter. *10* - liquid reservoir

The stainless steel tube 30 mm in outside diameter with the length of 1000 mm was employed in the experiment as a calorimeter. The fixing bolts at the end of tested tube allowed the possibility to regulate and to guarantee verticality of the tube. Water was pumped up to a liquid distributor by feed-pump. At the top end of the tube a slot distributive mechanism was installed to generate the uniform film flow. After flowing down the test tube, the water was gathered back to the reservoir. The gutter at the calorimeter end ensured a smooth falling of the water into the reservoir. The surplus water was discharged to the sewerage by exhaust-pump while the fresh water was supplied from water supply directly. Preliminary investigation has shown that the use of water from plumbing did not influence on the demanded experiment accuracy. That is why fresh water was employed in the research. The temperature of falling down film was measured by two calibrated thermocouples. The location of a thermocouple in the liquid distributor ensured the measurement of film temperature at the inlet. The thermocouple installed at the end of calorimeter had determined a film temperature at the exit correspondingly. As heat flux along the tested section did not change, so to the demanded accuracy of the experiment it was assumed that the bulk mean temperature of the liquid film conforms linear regularity. That circumstance allowed determining the liquid film temperature at any cross-section of the tested section accurately.

For the heat transfer research of falling down water film on the surface of vertical tubes the electric circuit (Fig. 3) was applied. The electric current supplied for the calorimeter provided a steady heat flux on the experimental section. In order to convert an alternating current into a direct current the rectifier was used. Voltages drop on the known value resistor fitted in as shunt determined the electric current strength in the circuit. Its readings were taken from the millivoltmeter. Voltage value on the calorimeter was measured by voltmeter.

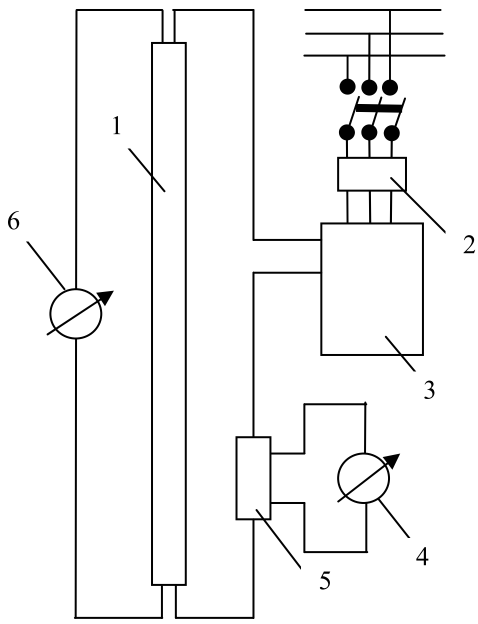

Fig. 3 Electric circuit: *1* - calorimeter; *2* - voltage regulator; *3* - rectifier; *4* - millivolmeter; *5* - shunt; *6* - voltmeter

To investigate the heat transfer intensity to the liquid film falling down a vertical surface the calorimeter (Fig. 4) was constructed.

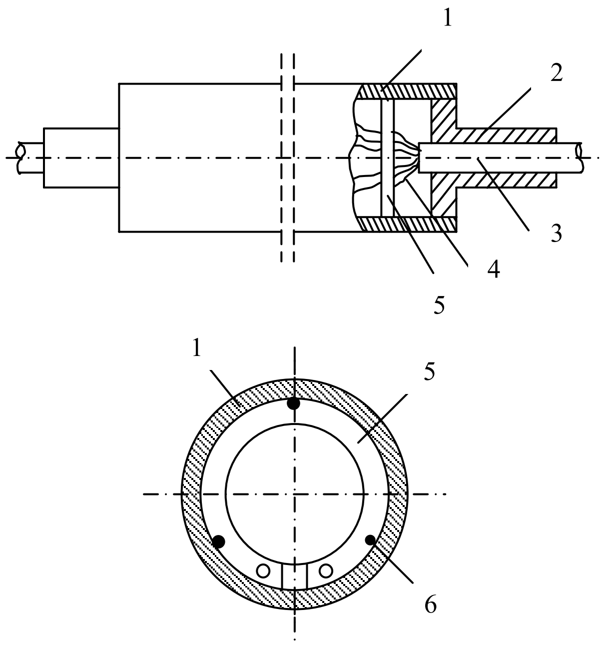

Fig. 4 Calorimeter: *1* - thin-walled stainless steel tube; *2* - tip; *3* - elastic tube; *4* - thermocouples; *5* - elastic plastic ring; 6 - head of thermocouple

The stainless steel tube 30 mm in outside diameter and 1000 mm length was employed in the experiment as the test section. The temperature of inner tube wall was determined by 0.12 - 0.15 mm copper-constantan thermocouples fixed by pressing them to the inner wall surface with elastic plastic rings. In order to avoid the electric current influence on the thermocouples their heads were covered with a thin layer of dielectric lacquer. Thirty thermocouples were located along the inner surface of the calorimeter, by three of them in each of ten cross sections respectively. The millivoltmeter registered the values of thermocouples electromotive force.

3 Local Heat Transfer for a Turbulent Film Flow on a Vertical surface

The water film flowing down a surface of vertical tube was used in experiments. The experiments were provided for Reynolds number ranged from $9.2{\cdot}10^3$ to $10.5{\cdot}10^3$. The temperature of the calorimeter surface and the film, electric current, voltage were measured and recorded during the experiment. After registration of electric current and voltage the heat flux density on the calorimeter surface was calculated. When records of heated tube surface and film flow temperatures were performed, the difference of temperature ΔT (between the mean temperatures of film $\overline{T}_f$ and tube surface T_w) was calculated. Local heat transfer coefficient was computed by formula

$$\alpha = q_w / \Delta T \tag{1}$$

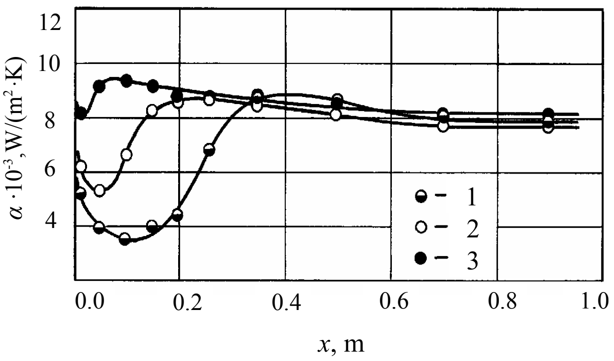

Fig. 5 Variation of local heat transfer coefficient in the entrance region of the film flow down a vertical surface: *1* - *Re*=9240, ε=0.89; *2* - 9300, ε=1.15; *3* - 10540, ε=1.2

Experimental data are presented in Fig. 5. As we can see, alteration of the local heat transfer coefficient in the entrance region is complicated. Three different regions may be delineated along the length of film flow in a case when initial average velocity of the film in the liquid distributor is less than an average velocity of stabilized flow. The significant decrease of the local heat transfer coefficient at some distance from liquid distributor while reaching minimal value is seen at the first region. This phenomenon one can explain by the development of thermal boundary layer and its laminar nature. In the second region, fluid fluctuations begin to develop while heat transfer increases to a maximum value. The beginning of heat transfer stabilization takes place in the third region of the film flow. Augmentation of a thermal boundary layer terminates with the film thickness. The variation of local heat transfer in the entrance region when initial average velocity of the film exceeds or is equal to an average velocity of stabilized film is not high. As we can see from Fig. 5, in all cases the heat transfer stabilization takes place at the distance 0.7 m from the liquid distributor when Reynolds number ranged from $9.2 \cdot 10^3$ to $10.5 \cdot 10^3$.

4 Evaluation of the Heat Losses in the Test Section

The heat losses in the experimental section must be evaluated. Therefore, the method for heat losses evaluation was proposed. Assume that the tube (Fig. 6) is heated electrically.

The heat balance equation for elementary volume of the tube δdx can be written as follows

$$q\delta dx - \lambda\delta \frac{d\vartheta}{dx} = \alpha\vartheta dx - \lambda\delta \frac{d}{dx}\left(\vartheta + \frac{d\vartheta}{dx} dx\right) \tag{2}$$

where: $\vartheta = T_w - T_f$

Let us denote that

$$\frac{\alpha}{\lambda\delta} = a \text{ and } 2\frac{q}{\lambda\delta} = b \tag{3}$$

Rearranging Eq. (2) with the following boundary conditions

$$\vartheta = \vartheta_0,\ \frac{d\vartheta}{dx} = 0 \text{ for } x = 0 \text{ and } \vartheta = \vartheta_L \text{ for } x = L \tag{4}$$

we obtain the following equation

$$\frac{d^2\vartheta}{dx^2} - a\vartheta + 0.5b = 0 \tag{5}$$

Solution of the Eq. (5) leads to the expression

$$\frac{2\left[ab(\vartheta_0 - \vartheta_L) - a^2(\vartheta_0^2 - \vartheta_L^2)\right]^{0.5} + 2a\vartheta_L - b}{2a\vartheta_0 - b} = \exp\left(L\sqrt{a}\right) \tag{6}$$

If notation $\vartheta_L = kb/2a$ is applied, the Eq. (6) can be rewritten to the following form

$$\vartheta_0 = \frac{b}{2a}\left[1 - \frac{2(1-k)\exp\left(L\sqrt{a}\right)}{1 + \exp\left(2L\sqrt{a}\right)}\right] \tag{7}$$

It is not difficult to make sure that

$$\frac{b}{2a} = \frac{Q}{F\alpha} \tag{8}$$

Considering that $\vartheta_0 = q_w/\alpha$, the real heat flux in the experimental section can be determined by the following expression

$$q_w = \frac{Q}{F}\left[1 - \frac{2(1-k)\exp\left(L\sqrt{a}\right)}{1+\exp\left(2L\sqrt{a}\right)}\right] \qquad (9)$$

It should be noted that the largest heat losses exist when $\vartheta_L = 0$ and $k = 0$ while they are not at $k = 1$.

The following inequality has taken place in our research for the experimental section in all cases

$$1 - \frac{2(1-k)\exp\left(L\sqrt{a}\right)}{1+\exp\left(2L\sqrt{a}\right)} \geq 0.995 \qquad (10)$$

Therefore, the heat losses during the experiments were minimal.

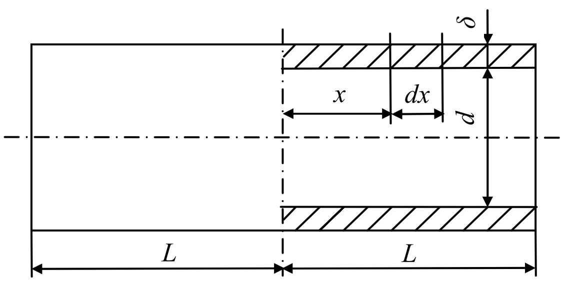

Fig. 6 Experimental tube

5 Conclusions

Heat transfer characteristics in the entrance region of the turbulent film flow were studied experimentally. All experimental tests were conducted on the outside surface of vertical tubes. On the basis of experimental results the following conclusions have been drawn.

1. The turbulent film flow is very complicated and difficult for theoretical study. It is well known that small disturbances associated with distortion in the fluid streamlines of laminar film can eventually lead to turbulent conditions. For a larger Reynolds number the inertia forces are sufficiently large to amplify the disturbances and a transition to turbulence occurs.
2. The existence of the turbulent flow can be advantageous in the sense of providing increased heat transfer rates. However, the motion is extremely complicated and difficult to study analytically. In this case the only possible way is the experiment.
3. The determining effect of film generation on heat transfer takes place in the entrance region of the film flow down a surface of vertical tube. The experimental data revealed that Reynolds number and initial velocity has a significant influence on local heat transfer. It is obtained that heat transfer stabilization occurs at 0.7 m distance from the liquid distributor when $Re > 9.2 \cdot 10^3$.
4. Method evaluating the heat transfer losses in the experimental section has been proposed. It was found that the value of exponent have appeared as $k \geq 0.995$ during the experiments therefore one can confirm that the heat loss is negligible.

Nomenclature

d	inner diameter of the tube (m)
F	surface area of the tube (m^2)
L	length of heated tube (m)
Q	heat flux (W)
q	heat flux density (W/m^2)
Re	Reynolds number of liquid film, $[4\,\Gamma/(\rho\, v)]$
T	temperature (K)
$\overline{w}$	average film velocity (m/s)
x	longitudinal coordinate (m)

Greek Letters

α	heat transfer coefficient $[W/(m^2 \cdot K)]$
Γ	wetted density [kg/(ms)]
δ	thickness of tube wall (m)
ε	relative film velocity, $\overline{w}_d / \overline{w}_{stab}$
λ	thermal conductivity $[W/(m \cdot K)]$
ν	kinematic viscosity (m^2/s)
ρ	liquid density (kg/m^3)

Subscripts

d	distributor
f	film flow
$stab$	stabilized flow
w	wall of tube

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