 


# ALTERATION OF VERTICAL FILM FLOW PARAMETERS IN THE ENTRANCE REGION

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***Abstract.*** *The purpose of the present investigation is to obtain a comprehension for the developments in the entrance region of a turbulent falling film. This paper is related with the analysis the liquid flow through a complicated distributing device that forms a parabolic velocity profile in the liquid film at the entrance to the wetted section. The object of this investigation was to throw more light on the mechanics of developing flow on the surface of vertical tubes in the entrance region. The method for measurement shear stress on wetted surface of vertical tube was proposed. Experimental data showed that shear stress close to liquid distributor depends on initial velocity of the film thoroughly. The length from liquid distributor in which film flow stabilization takes place is obtained. A simple model of laminar liquid film on vertical surface with cross curvature based on force equilibrium equations is presented in the paper. The model permits to evaluate the influence of cross curvature on hydrodynamic parameters of the film. The model can be useful in calculations of film hydrodynamic parameters in apparatus of vertical tube and other installations. Theoretical presumptions concerned with variation velocity field and thickness of falling liquid film are presented in the paper.*

***Keywords***. *shear stress, cross curvature, laminar film, entrance region, turbulent film*

## 1. Introduction

The determination of hydromechanic parameters of liquids in falling films emerging from a slit is interest in many applications of chemical engineering including the treatment of highly viscous fluids such as polymer, food, paint, lacquer and many others. Liquid coolant in the form of thin film has a significant potential utility in high heat absorbing capacity that includes the heat of vaporization. In typical falling film saline water evaporators produces evaporation water vapor from a thin film of saline water flowing down. Proper evaluation of heat exchanger performance and cooling schemes for devices as water-cooled turbine blade and computer chips requires the careful characterization of the transport mechanisms of liquid film. The most of the film apparatus for the thermal treatment of liquid products consists of vertical tubes with falling films on their external surfaces (Gantchev,1987). The topic is also of importance because it aids the understanding and design of pipe systems, heat exchangers, wind-channels and etc.

Casual observation of a thin film on a vertical surface reveals certain important characteristics of the flow. The most obvious feature is unsteadiness of motion. In heat and mass transfer it is extremely important to maintain a fully wetted surface, that is, a continuous film for optimum performance. Throughout the flow length the film is subjected to a wide spectrum of disturbances. The striking characteristic that one notice on observing a vertically flowing film is randomness and irregularity of the surface as well. No doubt effects of this kind leads to alteration of hydromechanic parameters of the liquid film. Simultaneously the intensity of the heat exchange between a wetted surface and liquid is altered. In order to apply a film flow efficiently, the knowledge of exact hydromechanic parameters and consequently heat transfer is very important.

Many papers concerning the film flow have been published. They are collected in references of Gimbutis (1988) and Gantchev (1987), however there is still much to be learned before precise calculations can be carried out for operations involving this phenomenon. Although many experimental methods (Tananaiko et al., 1975; Sinkunas et al., 2002) has been used to determine film thickness, velocity field and shear stress over the wetted surface, most investigations have been done in the stabilized flow region. Few works considered the entrance region both theoretically and experimentally. In chemical engineering applications an estimation of the entrance region length is often required. The question as to how the hydromechanic parameters of gravitational liquid film is affected by initial velocity of film has been investigated in several works (Sinkunas et al., 2002).

The reason for this is that analytical solutions provide better insight to the physical significance of various parameters affecting the film. Presumptions to predict the film thickness, velocity profiles and entrance region length have taken place.

## 2. Influence of cross curvature to shear stress of laminar film

For the elementary ring-form volume of liquid film flow the force equilibrium may be expressed

$$2\pi r\rho g dr dx - 2\pi r\tau dx + 2\pi(r+dr)(\tau+d\tau)dx = 0 \tag{1}$$

The force equilibrium equation can be modified

$$\rho g r dr + \tau dr + r d\tau + dr d\tau = 0 \tag{2}$$

The last member in Eq. (2) is negligible and can be ignored. After some transformation, we obtain the following differential equation describing the momentum transport in the film on the surface of vertical tube

$$r\frac{d\tau}{dr} + \tau + \rho g r = 0 \tag{3}$$

Solution of Eq. (3) in the limits of variable radius r from R to $R+\delta$ leads to the following formula

$$\tau = 0.5\rho\left[\frac{(R+\delta)^2}{r} - r\right] \tag{4}$$

In order to facilitate the analysis of momentum transfer in the film more reasonable is to express the variable radius r using the distance from wetted surface. Variable radius equals

$$r = R + y \tag{5}$$

Placing Eq. (5) into Eq. (4) one can obtain

$$\tau = 0.5\rho\left[\frac{(R+\delta)^2}{R+y} - (R+y)\right] \tag{6}$$

and also the following result

$$\tau = \frac{\rho g\left[(\delta - y) + \frac{1}{2R}\left(\delta^2 - y^2\right)\right]}{1 + \frac{y}{R}} \tag{7}$$

Having in mind that $\left(1 - \rho_g/\rho\right)$<<1, we can substitute the expression $g\left(1 - \rho_g/\rho\right)$ by g.

The shear stress on the wetted surface of the tube (*y*=0) may be determined by Eq. (7)

$$\tau_w = \rho g\delta\left(1 + \frac{\delta}{2R}\right) = \rho g\delta\left(1 + 0.5\varepsilon_R\right) \tag{8}$$

It is possible to find the variation of non-dimensional shear stress across gravitational liquid film dividing Eq. (7) by Eq. (8)

$$\frac{\tau}{\tau_w} = \frac{\delta - y + \frac{1}{2R}\left(\delta^2 - y^2\right)}{\left(1 + \frac{y}{R}\right)\delta\left(1 + \frac{\delta}{2R}\right)} \tag{9}$$

and the following form

$$\frac{\tau}{\tau_w} = \left(1 - \frac{y}{\delta}\right) C_{R\tau}$$

(10)

where the curvature correction factor of the film $C_{R\tau}$ is defined as

$$C_{R\tau} = \frac{1 + 0.5 \dfrac{1 - \dfrac{y}{\delta}}{\dfrac{1}{\varepsilon_R} + \dfrac{y}{\delta}}}{1 + 0.5\varepsilon_R} \qquad (11)$$

For plane wetted surface ($R = \infty$ and $\varepsilon_R = 0$) the curvature correction factor $C_{R\tau} = 1$ and Eq. (10) turns into

$$\frac{\tau}{\tau_w} = 1 - \frac{y}{\delta} \qquad (12)$$

In that way the curvature correction factor corrects shear stress deviations for curvature of wetted surface. Fig. (1) shows the influence of cross curvature of the film on the distribution of relative shear stress across the film.

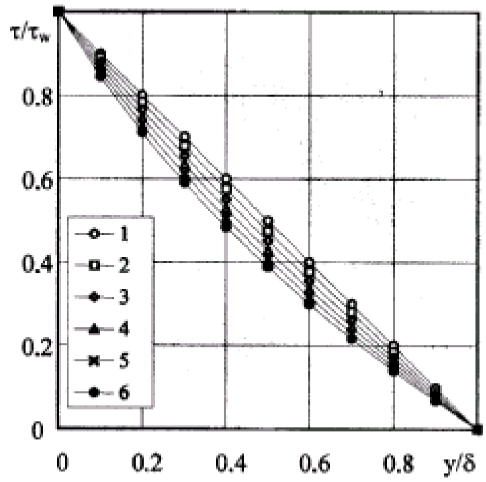



Figure 1. Variation of the relative shear stress in the film with different cross curvature: 1 – $\varepsilon_R$ = 0; 2 – 0.2; 3 – 0.4; 4 – 0.6; 5 – 0.8; 6 – 1.0.

**3. Experimental set-up and procedure**

In order to produce the liquid film flow the experimental arrangement (Fig. 2) was applied. The stainless steel tubes 30 mm in outside diameter and from 500 mm to 2500 mm length were employed in the experiment as a wetted surface. The average roughness of surfaces of tubes has come from 0.008 mm to 0.01 mm and calibrator tested it. The fixing bolts at the end of tested tubes guaranteed verticality of a 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 gravity liquid film flow. After flowing down the test tube, the water was channeled back to the reservoir. The gutter at the end of the tube ensured a smooth falling of the water into reservoir. The surplus water was discharged to the sewerage by exhaust-pump while the fresh water was supplied from plumbing directly. Heater kept the necessary temperature of water. Preparatory investigation has shown the use of water from plumbing did not influence on the demanded accuracy of experiment. That is why the fresh water was employed in the further research.

This test facility was applied to research experimentally both momentum and heat transfer of a liquid film falling down a vertical surface. Few rearrangements in the rig were need. It should be noted that a liquid of great viscosity such as transformer oil was employed without difficulties in this arrangement. Such a sensitive points as an even and smooth liquid distribution in kind of experimental set-up were taken into account to avoid an inaccuracy in measurements. The experiments were performed with an adequate accuracy. Measurement accuracy for determination of the film flow parameters was of range 1.85 – 5.8%.

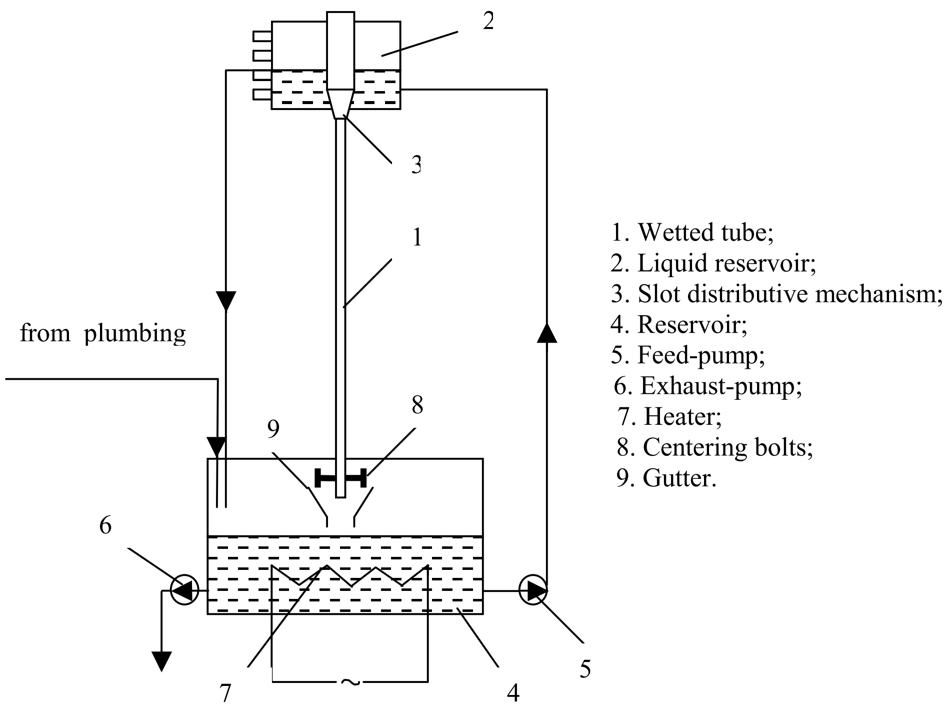



Figure 2. Experimental arrangement.

The construction of a distributing mechanism was carefully adjusted to produce a perfectly annular, evenly distributed flow down the outer surface of the tube is shown in Fig. (3). The axial centering of orifices of the details in liquid sprinkling section took a serious consideration. The contact between surfaces of the components was conforming to a perfect sliding fit as well. These arrangements ensured a uniform distribution of the water in a film of even thickness around the perimeter of the tested tube. The clearances between the tube and distributor were adjusted for a given flow rates by motion several details of distributor. The fixing bolt provided the stability of chosen clearances.

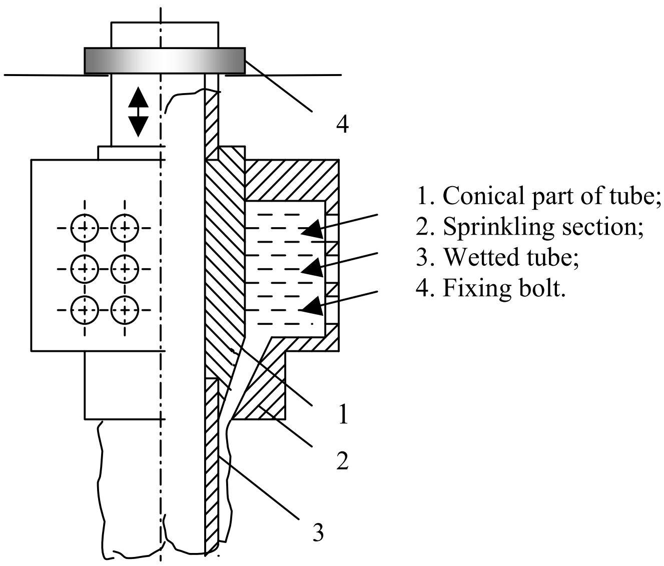



Figure 3. Distribution device for generation of liquid film flow on vertical tubes.

In order to control even water distribution down the surface of the test tube the special device of selection was applied as shown in Fig. (4). The duct brought near the wetted tube would take the portion of the film and channel to the measurement vessel while the protective screen perverted the spray of water getting into one. The yield of water through the duct around the tube was the indicator of even flow distribution. Measurement vessel and timing device was employed to determine the total flow rate. The flow rate was checked at different points of tube perimeter.

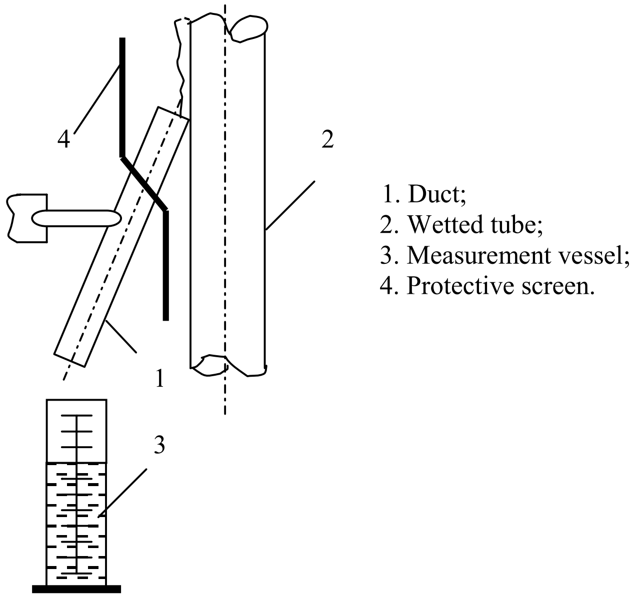



Figure 4. Construction of control device.

The physical situation considered here for a falling liquid film emerging from a ring-shaped slot and flowing along external surface of a vertical tube. We know that when the fluid makes contact with the surface, viscous effects become important and a boundary layer develops with increasing hydrodynamic entry length. This development occurs at the expense of a shrinking in viscid flow region and concludes with boundary layer merger. Following this merger, viscous effects extend over the entire length and the velocity profile no longer changes with increasing wetted section and the distance from the entrance at which this condition is achieved is termed as hydrodynamic entry length.

Before developing a prediction, it is instructive to describe in short the evolution of a thin film flowing down the surface. Consider the slot is sufficiently smooth that flow is established well at edge and continuing surface of a vertical tube is polished enough that gravity driven flow develops downstream. The ambient air exerts negligible viscous traction on the interface and being much less dense than the liquid is modeled by uniform pressure.

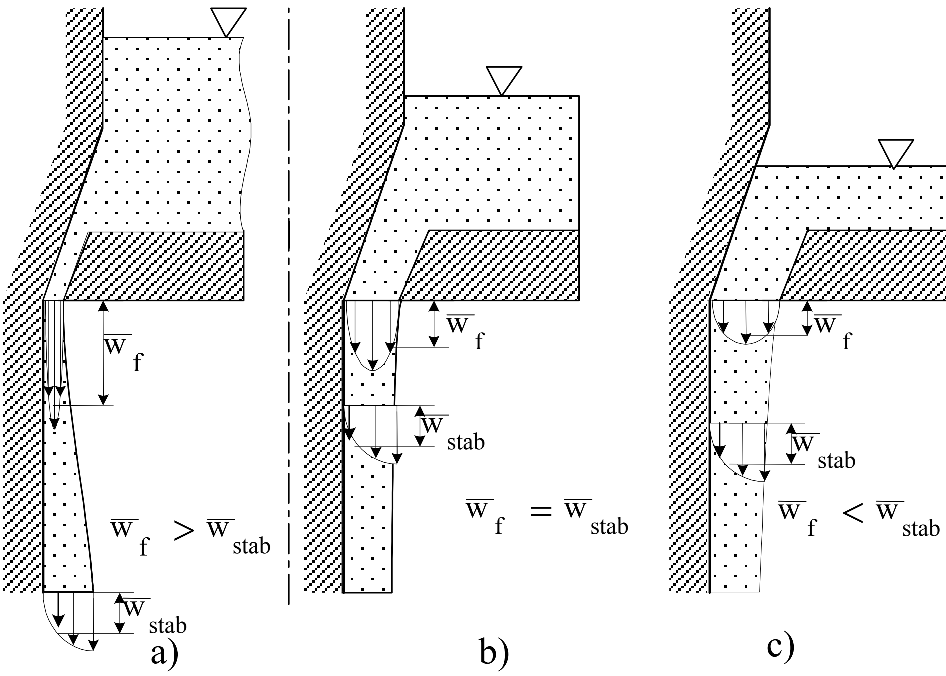



Figure 5. Velocity profiles predictions for the falling film in the entrance region at Re=const: $\overline{w}_f$ – average velocity of film flow in distributor; $\overline{w}_{stab}$ – average velocity of stabilized film flow.

Both the thickness and velocity profile determine the hydrodynamics of a liquid film in essence. These variables have substantial influence over shear stress on wetted surface. The tendency shows itself in the hydrodynamic entrance region especially. The stability of the uniform flow occurs far downstream from the entrance region when the gravity and friction forces on the wetted surface keep their balance. The thickness and velocity profile of the film vary on a large scale. It depends on the initial average velocity in the liquid distributor.

Figure 5 illustrates the assumed entrance region scheme. Let us consider the entrance region model as Reynolds number constant (Re = const). It is presumed that initial parabolic velocity profile is generated at the slot outlet of liquid distributor in any case. The Reynolds number defines the character of the velocity profile in the slot. In the 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 when initial average velocity of the film is equal an average velocity of stabilized flow (case b). The alteration of shear stress on the wetted surface occurs in any case while the turbulent film stabilizes at different distance from the liquid distributor.

**4. Shear stress on vertical surface in turbulent film**

Assume that the shear stress on the wetted surface of tubes under experimental conditions depends on the following factors

$$\tau_w = f(\overline{w}, \rho, \nu, d) \tag{13}$$

From this regularity one can obtain the following dimensionless function

$$\frac{\tau_w}{\rho \overline{w}^2} = f(\mathrm{Re}) \tag{14}$$

where $\mathrm{Re} = 4\,\Gamma/(\rho\nu)$ – Reynolds number; $\Gamma$– wetting density, kg / (ms); $\rho$ – liquid density, kg / m$^3$; w – average velocity of film flow, m/s.

The obtained relationship is inconvenient for working up the experimental data since the calculations of an average velocity of the film $\overline{w}$ is complicated. Thus, by expressing $\overline{w}$ through the equivalent diameter of the film $d$ and by making simple rearrangements, we obtain the function

$$\left(\frac{\eta_d}{\mathrm{Re}}\right)^2 = f(\mathrm{Re}) \tag{15}$$

or

$$\eta_d = f(\mathrm{Re}) \tag{16}$$

where $\eta_d = v^* d/\nu$ – dimensionless film diameter; d – film equivalent diameter, m; $v^* = (\tau_w/\rho)^{1/2}$ – dynamic velocity.

It is not difficult to prove that relation between variables $\tau_w$ and d as follows

$$\tau_w = 0.25\rho d g \tag{17}$$

for the plane wetted surface

$$d = 4\delta \tag{18}$$

for the external wetted surface of vertical tubes

$$d = 4\delta\left(1 + \frac{\delta}{2R}\right) \tag{19}$$

and for internal wetted surface of vertical tubes

$$d = 4\delta\left(1 - \frac{\delta}{2R}\right) \quad (20)$$

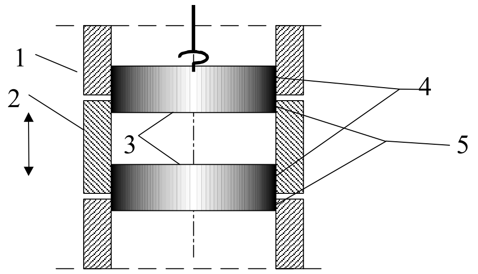
In that way the dimensionless function (16) is more convenient for treatment of experimental data of shear stress on the wetted surface of vertical tubes.

It should be noted that the equations to determine the parameters of the gravitational film are sufficiently complicated. In order to find more simple approach for the evaluation of shear stress on the wetted surface of vertical tubes an experimental method was suggested on the base of formula

$$\tau_w = \frac{P}{S} = \frac{mg}{\pi dl} \quad (21)$$

where m – mass of liquid film on the segment, kg; d – tube diameter, m.

The friction on the wetted surface was determined by weighting a segment of the wetted tube that could move vertically Fig. (6). The experimental measurements have been performed at various initial velocities of the film falling down from liquid distributor. Regulating water level height in the tank of above-mentioned device altered the initial velocity of flow. The segments of different length (from 100 mm to 200 mm) were employed for evaluation of finite effects as the film flowed on and down the segment surface. However, these factors did not influence to the demanded accuracy of experiment. Even if, when the segment was placed at the end of wetted tubes, analytical balance measured the force of shear stress and segment weight exclusively. It should be noted that a vertical motion of the segment between the two fixed tubes was limited to the tune of 1 mm. Water temperature was equal $10^0$C




1. Tube;
2. Segment;
3. Pressed-in cylinder;
4. Sliding surface;
5. Pressing section.

Figure 6. The device for friction determination on the wetted surface of tube.

Experimental data are shown on Fig. (7). As we can see from Fig. (7), the shear stress on the surface of vertical tubes depends upon initial velocity flow from the liquid distributor. In the case when initial average velocity of the film flow less an average velocity of stabilized film the shear stress becomes less than for the stabilized flow. The reverse phenomenon comes about when initial average velocity of the film more than in the stabilized regime. The experimental data revealed that 0.2 m distance from liquid distributor isn't sufficient for the film flow stabilization. The film flow stabilizes at 0.5 m distance from the liquid distributor as a result when Re > $10^4$.

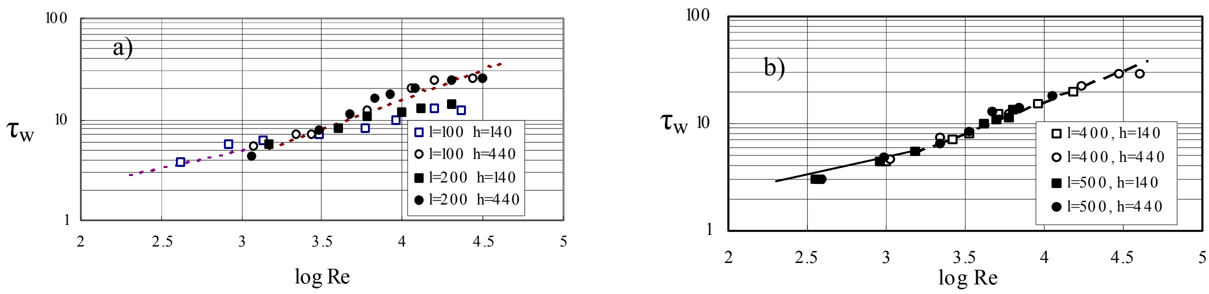



Figure 7. Experimental results of shear stress on the wetted surface: a – distance from liquid distributor 100 – 200 mm; b – distance from liquid distributor 400 – 500 mm; l – distance from liquid distributor to the middle of test segment, mm; h – water level height in the tank, mm.

## 5. Conclusions

1. The model allowing theoretical evaluation of cross curvature influence on shear stress distribution across the laminar film using curvature correction factor is suggested. Relationship for the definition of this factor has been presented in the paper.

2. Theoretical calculations of hydromechanical parameters of the turbulent film in the entrance region of flow by differential equations are complicated. Therefore the experimental method to determine shear stress on the wetted surface of vertical tube for turbulent film was suggested. The shear stress for turbulent liquid film were measured for the film Reynolds number in range from $10^3$ to $10^5$.

3. The shear stress distribution is found to be a function of the Reynolds number and depends upon the initial velocity of the film.

4. Examination of the experimental data revealed that beginning of the film flow stabilization occurs at the 0.5 m distance from the liquid distributor.

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