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Effect of the Flow Velocity of Gas on Liquid Film Flow in a Vertical Tube

Petr Kracík*, Filip Toman, Jiří Pospíšil

Energy Institute, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 61669 Brno, Czech Republic
kracik@fme.vutbr.cz

When gas flows inside a vertical tube in which a thin liquid film runs down its wall, interfacial shear stress occurs at the gas-liquid interface. This stress is caused by the imperfectly smooth surface of the film running down. For intensification of heat transfer in heat exchangers where the vapour condenses, it is necessary to pay attention not only to the thickness of the liquid film on heat exchange surface, but also the character of the liquid film. This paper describes the influence of a gas flow velocity on a liquid film flow. The gas velocity effect is examined for a constant thickness of the liquid film. When the velocity of the gaseous medium changes, it is necessary to increase or decrease the liquid flow in order to keep the film thickness constant. The effect of shear stress is described for three different inner tube diameters (15.0, 20.0, and 25.0 mm) and for three different theoretical film thicknesses derived from the Nusselt criterion. The results are compared with theoretical, analytical relationships. In all the three tube diameters tested, the influence of the gas velocity is the most significant at low speeds, where the deviation from the theoretical course is the greatest. As the tube diameter decreases, the shear stress effect increases. At higher speeds of the gas and liquid film flow, pulsations start to occur, the film flow stops increasing, and the trend follows the theoretical, analytical relationships published in the professional literature.

1. Introduction

Simultaneous motion of gas and a liquid film occurs in a lot of devices used in power engineering and chemical technology. When a liquid film moves along a vertical wall, gravity causes its collapse, which manifests itself on the film surface in the form of waves. If there is a gas with non-zero velocity next to the film, the film oscillation at the gas-liquid interface causes shear stress, which influences the liquid film flow. The theory of laminar film flow caused by gravity was first developed by Nusselt (1916). However, the first mathematical analyses of condensate film flow stability were not performed until the 1970s. Marschall (1973) studied the linear stability of the condensate film flow. The results show that the condensation mass transfer has a stabilizing effect if the temperature drop across the film is constant. Lin (1975) in his work shows that the surface tension variation caused by the temperature fluctuation stabilizes condensate films. Spindler (1982) studied the conditions are studied under which waves are formed on the film surface confirming that the film stability is increased by the condensation process and decreased by vapours, but the critical Reynolds number of the film is very small, and the condensate film is almost constantly located in an unstable area. This fact is supported by drawing conclusions from Marschall (1973)

Trifinov (1996) in his work investigated the formation of waves in the parallel flow of gas and liquid with respect to phase transition and shear stress on the film surface at different angles of inclination using Orr - Sommerfeld equations Francaviglia (1991). The solution shows that the existence of shear stresses on the film surface due to gas movement is significant in the formation of waves even without a phase conversion process. However, the mathematical description of the film wave description brings many difficulties. However, this problem can be simplified in many cases by using several assumptions about the properties of gas and liquid, creating a solid and stable liquid boundary.

Gogonin et al. (1993) described two opposite effects of mass transfer on the film surface. The first mechanism increases the film stability by decreasing its kinetic energy due to the new condensate mass accumulation. The

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second one decreases the film stability due to reaction forces acting on the wavy surface. This effect only occurs at higher condensation intensity. Aktershev and Alekseenko (2005) compared the stability boundaries for co-current and counter-current flow of film and gas in a vertical direction, and they deduced theoretically that during counter-current flow, when the film thickness is small, the condensate flow stops and turns against the gravitational acceleration until the film reaches a critical thickness at which the condensate flow turns back again due to gravitational forces. This critical thickness is a Reynolds number function. When the flow is co-current, the liquid film velocity increases due to the flow speed, which causes a decrease in its thickness. Aktershev (2017) used numerical methods to investigate nonlinear waveforms and their effects on heat transfer. Using an integral boundary model, he created a mathematical model that allows theoretically quantifying heat flow values along a condensing line. It has been shown that the frequency of wave oscillations has a significant influence on the heat transfer. As the frequency of the waves increases, the heat transfer increases.

Condensation film waves have a direct impact on heat and mass transfer in process equipment called condensers. Pashkevich (2015) investigated the influence of Reynolds film number and steam flow on heat transfer in a large diameter tube (about 200 mm). It has been found that increasing the mass flow, which causes an increase in the steam velocity inside the tube, leads to an increase in heat transfer due to greater turbulence and disruption of the condensate film. The waviness of the condensation film is also influenced by the viscosity of the liquid and by the internal stress inside the liquid. This is evidenced by experiments conducted by Kubín (2016), where the effect of mixture velocity on heat transfer in a small diameter tube (about 2 mm) was investigated. Experiments have shown that the effect of mixture velocity on heat transfer is negligible. Phan and Won (2018) created a numerical simulation of condensation inside a vertical pipe with Kuhn (1997) data validation and due to mathematical model can also identify radial components of vapour flow velocity, which have a not negligible effect on the film ripple and on the heat transfer during the phase change. In this work, experiments are conducted to determine the effect of gas flow velocity on the liquid film flow and the results are compared with analytical formulas to calculate the thickness and velocity of the liquid film, including the shear stress at its boundary.

2. Analytical models

The original Nusselt's derivation of a liquid film thickness is a function of the gravitational acceleration. However, it did not include the impact of shear stress between the gas and the liquid. Since the impact of the gas stream on the liquid film is not negligible, it was necessary to extend Nusselt's relation with the impact of shear stress. Shear stress at the gas-liquid interface can generally be written as

$$\tau(y) = \eta_f \frac{du}{dy} \, , \tag{1}$$

where $\frac{du}{dy}$ is a velocity gradient perpendicular to the vertical velocity. For use in calculations, Blangetti (1980, 1982) used the following analytical formula for shear stress

$$\tau_g = \frac{f}{2} \cdot \rho_g \cdot \left(u_g^2 - u_f^2\right) , \tag{2}$$

which involves the gas velocity relative to the liquid and a friction factor whose value can be graphically read from Bergelin (1949). This modification was later adopted by many authors. For example, Maheshwari (2004) simplified a form of Eq(2), where he neglected the liquid velocity, and the shear stress is only calculated from the absolute gas velocity. In 2008, Lee and Kim (2008) suggested an analytical relation for the friction coefficient at a two-phase flow interface

$$f = \, 0{,}316 \cdot Re_g^{-\frac{1}{4}}. \tag{3}$$

The Reynolds number linking the inertia force and viscosity are important for determining the gas flow mode in the tube. The value of the Reynolds number for forced flow inside the pipe can be calculated according to VDI Heat Atlas (2010)

$$Re_g = \frac{u_g (d_i - 2 \cdot \delta) \rho_g}{\eta_g} . \tag{4}$$

It is obvious from the equation that to determine the film thickness, we must know the liquid mass flow related to the tube circumference.

$$\Gamma = \frac{g \cdot \rho_f \cdot (\rho_f - \rho_g) \cdot \delta^3}{3 \cdot \eta_f} + \frac{\rho_f \cdot \tau_g \cdot \delta^2}{2 \cdot \eta_f}. \tag{5}$$

Lee and Son (2018) carried out a numerical simulation of steam condensation in a vertical tube and proposed a relation for shear stress

$$\tau_g = 3 \cdot \eta_g \cdot \frac{u_g}{R_i}. \tag{6}$$

The average liquid film velocity, besides others, was expressed from the simulation based on the following equation

$$\overline{u_f} = \frac{\frac{(\rho_f - \rho_g) \cdot g \cdot \delta^2}{3 \cdot \eta_f} + \frac{\delta \cdot \tau_g}{2 \cdot \eta_f}}{1 + \frac{3 \cdot \eta_g \cdot \rho_f \cdot \delta^2}{2 \cdot \eta_f \cdot \rho_g \cdot R^2}}, \tag{7}$$

which can be modified and used to calculate the liquid mass flow related to the cross-sectional area of the tube. If the liquid film mass flow is known, wthe film thickness can be determined in much the same way as from Eq(5).

3. Experiment

3.1 Experimental device

Figure 1 shows a diagram of the testing device, which is primarily composed of a top container, a bottom container and a monitoring glass tube. The glass tube is attached to the top container with a flange in which the glass tube is glued. The length of the experimental section of the tube is 1.2 m. The thickness of the film running down inside the tube is controlled by a cone through which a gaseous medium can run into the tube. The same cone is also placed at the bottom tube opening, and it enables driving the gaseous medium in against the liquid film flow.

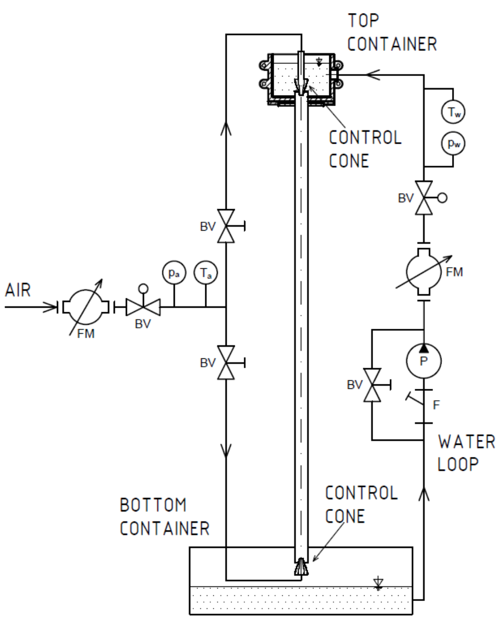

Figure 1: Experimental loop scheme

Due to this fact, it is possible to measure the effect of flowing air on the liquid film for co-current and counter-current flow of liquid and air. As the gaseous medium, the authors used compressed air, which was brought from the central air distribution system . The water circulation is secured using a pump. On the side of both the water and air mass flow is measured. Air and water are not heated or cooled, and due to this, their temperature is around 20 °C.

3.2 Determining the shear stress effect

When the air was not driven in the tube through the cone (approx. 0.0 m·s^{-1}), the water level in the top container was measured for the selected flow rate. From the circumferential flow, the theoretical film thickness was calculated based on Nusselt's gravitational theory using the following equation

$$\delta = \sqrt[3]{\frac{3 \cdot \eta_f \cdot \Gamma}{g \cdot \rho_f \cdot (\rho_f - \rho_g)}}. \tag{8}$$

The impact of the airstream on the liquid film flow is given by the decrease in the water flow rate, according to Eq(5) necessary to keep the water level in the top container constant. A constant water level ensures theoretically a constant film thickness at any water flow rate.

4. Experiment

The effect of shear stress was tested on glass tubes with the inner diameter of 15.0, 20.0 and 25.0 mm. Figure 2 shows the values of the circumferential flow depending on the flowing air velocity with the theoretical constant thickness of the liquid film being 2.0 mm. The theoretical flow behaviours are also plotted in Figure 2 based on Blangetti (1982), curve marked "BLANGETTI", and Kim (2008), curve marked "KIM", analytical equations. A positive value for air velocity means a co-current flow of air and liquid; negative values for air velocity indicate a counter-current flow.

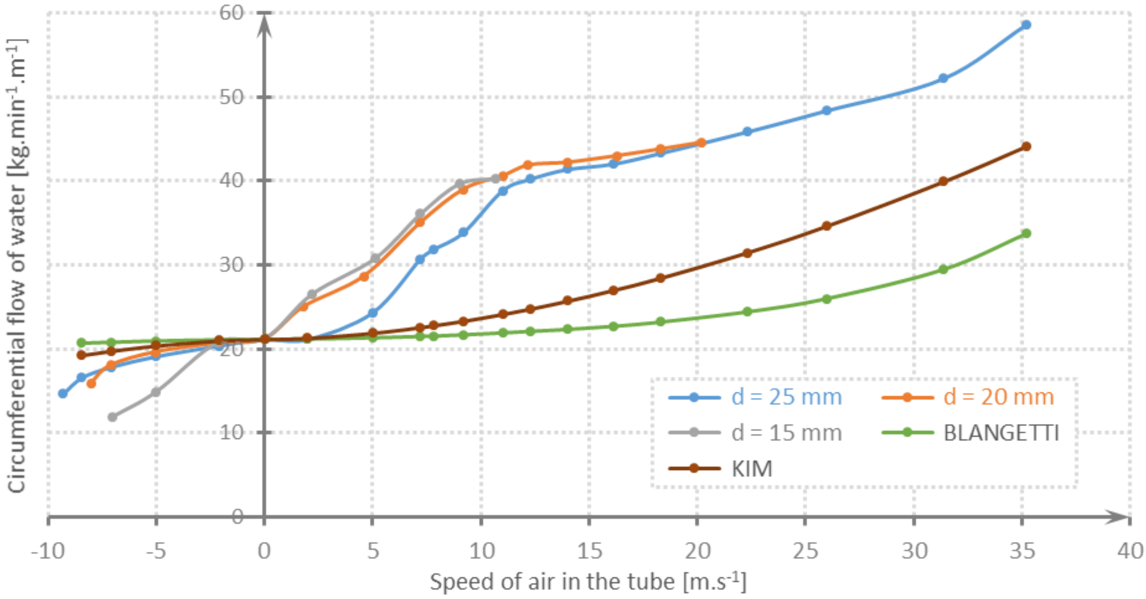

Figure 2: Circumferential flow for the given tube diameters

It is clear from the comparison that for the co-current air and film flow, the real flow rates differ considerably from the theoretical ones. Shear stress at a lower air velocity has the greatest impact on the liquid film flow rate. In the interval from approx. 2 to 10 m·s^{-1} the flow rate increases rapidly for all the diameters tested. From the velocity of approx. 10 m·s^{-1} the flow rate increase gets slower, and the shape of the curve representing the further flow rate increase resembles the theoretical behaviour. With a larger tube diameter, the flow rate increases more slowly at a lower air velocity; however, at the velocity of about 12 m·s$^{-1,}$ the difference between the diameters is equalized. From this behaviour, we can deduce that, at a lower air velocity, the effect of shear stress on the liquid film of the same thickness increases as the tube diameter decreases.
The effect of the air stream in the counter-current flow is opposite to that in the co-current flow. As the tube diameter decreases, the effect of shear stress on the liquid film increases and its flow rate through the tube decreases.

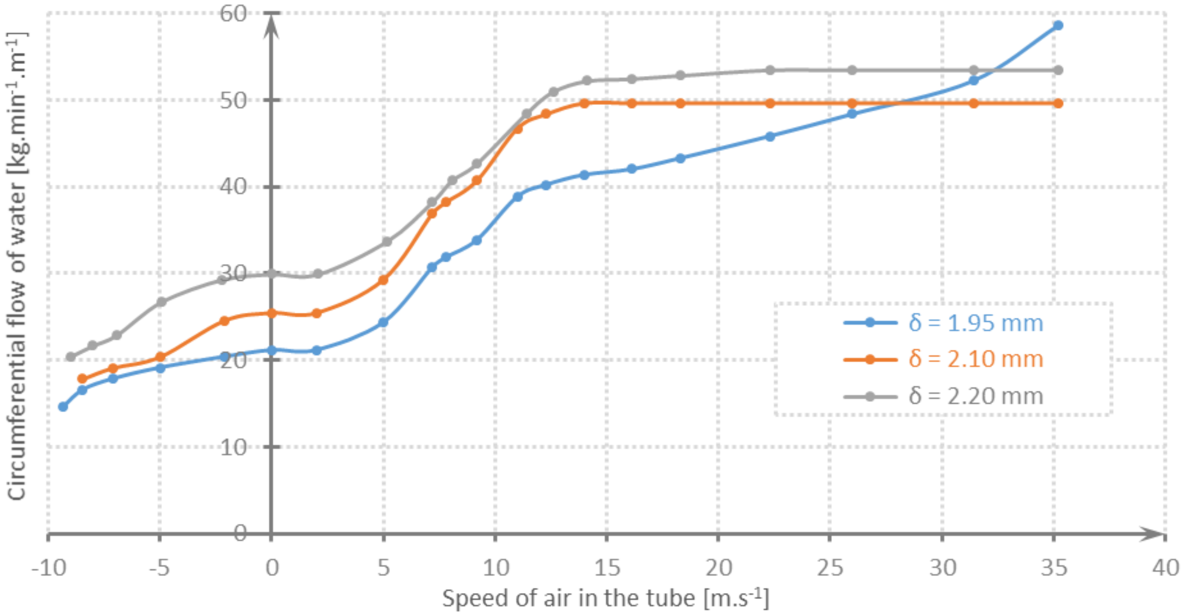

Figure 2: Circumferential flow for a given liquid film thickness in a tube of 25 mm

Figure 3 shows the effect of an airstream on the liquid film of given thicknesses. It is clear from the figure that the effect of shear stress is very similar to the film thickness increases. If the air velocity is higher than approx. 12.5 m·s^{-1} for the theoretical film thickness of 2.1 and 2.2 mm based on Nusselt's relation, the flow rate does not increase anymore because the air stream is not able to accelerate the liquid film sufficiently and the inlet tube flare gets flooded, which leads to the occurrence of pulsation. This effect could be suppressed by a larger pipe diameter.

5. Conclusions

This paper examines the effect of shear stress on a liquid film flow rate in a vertical tube. Experiments have shown that the effect of shear stress is significant. When the air velocity inside the tube increases, shear stress at the gas-liquid interface increases. As a result of this phenomenon, the film velocity, with a constant thickness, increases, and so does its flow. The most significant effect of air was detected at a lower velocity of up to approximately 10 m·s^{-1}. At higher speeds, the film flow is gradually increasing, and the growth curve corresponds to the theoretical charts, but it is shifted by initial rapid growth. Another factor influencing the film flow rate is the tube diameter. The experiments showed that as the tube diameter decreases, the effect of shear stress increases up to certain air velocity. At higher film thicknesses, as the airspeed increases, pulsations occur, where the flow of liquid stops for a while, and then more amount of liquid is plucked. These pulsations cause tube flooding, and the film flow can no longer be increased.

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