Gas content of a liquid in threaded roughness recesses and its effect on heat and mass exchange

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Abstract. This paper proposes a mechanism of gas bubble formation in a down-flowing liquid film as a result of reduced pressure in circulation zones of threaded roughness recesses. Simulation modelling on the Comsol Multiphysics software was used to calculate circulation loops, liquid velocities, and pressure. Thus, the accepted of gas bubble formation was justifying. We experimentally determined gas content along film thickness and its average value, and proposed an equation for calculating gas content along liquid layer thickness. The effect of gas content on the average thickness of a liquid film, as well as its heat and mass transfer, was confirmed.

1. Introduction

The use of falling film tubular apparatus is widely encountered in the chemical, petrochemical and other industrial process equipment, where heat and mass transfer phenomena take places, such as absorber, column, falling film reactor, and liquid film evaporator [1-6].

The location of large-scale threaded roughness on the inner surface of tubes in the machine with a down-flowing film (figure 1) contributes to an increase in the interphase surface and liquid output [7-10]. Threaded roughness provides the translational and rotational motion of a liquid, which allows maintaining a stable film flow on the film-forming surface. The flow around the roughness projections causes circulation loops [11-13], which intensifies liquid mixing and ensures gas bubble formation in a liquid.

Various devices have been developed on the basis of this phenomenon. For example, gas-liquid bioreactors in which pipes with helical roughness are installed. This made it possible to increase their productivity and reduce operating costs, [5,14]. We tested the design of a scrubber of high gas and liquid throughput with its tubes having threaded roughness [15]. An anti-foaming agent and a flotator [16] with low power consumption were developed. We additionally studied a barometric condenser in which a gas condenses on the surface of a liquid film, which is actively mixed due to the presence of threaded roughness, which allowed intensifying heat transfer during vapour-gas medium condensation.

A design of a film heat exchanger [17] made of profiled plates forming cylindrical channels with a stable flow of a liquid film provided by threaded roughness was developed.

One of the factors limiting the widespread introduction of the studied film machines with large-scale threaded roughness is insufficient knowledge of the hydrodynamic parameters of a down-
flowing liquid film, and the mechanism of gas bubble formation and distribution in roughness recesses, which affects both the flow hydrodynamics and heat and mass exchange parameters.

![Image](image1.png)

**Figure 1.** Tubular packing of a film apparatus with a roughness (a) and a gas-liquid layer on the surface of the packing (b).

We suppose that gas bubbles in a liquid film are formed due to the movement of gas located above the film into the recess of the circulation zones formed behind the roughness projection.

To confirm this hypothesis, we conducted experimental studies and simulated the parameters of a down-flowing liquid film along threaded roughness turns.

2. Results and discussion

The studies were conducted using in tubes with an internal diameter of 0.04 and 0.05 m, up to 2.0 m long. A water film flowed down the inner surface of the tubes and absorbed air from the atmosphere. Threaded roughness was made of wires of diameter h = 1.5-4.0 mm in the form of a spiral of along the tube with parameter s/h = 3-12, where s is the distance between the spiral adjacent turns.

Average flow and angular velocities were determined by the tracer method consisting in injecting dye into a down-flowing film while simultaneously surveying the tracer motion trajectory in slow mode. With the loop closed, the survey was stopped and the time the tracer took following the trajectory determined.

The magnitude of gas content (a gas volume fraction in a liquid) along the height of the liquid layer was determined in the recess using the volumetric method by removing the gas-liquid mixture from a specific distance from the tube wall through a hollow needle equipped with a small transparent pipe of diameter 3.0 mm.

The liquid surface tension was changed by adding ethanol to the tubular nozzle, and ranged from 760 to $550 \times 10^{-4} \text{ kg/s}^2$.

Simulation modeling was carried out using the interactive environment Comsol Multiphysics based on partial differential equations [18]. The calculation was carried out using the “Fluent” package with automatic generation of the mesh and its refining in the area of changing modes and directions of movement.

According to the data obtained, we established water film flow modes on the surface of the threaded roughness tube (figure 2). With small liquid flow rates, there is a jet flow mode where the liquid escapes from the surface of the threaded roughness turns and forms jets, and gas bubbles are locally observed in the roughness recesses (figure 2a). With an increase in liquid flow rates, an annular film flow mode occurs (figure 2b and figure 2c). The roughness recesses have accumulated gas bubbles that are formed at a specific distance (equal to $\delta_o$) from the tube wall. The thickness of the
liquid layer in the tube $\delta_o$ is influenced by the volumetric flow rate of the liquid and the dynamic viscosity coefficient. When the tube cavity is flooded with a liquid, a flooding mode occurs (figure 2d), and gas bubbles are washed out and taken away with the liquid flow.

![Image](image1.png)

**Figure 2.** Modes of a falling water film on the inner surface of a pipe with roughness: $d=40$ mm, $h=3$ mm, $\mu=0.0015$ Pa·s, $s/h = 10$.

Based on the hypothesis on the gas bubble in the film are formed in a roughness recess, flow parameters were simulated. Figure 3 shows the research results. According to the data obtained, circulation vortices are observed behind the roughness projection (figure 3a). The formation of these vortices and the occurrence of reverse currents (figure 3b) are influenced by the flow rate, the parameter $s/h$, the increase in the roughness projection and the dynamic viscosity coefficient of the liquid.

![Image](image2.png)

**Figure 3.** Distribution of fluid velocity in the cavity over the pipe section a) $s=15$ mm, b) $s=38$ mm.

It was also established that in the roughness recesses, at a distance of $y_1$ from the wall, local circulation zones are formed with the lowest pressure as compared to the gas pressure above the film surface. With an increase in the roughness projection height, roughness parameter $s/h$ and liquid average flow rate, the pressure drop $\Delta P$ between the gas above the film surface and the pressure in the circulation zone increases (figure 4a). At that, the distance $y_1$ from the tube wall to the local zone centre increases (figure 4b).
The fact that the $y_1$ design value and the $\delta_0$ experimental value coincide allows asserting that the local zones with a reduced pressure of 4-100 Pa, Figure 4a are gas bubble formation centres in the roughness recesses.

The experimental change in the local gas content along the thickness of the down-flowing liquid film is shown in figure 5. As the liquid flow rate increases leading to an increase in the liquid film thickness, the gas content decreases.

At $h = 4$ mm, $s/h = 6$. Experimental points: (1) $\mu = 0.00134$ Pa·s; $h = 1$ mm; (2) $h = 2$ mm; (3) $h = 4$ mm; (4) $h = 5$ mm; (5–7) $\sigma = 550 \times 10^{-4}$ kg/s$^2$; (5) $y = 1.5$ mm; (6) $y = 3.5$ mm; (7) $y = 4.5$ mm.

**Figure 5.** Dependence of the gas content over the thickness of the liquid layer depending on the density of irrigation (a) and the average gas content on the height of the protrusion (b) at $Re = 5600$, $s/h = 6$, $\mu = 0.00134$ Pa·s (a) and average gas content (b) at $d = 51$ mm; $s/h = 5$; $L = 2$ m; $\mu = 0.001$ Pa·s; $G = 0.0055$ m$^3$/s/cm).

Based on experimental data, a dependence was obtained to calculate the gas content along the liquid layer thickness in the recess in the form of

$$\phi_i = A \cdot G^{1.2} (y/h)^{0.4} (\sigma/\sigma_0)^{-1.5},$$  

When $A = 4 \cdot 10^{-4}$, at $\mu = 0.00035 - 0.0014$ Pa·s, $\sigma = (760-500) \times 10^{-4}$ kg/s$^2$, $y/h < 1.25$. 

(a) parameter $s/h$ (b) at $x/s = 0.5$ a) calculated lines (1–3): 1) $s/h = 4$, $u_{av} = 0.8$ m/s; 2) $s/h = 10$, $u_{av} = 0.8$ m/s; 3) $s/h = 7$, $u_{av} = 1.0$ m/s; 6) $h = 3$ mm, $u_{av} = 0.8$ m/s.

**Figure 4.** Dependence of the pressure drop on the height of the protrusion of the round profile: (a) and ratio $x/s$ (b): a) $s/h = 6$; $x/s = 0.5$; calculated lines (1–2): 1) $u_{av} = 1.0$ m/s; 2) $u_{av} = 0.5$ m/s; b) $h = 4$ mm; $s/h = 10$; $u_{av} = 0.5$ m/s.
It is recommended to calculate the thickness of the wall single-phase layer $y_1$ corresponding to the minimum value $y$ in equation (1) using the numerical modelling method described above.

Figure 6 shows the average velocity measurement results of the gas-liquid medium down-flowing film

![U, m/s](image1)

![ω, s⁻¹](image2)

**Figure 6.** Change in the average speed of the film flow down (a) and the angular speed of rotation (b) from the Reynolds number at $d = 46$ mm; $h = 4$mm; $s / h = 4 - 6$. Experimental points at water temperature: ◊ – 12 °C; □ – 26 °C; ■ – 60 °C.

According to the data, the average film velocity varies from 0.4 to 0.8 m/s and grows as the Reynolds number of the liquid increases. An increase in the dynamic water viscosity coefficient leads to an increase in the liquid flow rate, which contradicts known information [19-21]. This is apparently due to the presence of gas bubbles in the liquid [22] and their effect on the viscous friction force. The liquid rotation rate increases with an increase in the supplied liquid flow rate and the dynamic viscosity coefficient, and is $10^{-50}$ s⁻¹ (figure 6b).

As established experimentally, the presence of gas content in the film increases the average film thickness by 1.3 - 1.5 times, which is consistent with the data.

The results of the heat transfer study during heating in the film of liquid [16] flowing down the heat exchange surface with threaded roughness also show a significant effect of the gas content on heat transfer, which is due to the formation of gas bubbles in the liquid and, as a result, a decrease in the thermal conductivity of the gas-liquid medium.

During the absorption in the film of water flowing down the threaded roughness surface [10], in connection with gas bubble formation, gas contact with the film surface and gas bubble interaction in the liquid film are considered mass transfer. Using this approach, the mass transfer coefficient between the gas bubbles and the liquid is $(0.8-2.0)10^{-3}$ m/s, and the magnitude of the mass transfer coefficient in the film is $(2 - 8)10^{-3}$ m/s.

The results obtained are used to calculate and design tubular film machines.

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References
[1] Salvagnini W M and Taqueda M E S 2004 A falling-film evaporator with film promoters *Ind. Eng. Chem. Res.* **43** 6832-
[2] Ma X, Chen J, Li S, Sha Q, Liang A, Li W, Zhang J, Zheng G and Feng Z 2003 Application of absorption heat transformer to recover waste heat from a synthetic rubber plant Appl. Therm. Eng. 23 797-806

[3] Leu J S, Jang J Y and Chou Y 2006 Heat and mass transfer for liquid film evaporation along a vertical plate covered with a thin porous layer Int. J. Heat Mass Transf. 49 1937-45

[4] Battisti R, Machado R A F and Marangoni C 2020 A background review on falling film distillation in wetted-wall columns: From fundamentals towards intensified technologies Chem. Eng. Process. - Process Intensif. 150 107873

[5] Voinov N A, Zhukova O P and Nikolaev A N 2013 Intensification of yeast biomass culturing in a film bioreactor Foods Raw Mater. 1 57-66

[6] Guichet V and Jouhara H 2020 Condensation, evaporation and boiling of falling films in wickless heat pipes (two-phase closed thermosyphons): A critical review of correlations Int. J. Thermofluids 1-2 100001

[7] Voinov N A, Konovalov N M and Nikolaev A N 1993 Features of free flowing of a liquid film along the inner and outer surfaces of pipes with a regular helical roughness Theor. Found. Chem. Eng. 638

[8] Kohrt M, Ausner I, Wozny G and Repke J U 2011 Texture influence on liquid-side mass transfer Chem. Eng. Res. Des. 89 1405-13

[9] Voinov N A, Nikolaev A N and Vojnova O N 2009 Hydrodynamics, warm mass transfer in film bioreactors Chem. plant raw mater. 4 183-93

[10] Voinov N A and Nikolaev A N 2008 Film tubular gas-liquid reactors (Moscow: Otechestvo)

[11] Cao B Y, Chen M and Guo Z Y 2006 Effect of surface roughness on gas flow in microchannels by molecular dynamics simulation Int. J. Eng. Sci. 44 927-37

[12] Davies J T and Warner K V. 1969 The effect of large-scale roughness in promoting gas absorption Chem. Eng. Sci. 24 231-40

[13] Brumfield L K, Houze R N and Theofanous T G 1975 Turbulent mass transfer at free, gas-liquid interfaces, with applications to film flows Int. J. Heat Mass Transf. 18 1077-81

[14] Voinov N A, Zhukova O P, Temerov F V and Alashkevich Y D 2015 Film gas-liquid bioreactor Chem. Ind. 92 156-9

[15] Voinov N A, Nikolaev N A and Eremenko N A 2006 Film tubular apparatus with helical roughness Chem. Ind. 83 285

[16] Voinov N A and Nikolaev A N 2011 Heat Withdrawal in Liquid Film Flow (Otechestvo)

[17] Vojnov N A and Zemtsov, Denis Andreevich Zhukova, Ol’ga Petrovna Alashkevich J D 2006 RU 2 569 118 1-10

[18] Abd Ali M K 2014 CFD simulation of bubbly flow through a bubble column Int. J. Sci. Eng. Res 5 904-10

[19] Laptev A G, Basharov M M, Lapteva E A and Farakhov T M 2015 Models of interphase transport and calculation of process efficiency

[20] Laptev A G and Lapteva E A 2015 The model of heat and mass transfer in rough and irrigated ducts Thermophys Aeromechanics 22 435-40

[21] Picioreanu C, Van Loosdrecht M C M and Heijnen J J 2000 A theoretical study on the effect of surface roughness on mass transport and transformation in biofilms Biotechnol. Bioeng. 68 355-69

[22] Salmi T O, Mikkola J-P and Warna J P 2010 Chemical reaction engineering and reactor technology (CRC Press)