Thin film flow of a liquid down smooth and rough surfaces
Proceedings of European Congress of Chemical Engineering (ECCE-6)
Copenhagen, 16-20 September 2007

# Thin film flow of a liquid down smooth and rough surfaces

L. Broniarz-Press, D. Dulska, S. Woziwodzki

*Department of Chemical Engineering and Equipment, Poznan University of Technology, pl. M. Sklodowskiej-Curie 2, PL 60–965 Poznan, Poland*

## Abstract

In the paper the results of the studies on an effect of surface modification on the thickness of falling liquid film, have been presented. The artificial roughness of the surface was obtained by coating using the corundum grains. It has been shown that the increase of the mean film thickness, in comparison with smooth plate, for all rough surfaces in turbulent flow range exists. The greatest effect (about 50%) for the plate coated by the grain-size distribution from 300 to 710 μm was observed

Keywords: falling film, film thickness, rough plate

## 1. Introduction

One of the most effective methods of increasing the rate of processes of heat and mass transfer is to carry them out in thin films. Very often in such a system the liquid flows in the form of a film in a pit along a wall, and the external surface of the film is free. Apparatus of the film type (plane-parallel or tubular) has a very low hydraulic resistance and a relatively high throughput of gas and liquid (Fulford, 1964). The occurrence and applications of film flow in modern technology are numerous and important. Omitting the field of chemical engineering for the moment, the following applications of the thin film flow have been found: film cooling of rocket motors, turbine blades, reactor tubes, conveying of liquids by co-current gas streams (in oil pipelines, boiler tubes etc.), design of channels, camber of roads, drainage works. In chemical engineering the interest in film flow has increased rapidly last years with special attention to the effects of wall roughness and surface active materials. Typical modern applications of gas/film flows in the process industries are trickling-type cooling towers, wetted-wall towers for rectification and gas absorption/desorption as well as various types of coolers, condensers and evaporators.

The flow of a liquid film down smooth surfaces is very complex and various mechanisms are distinguished in it. In literature there is an ambiguity concerning the mechanisms themselves and the critical values characterizing the change in flow conditions (Broniarz-Press, 2004).

In most of the works reported in the literature it is assumed that the roughness effect on enhancement of transfer processes in the turbulent region of a process has existed. There are several reports in the literature of the critical Reynolds number at which the turbulent film flow commences. These values are usually determined from the breaks which appear in the curves of film thickness, surface velocity of the film as well as heat or mass transfer coefficients in the film when plotted against Reynolds number.

The effect of natural and artificial roughness on mean film thickness flowing down vertical steel tubes was an object of the studies of Voroncov (1969, 1978). The surfaces used were as follows: with perpendicular, longitudinal and chessboard incisions. The effect of the corrosion was also studied. The measurements were performed in the range of Reynolds number ($Re_e$) values from 15 to 16,800. It has been shown that shape and dimensions of the rough elements effect on hydrodynamics of falling liquid film. Mean thickness of films flowing down the tubes with artificial roughness was greater than this one observed in a flow down smooth or corrodible surfaces.

## 2. Experimental

The experiments were performed using two types of plates of 241 mm width and 1165 mm length: smooth constructed from organic glass and rough (coated with grains of abrasive material of various size distributions). The test installation is presented in Figure 1. The plates were inclined to horizontal at an angle $\theta$ equal to $24^o$.

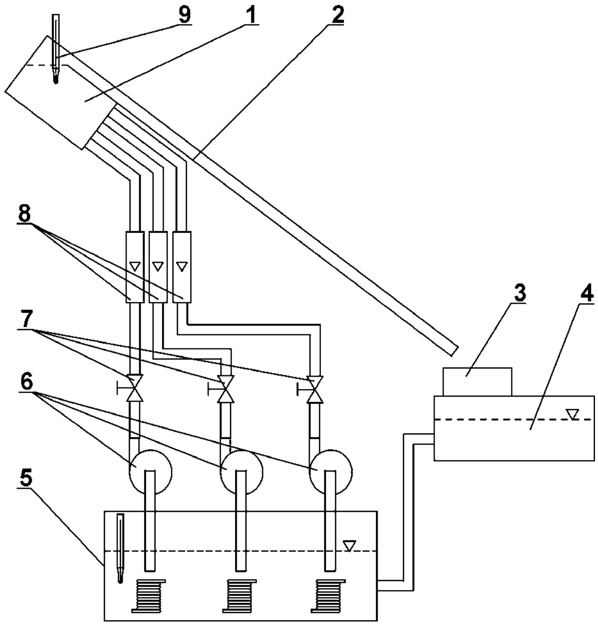


Fig. 1: Experimental setup: 1 – overflow tank, 2 – plate, 3 – calibrating tank, 4 – auxiliary tank, 5 – main tank, 6 – pumps, 7 – valves, 8 – rotameters, 9 – thermometers

In the study two Newtonian liquids were used: water of viscosity of $\eta = 10^{-3}$ [Pa·s] and density of $\rho = 998.2$ [kg/m$^3$], and aqueous solution of glycerol (55%) of viscosity of $\eta = 7.24 \cdot 10^{-3}$ [Pa·s] and density of $\rho = 1120$ [kg/m$^3$] at measurement temperature of $T = 293$K. The measurements of the mean film thickness $s$ were carried out using the flow cut-off technique proposed by Classen (1918). In this place it should be underlined that in thesis of Dulska (2004) it has been shown that the mean values of liquid film thickness obtained using various techniques are comparable.

The artificial roughness of the wall down which the liquid film flowed was obtained by monolayer coating of the plane surface using the corundum grains of various sizes: 125÷300 μm (plate branded as P100) and 300÷710 μm (plate branded as P40).

The experiments were performed for surface wetting rates $\Gamma$ changed from 0.075 to 0.8 [kg/(m·s)]. The experimental results are presented in Figs. 2 and 3, separately for laminar (glycerol aqueous solution) and turbulent falling flow regimes.

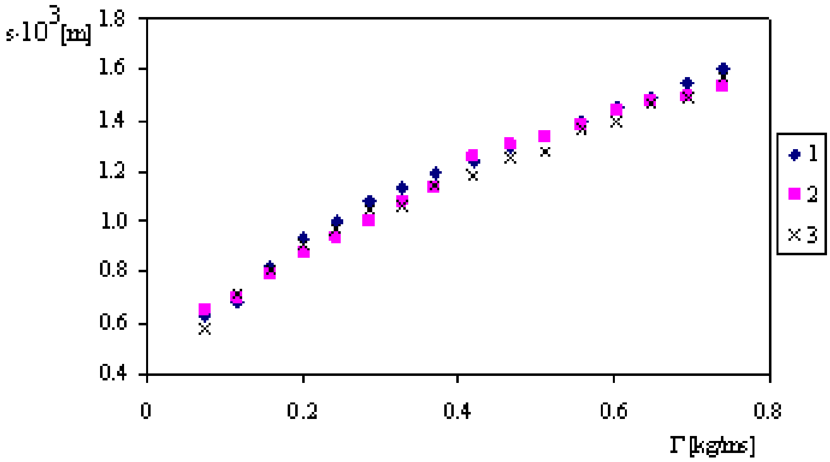


Fig. 2. Effect of surface coating on mean film thickness in laminar flow (glycerol aqueous solution): 1 –plate P40, 2 –plate P100; 3 – smooth plate

It has been shown that in laminar falling liquid film the roughness does not effect on the mean film thickness. The values are comparable and lie in the region of the measurement error. The evident effect is observed in turbulent film flow (water data). With the increase of the mean surface roughness the mean thickness of a film has increased.

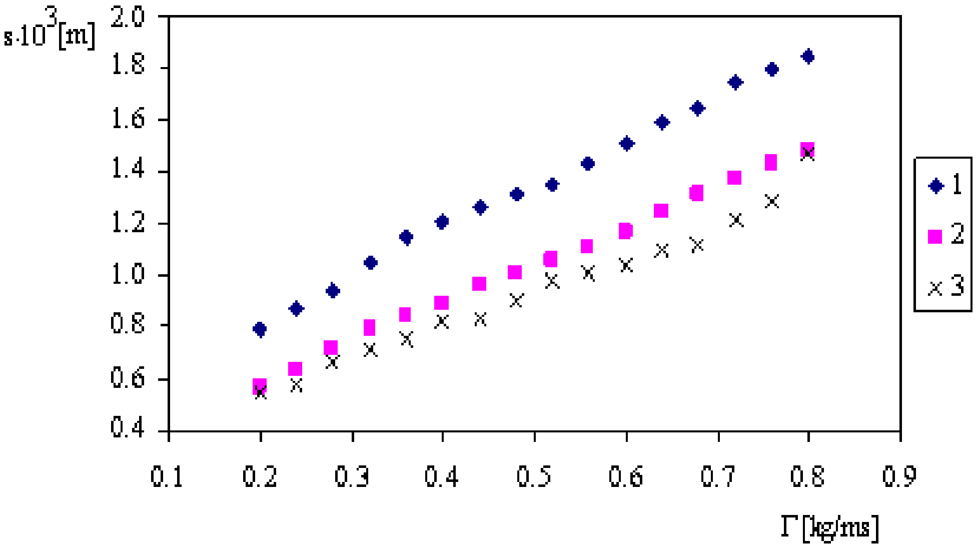


Fig. 3. Surface effect on mean film thickness in turbulent flow (water data): 1 –plate P40, 2 –plate P100; 3 – smooth plate

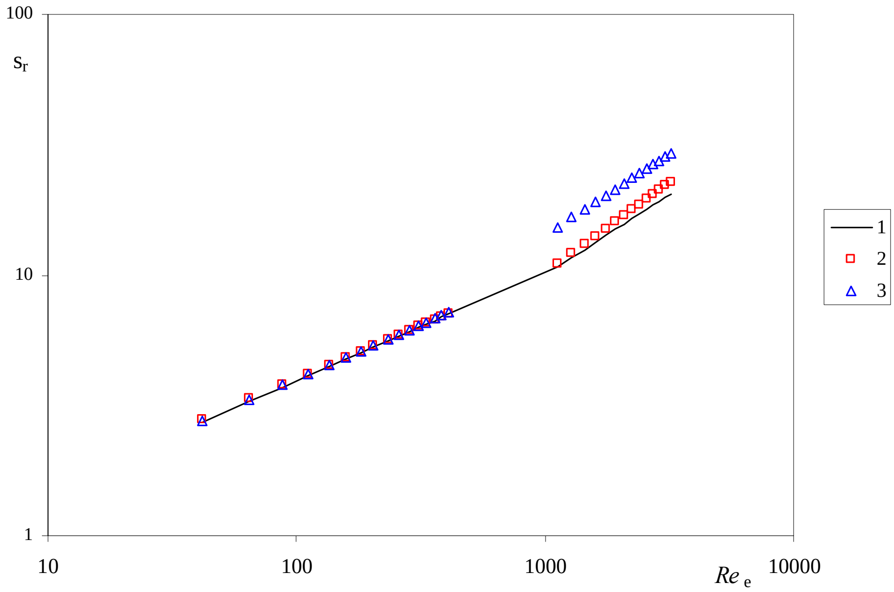


Fig. 4. Reduced mean film thickness of a liquid vs. modified Reynolds number (2): 1 – smooth plate, 2 – plate P100, 3 – plate P40

To compare the data obtained their elaboration was directed on the ground of the dimensionless relationship as follows:

$$s_r = \frac{s}{\delta_e} = C\,Re_e^A \qquad (1)$$

where:

$$Re_e = \frac{4\Gamma}{\eta} = \frac{4us\rho}{\eta} \tag{2}$$

$$\delta_e = \left( \frac{\eta^2}{g\rho^2 \sin\theta} \right)^{1/3} \tag{3}$$

and $s_r$ is so called reduced thickness of a film flowing down the surface inclined to horizontal under angle $\theta$, $u$ describes the mean velocity of a film and $g$ is gravity acceleration.

For thin liquid film of Newtonian solution flowing down a smooth surface the reduced mean thickness $s_{r,o}$ is described by the following correlation equations:
– at $Re_e \in (40;1100)$

$$s_{r,o} = 0.6308\, Re_e^{0.40} \tag{4}$$

– at $Re_e \in (1100;4000)$

$$s_{r,o} = 0.1294\, Re_e^{0.62} \tag{5}$$

From the pattern shown in Fig. 4, it has been resulted that the detailed relationships of $s_r = f(Re_e)$ depend on the grain size of surface roughness. The reduced values of mean film thickness for plate P100 (with the grain sizes changed from 125 to 300 μm) when the height of the roughness elements was either equal to or a little greater than the liquid film thickness, were comparable with these ones resulted from relationships obtained for smooth plate.

For thin liquid film flow down a rough surface in turbulent range the reduced mean thickness $s_{r,r}$ is described by the following correlation equations:
– for plate P40

$$s_{r,r} = 0.2104\, Re_e^{0.61} \tag{6}$$

– for plate P100

$$s_{r,r} = 0.0902\, Re_e^{0.69} \tag{7}$$

Comparison of the values of reduced mean film thickness on smooth surface $s_{r,o}$ and on rough surface $s_{r,r}$ is presented in Figure 5 in the terms of increase factor:

$$\varphi_s^r = \frac{s_{r,r}}{s_{r,o}} \tag{8}$$

vs. Reynolds number.

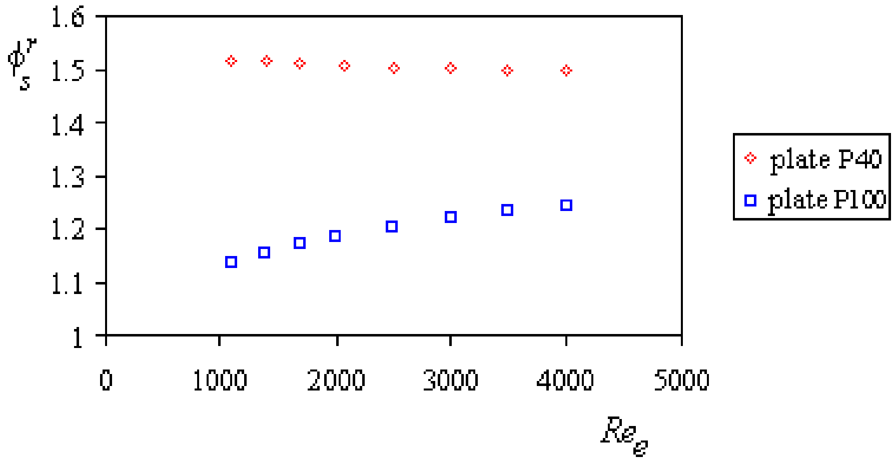


Fig. 5. Increase of the reduced thickness of a film flowing down modified surfaces

The effect of the wall roughness was found as the evident one in turbulent film flow down the surfaces studied. The increase in thickness values in a film flowing turbulently down the plate P40 (in comparison with the data for smooth plate obtained) was practically independent of Reynolds number. The increase in values of $s_r$ was about 50.6%. For a plate P100 the increase of reduced mean thickness with the increase of Reynolds number was observed. For example at $Re_e$ = 1100 the increase was equal to 13.8%, and at $Re_e$ = 4000 24.6%, respectively.

**Acknowledgement**: This research was supported by Ministry of Science and High Education of Poland through grant PUT DS ICt 32/113.

**References**

Broniarz-Press, L., *Hydrodynamics of the falling liquid film and transport phenomena in film-apparatus.* Poznan University of Technology, Poznan, Poland (2004).

Classen, H., (1918), *Zentralblatt für Zuckerindustrie,* 26, 497, from Fulford, G. D., (1964).

Dulska, D., *Analysis of the film flow of liquids of complex rheological properties*. . Poznan University of Technology, Poznan, Poland (2004).

Fulford, G. D., *Advances of Chemical Engineering*, 5, 151-235, Academic Press, New York, USA (1964).

Vorontsov, E. G., (1969) *Journal of Applied Chemistry (Russia)*, 42,1799-1802.

Vorontsov, E. G., (1969) *Journal of Applied Chemistry (Russia)*, 42,2037-2044.

Vorontsov, E. G., (1978) *Journal of Applied Chemistry (Russia)*, 51,773-779.