Capillary-gravitational instability of counter-current
gas-liquid flow in structured packing

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Abstract. The paper considers the large-scale characteristics of counter-current gas-liquid flow in the column filled with Mellapak 500Y structured packing. The effect of ascending gas flow on the development of capillary-gravitational instability is determined using flow pattern observations, local liquid flow rate characterization and pressure drop measurements. The correlation for prediction of the critical gas flow factor corresponded to flow flooding is proposed and verified.

1. Introduction
The development of large-scale maldistribution in two-phase flow leads to the deterioration of heat and mass transfer in various technological processes. Especially it is important for apparatus with high productivity in chemical engineering and cryogenic. In recent times, the investigations of the local characteristics of counter-current gas-liquid flow are conducted for complex channel systems of various types of structure packing and new methods for predicting of the separation efficiency for gas mixtures are developed [1]. Deterioration in separation efficiency for binary mixture of the refrigerants R-21/R-114 due to the appearance of large-scale maldistribution in the component concentrations was obtained in [2]. In this paper, we consider the local characteristics of counter-current gas-liquid flows in the rectangular element of the column filled with Mellapak 500Y packing. The effect of ascending gas flow on the development of capillary-gravitational instability is determined using flow pattern observations, local liquid flow rate characterization and pressure drop measurements. The correlation for prediction of the critical gas flow factor corresponded to flow flooding is proposed and verified.

2. Experimental apparatus and measurements procedure
One of the visible reasons for the formation of large-scale structures in the counter-current flow of liquid and gas is capillary-gravity flooding in the layers of structure packing. The conditions for the emergence of capillary-gravity instability are determined for the Mellapak 500Y multilayer packing in the range of flow parameters that are practically realized during the cryogenic distillation. The scheme of the experimental equipment is shown in figure 1. The experiments were performed using the transparent rectangular elements of the column with transverse dimensions of 800 mm and 100 mm. The column is filled with nine sequentially located layers with nine sheets of packing in each layer. The packing layers are moved away from the column walls and fixed through a system of the vipers to
During the experiments, the distilled water with surfactant and antifoaming agent is pumped through the heater and flow meter to the top of the column, where the liquid distributor is located. The working fluid temperature in the top of the packing equals 25-27 degrees. Air from the high pressure system enters the lower part of the column, where the gas distributor is located. It includes the grate that has 1650 holes with a diameter of 2.2 mm. A vortex flow meter is used to measure air flow rate. The liquid and gas temperatures are measured at the top and bottom of the column by the thermocouples as it shown in figure 1. The surface tension coefficient is measured by the drop-weight method for a sample of the liquid collected at the bottom of the column and equals approximately to 0.03 N/m (the surface tension coefficient is dependent on the surfactant concentration and liquid temperature). Measurements of the local flow rates of the liquid at the bottom of the column are made by measuring cuvettes. For the registration of flow patterns, high-speed video camera is used.

3. Experimental results
The experiments allow obtaining the distribution of the local liquid flow rate along lower edge of the structure packing without ascending gas flow. Figure 2 shows the variation of the local liquid flow rate divided on average flow rate after nine layers of Mellapak 500Y packing for two mass flow rates of the liquid. As seen, flow rate of the liquid is increased in near wall area despite of wiper existence.

![Figure 1](image1.png)  
**Figure 1.** Scheme of the experimental equipment.

![Figure 2](image2.png)  
**Figure 2.** Variation of local liquid flow rate across the half width of the column.
To determine the critical gas flow factor at which the formation of large-scale capillary-gravity structures occurs, pressure drop measurements were made under conditions of uniform irrigation of the upper part of the column at different mass flow rates of liquid and gas. It has been obtained that for gas superficial velocities corresponding to gas flow factor \( F_s \) higher than 2.09, where \( F_s = U_{gas}/\sqrt{\rho_{gas}} \), the pressure drop is stratified as a function of the ratio of the liquid \( G_{liq} \) and gas \( G_{gas} \) mass fluxes, as shown in figure 3. An increase in the gas flow rate increases the pressure gradient that becomes higher also with increasing the liquid flow rate. As seen in figure 3, the critical gas flow factor attains when grows of pressure gradient increases considerably. The results of high-speed video and laser scanning show that when critical gas flow factor archives, the flooding of the lower layer of the packing is set in. With an increase of the gas flow rate, the extension of the flooding zone occurs and is accompanied by the appearance of areas with a high content of the liquid. The accumulation of liquid takes place first in the lower layer of the column and manifests itself in the flooding of the lower layer of the packing. As the gas velocity increases, the flooding occurs in the overlying layers of the packing and spreads to the entire column, leading to an increase in the pressure gradient. High-speed video recording using the camera located opposite the gaps between the layers, and backlighting with a laser knife showed that at gas velocities higher the critical one, the liquid accumulates above the lower edge of the structure packing layer and liquid flow in the gap between the layers becomes irregular.

To generalize the data obtained, a physical model of flooding is developed for the counter-current flow of gas and liquid in a column with a structured packing, based on the mechanism of the capillary-gravitational instability in the field of gravity. The model is based on the approach of [3] that used equations to determine the onset of flooding in pipes. Taking into account the geometric characteristics of the gas flow in structure packing channels, one can obtain the general equation in the coordinates of Kutateladze-Sorokin K and N to find the flow parameters at which the liquid layer is weighed in the ascending gas flow as follows:

\[
K = \frac{F_s}{\varepsilon \cos^{1.25} \left( \theta/2 \right) \left( \cos \left( \rho_{liq} - \rho_{gas} \right) \right)^{0.25}}
\]

\[
N = \frac{G_{liq} \sqrt{\sigma}}{4 \cos^2 \left( \theta/2 \right) \left( \rho_{liq} \cos \left( \rho_{liq} - \rho_{gas} \right) \right)^{0.5}} \left( 1 + \frac{31}{Ga^{0.55} \cos^{0.55} \left( \theta/2 \right)} \right)
\]

where \( \theta \) is the angle between the directions of the channels in the packing sheets, \( \sigma \) is the surface tension, \( g \) is the acceleration of gravity, \( D_h \) is the hydraulic diameter of packing, \( Ga \) is the Galilean number, \( \rho_{liq} \) and \( \rho_{gas} \) are liquid and gas density and \( \varepsilon \) is the porosity.
Figure 4. Comparison of the experimental data for $K_{cr}$ with the calculation according to equation (3).

Figure 4 shows the comparison of the experimental data on the onset of liquid accumulation in the column, determined from the point of inflection in the friction factor, with the calculation according to the equation:

$$K_{cr} = 0.095 \cdot N^{-0.347} \quad (3)$$

The calculation result is shown as the solid line. The experimental data [4] on the beginning of liquid accumulation in a column packed with Mellapak 250Y for counter-current flow of water and air also shown in figure 4. As seen, a fairly good agreement between the experimental data and the calculation from Eq. (3) is observed. It is important that proposed equation contains physical properties of the gas and liquid and can be checked for prediction of the capillary-gravitational flooding in other conditions.

4. Conclusions
The presented results make it possible to quantify the conditions needed for the development of capillary-gravity instability during counter-current gas-liquid flow in structured packing. The flooding mechanism was identified using video recording and pressure drop measurements. The conditions needed for the formation of large-scale heterogeneity due to flooding in the packing layers are identified in the range of flow parameters practically realized in distillation. These results could be applied for prediction of the mass transfer deterioration for the columns at high gas flow rates.

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References
[1] Hanley B and Chen C C 2012 *AIChE J.* **58** 132
[2] Pavlenko A, Zhukov V, Pecherkin N, Chekhovich V, Volodin O, Shilkin A and Grossmann C 2014 *AIChE J.* **60** 690
[3] Kutateladze S S and Sorokin Y L 1969 The hydrodynamic stability of vapour liquid systems *Problems of Heat Transfer and Two-Phase Media* ed S S Kutateladze (Oxford: Pergamon Press) pp 385–395
[4] Brunazzi E, Paglianty A and Pintus S A 2001 *Ind. Eng. Chem. Res.* **40** 1205