Experimental investigation of the influence of flow rate pulsations on the rivulet flow regime

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Abstract. The influence of flow rate pulsations on the rivulet flow regime has been investigated. The experiments were carried out on the underside of a smooth polyethylene plate. The investigation has shown that the influence of flow rate pulsations on the stream patterns is determined by flow peculiarities in the steady-state regime. Disturbances arising from pulsations of liquid flow rate can affect the stream liquid pattern of the rivulet. Such disturbance can cause the development of latent instability at individual points situated along the length of rivulet. The greatest effect on the stream structure is observed for the flow rate pulsation at liquid discharge with the ambiguity of rivulet regime. If the flow rate pulsations affect periodically the meandering rivulet, then it is possible to reduce the degree of meandering and convert the stream into the straight rivulet. In the regime of unstable meandering, it is impossible to identify correctly the effects caused by the flow rate pulsations at the initial area of the rivulet because of great self-acting pulsations of flow rate appearing in different sections along the rivulet.

1. Introduction

To intensify heat and mass transfer, the film flows of liquid are used in the absorbers, condensers, and heat exchangers. With flow rate pulsations, the probability of dry spot formation increases because the liquid film fractionizes and begins flowing in the form of jets or rivulets, and this impairs the average characteristics of heat and mass transfer [1, 2]. The nature of the rivulet flow is determined by the properties of liquid, specific flow rate, properties of substrate, coefficient of surface tension, and gravity [3-8]. The purpose of this work is to experimentally study the effect of liquid flow pulsations on characteristics of a rivulet flow.

2. Experiment

The schematic diagram of experimental setup is shown in figure 1. Distilled water was used as a working liquid. The experiments were carried out on the underside of a smooth 300 mm wide and 1400 mm long polyethylene plate $I$. The slope of the plate surface relative to the vertical $\theta$ varied from zero to 20 degrees ($90 < \phi < 110^\circ$). To create the rivulet, a jet of liquid was supplied perpendicular to the plate surface from tube $4$ with an internal diameter of 0.8 mm. The gap between the plate surface and feed tube shear did not exceed 1.2 mm. Mariott’s vessel $2$ of 8 liters allowed maintaining constant pressure at the inlet to the liquid flow adjustment system $3$. To reduce the level of pressure pulsations in the air tube of the Mariott’s vessel, the rubber cones with a central hole of 2 mm were installed. The
liquid flow adjustment system consisted of a needle valve and mechanism for changing the flow section of the silicone tube. With the help of a needle valve, the basic value of the flow rate was set. Flow pulsations were created by changing the flow cross-section of the silicone tube arbitrarily. To determine the time characteristics of flow pulsation, the movement of elements of the adjusting mechanism was recorded by digital camera. The value of the flow rate for different values of the flow cross-section was determined by the volumetric method to change the level of liquid in measuring vessel. The accuracy of measuring flow rate was 0.002 ml/s. Instability of flow rate with a decrease in the volume of liquid per 4-liter in the Mariott’s vessel for \( q \) = 0.1 ml/s was 0.005 ml/s, and for \( q \) = 1 ml/s, it was 0.01 ml/s. During the experiment, high-speed video of flow patterns was made by digital video camera in different sections of plate 1. The video was recorded at a speed of up to 1200 fps. The speed of video recording with an accuracy of 0.1 fps was determined when recording the electronic stopwatch screen. Speeds and acceleration of the movement of individual structures, which can be visually identified on the rivulet, were determined when processing video frames. The \( Y \) coordinate along the plate was measured from the lower edge of plate 1.

The effect of single and periodic pulsations of flow rate on stability of the rivulet flow regimes was investigated. The flow regime of the rivulet (droplet, stable meandering and unstable meandering) was set for constant flow rate \( q \). The value of flow rate pulsation \( \Delta q \) was chosen so that new "structures" in the rivulet were noticeable, or a change of the flow regime occurred. For a single pulse \( \Delta q \), pulse duration \( \tau \) varied, for periodic pulsations, frequency \( f \) of pulses \( \Delta q \) was varied.

3. Result and Discussion
The investigation has shown that the influence of flow rate pulsations on the rivulet flow regime is determined by flow peculiarities in the steady-state regime. Pulsations have the most profound effect on the flow regime in the hysteresis zone. This is the zone, where different flow regimes can exist for the same flow rate. Figure 2 shows a diagram defining the regions of the observed stream patterns, i.e. the droplets, stable meandering rivulet and unstable meandering rivulet. Abscissa and ordinate are the surface slope and discharge rate, respectively. The lines show the regime boundaries from [3]. The feature of the flow at inclination angles \( \phi \) greater than 90 degrees is that the unstable meandering regime can be observed at the same rates, when it is possible to observe the drop flow regime. Another specific feature, observed with discharge pulsations, is a change in the jet shape near the feeding
orifice. Namely, the jet takes up a drop-like shape, which leads to a change in the flow regime at the initial part of the rivulet.

For the range of flow rates, where only the stationary meandering regime of the rivulet flow was observed, there was no particular effect of pulsations on the flow character. The sign of a change in the flow rate $\Delta q$ (increase or decrease) did not matter if the flow rate did not leave the boundaries of the zone of stationary meandering regime. However, at periodic positive flow pulsations of about 10% of the initial flow rate (for example, for $q = 0.31$ ml/s at $\Delta q/q \approx 10\%$, pulsation time is $\approx 100$–200 ms, and pulsation period is 0.7–1 s) it was possible to reduce significantly the amplitude of meandering and to make the shape of rivulet almost linear. In this regime, a sliding drop-shaped structure is formed in the initial section of the rivulet. When the “drop” slides through the rivulet, acceleration value $a$ decreases from 4 m/s$^2$ to 0.5 m/s$^2$, and if the mass of such a “drop” is sufficient, then, at the point of flow bending, the rivulet “curvature” decreases, when “hitting” the bend point. Thus, under the influence of several “drops”, a straight section is formed in the place of a meander. Such “drops” also prevent formation of new meanders at repetition rate of about 1 Hz. In itself, such a rectified rivulet is unstable. When the effect of pulsations ceases, the rivulet breaks down in different parts, and the meandering form of rivulet is restored.

In the droplet regime, it is possible to get a straight rivulet by periodic negative pulsations of the flow rate. A special feature of such straight rivulet is very small cross-section height. The weakly curved rivulet is very unstable and easily breaks up into separate areas, which transform into droplets. The flow of liquid on the underside of the plate is characterized by the variety of the flow rate along the length at discharge with the ambiguity of the rivulet regime (stable meandering and unstable meandering). This is because of the fact that due to local pulsation of flow downstream, the shape and cross-section of the flow can vary greatly. Local changes in the flow rate are associated with appearance of sinusoidal instability, drop-like structures and flow discontinuities in different sections along the length of the rivulet. The value of a local change in the liquid flow rate is commensurable with the flow rate value on the feeding orifice. The characteristic time of flow rate pulsation is commensurable with the shaping time of the drop-shaped structure or sinusoidal instability. Under this condition, any flow ripple can cause the development of latent instability at individual points along the rivulet. For example, Figure 3 shows the effect of small positive short-time flow rate pulse on the stream pattern near the meandering point. Because of flow rate pulsing, "disturbance" appeared as a small gobbet moving along the rivulet at the speed of about 0.25 m/s. "Disturbance" (when rivulet reached the meandering area) led to appearance of several varicose structures. As a result of liquid flow redistribution, a region with small cross-section formed. Therefore, the liquid flow rate below point 3 decreased and a series of liquid stream ruptures (points 3, 4, 5 and 8) occurred there. In the area of the meander location, individual drops 7, 9, 10 and 11 remained. At the edge of the rivulet 6, a drop-shaped structure appeared where liquid began accumulating. When structure 6 merged with
drops 10, 11, integrity of stream could be observed. Note that such a scenario of changing the rivulet shape could occur without flow rate pulsation, for example, due to the development of any sinusoidal instability in region 3.

In the regime of unstable meandering, single pulsations of liquid flow do not have any noticeable effect on the character of rivulet movement. The fact is that in this regime, the ruptured zones of the liquid flow appear and disappear periodically along the length of the rivulet. In this case, pulse of flow $\Delta q \sim q$ takes place in the rupture zone, since in the unsteady meandering regime in the rivulet, there are several zones in the form of varicose extensions in the rivulet. In this case, each of these structures along the rivulet has its own independent phase of growth. In the final phase of growth, a bead-like structure grows and breaks, which slides downward along the stream with acceleration of motion. A sliding drop can absorb other "drops", and when a certain mass is reached during breaking in the zone of varicose expansion, this causes an unpredictable change in the varicose structure. Most often, there are two options. The break of rivulet occurs. Then, at the edge of the rupture, a droplet grows, which is stretched and gives a new direction of flow, similar to that shown in figure 3. In the second case, the slip speed of the droplet and growth of the volume of varicose zone decelerate, this causes redistribution of the flow in favor of one of the arms, regardless of its orientation (including upwardly directed sleeves). Therefore, against such background it is impossible to identify correctly the effects caused by flow pulsations at the beginning of the rivulet.

The study has shown that a large role in the rivulet flow regime is played by the drop-like structures. When the droplet is small, it works as a point of change in the curvature of the jet. The point of curvature increases from one side of the drop, and on the other side it decreases. This leads to a change in the shape of the rivulet and direction of jet motion.

In the second case, the flow direction changes as a result of the growth at the break point of the drop-like formation. In the second case, it changes due to the growth at the break point of the drop-shaped formation. Due to the complex structure of the flow in the drop-shaped formation, a wave-like contact line with finger-shaped projections is formed in the contact zone of the liquid with the plate. Therefore, a new flow direction will be along one of the projections. Also, for small negative slopes of the surface relative to the vertical in the "drop", the change in the magnitude of resultant clamping force is comparable with the action of gravity. For example, figure 4 shows how the direction of motion of the droplet starting to break away from the substrate changes. When the drop moves along the normal to the surface, a rivulet is formed in the contact zone with the wall. At a low sliding speed, the drop A cannot overcome the surface tension forces in the contact zone with the rivulet and starts being attracted to the plate (figure 4a). At higher values of the sliding speed, the drop can break off
from the rivulet and wall. In this case, the drop is divided into two parts; one B goes into free fall, another C moves along the wall with the rivulet, while the velocity of rivulet moves significantly at time of drop separation (figure 4b).

4. Summary

The study has shown that due to a change in the flow rate, perturbations that move along the rivulet are generated at the inlet. These perturbations are the cause of rapid development of flow instability at individual points of the rivulet. The greatest influence of flow pulsations on the flow structure is observed under the flow regimes with an ambiguous rivulet shape (for example, for a given constant flow rate, both the drop and meandering regime or other combinations of regimes are observed there). With the help of periodic flow pulsations at the inlet, it is possible to change the shape of the rivulet, for example, to change the rivulet meandering shape to the rectilinear one. At non-stationary meandering, it is impossible to determine reliably the degree of influence of flow rate pulsations at the inlet on the flow regimes due to the fact that in such a regime there is a large number of spontaneous pulsations of flow velocity and shape of the rivulet, appearing in different regions along the rivulet.

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Figure 4. Video frames and location of bottom edge of drop and rivulet. Slope of the plate $\theta = 14$ degrees: a) attraction of the drop to the plate, b) droplet detachment from the plate.