**Wavy structure and liquid entrainment in annular flows**

Dmitriy Markovich, Sergey Alekseenko, Andrey Cherdantsev, Mikhail Cherdantsev and Sergey Isaenkov

Kutateladze Institute of Thermophysics

1 Lavrentiev ave., Novosibirsk 630090, Russia

Novosibirsk State University, Pirogova St. 2, Novosibirsk 630090, Russia

 cherdantsev@itp.nsc.ru

In annular gas-liquid flow liquid flows as a film along walls of a duct being sheared by high-velocity gas stream in the duct's core. Due to interaction between gas and liquid so-called disturbance waves appear on the film surface. These waves represent huge lumps of liquid traveling with high speed over long distances. They increase roughness of the interface and, hence, the pressure drop in the channel. They serve as the main source of entrainment of liquid droplets into the gas core. Experimental study of these waves is of high practical and scientific importance; though, it is a challenging task because of highly agitated interface, covered by waves of small spatial scale, high and irregular velocity, steep slopes, high curvature, strong degree of three-dimensionality and complex interactions between the waves. Measurement techniques must satisfy to strong requirements: the measurements should be spatially and temporally resolved with high spatial and temporal resolution and large area of interrogation. Comparative analysis of the available experimental techniques shows how few of them are able to fit the requirements. On this reason, knowledge of structure and dynamics of disturbance waves remains incomplete despite the intensive efforts of experimentalists for over 60 years. It is even unclear if the term "waves" is applicable to these objects.

The main amount of the results presented in this paper is obtained with brightness-based laser-induced fluorescence technique. This method was used intensively by our group to study gas-sheared liquid films for over eight years. The processes of generation of ripple waves of different spatiotemporal behavior were studied systematically for the first time. The ripples are generated at the rear slopes of disturbance waves; they can move either faster or slower than the parent disturbance wave depending on the position of the point of inception of a ripple. Slow ripples decelerate and move over thin base film layer behind the disturbance wave until the following disturbance wave absorbs them. Fast ripples move across the top of disturbance wave towards its front until either being decayed at the steep front of the disturbance wave or being broken by the gas stream into droplets. Presence of fast ripples is necessary for liquid entrainment. Fast ripples may be broken in two mechanisms, known as bag break-up and ligament break-up. Bifurcation in spatiotemporal evolution of the ripples may be explained by existence of eddy motion under the humps of disturbance waves.

A method of automatic identification of spatiotemporal trajectories of individual disturbance waves was devised. This method allowed us to analyze the disturbance waves and also the properties and evolution of fast and slow ripples in a reference system of parent disturbance wave. The average spatial length of crest and rear slope of disturbance waves was measured together with the length required for stabilization of slow ripples properties (the latter could be referred to as "wake" of a disturbance wave).

One of the ways to understand the nature of disturbance waves is to study how they are created. It was shown that the disturbance waves are formed near the inlet due to coalescence of high-frequency initial waves which appear due to Kelvin-Helmholtz instability of gas-sheared film. This mechanism was also found to occur far from the inlet, where so-called ephemeral disturbance waves are generated and where transition to entrainment occurs. Thus, the mechanism is universal and it is not defined by the inlet configuration. The initial waves were shown to be two-dimensional; not far from the inlet they are broken into localized 3D waves. Multiple coalescence of such waves leads to formation of the disturbance waves. After the disturbance waves are formed, the transverse coherence of the flow starts to increase downstream. The disturbance waves undergo strong individual acceleration at the initial stage of their evolution. The value of acceleration strongly correlates with the value of gas shear. Further downstream, acceleration decreases and can even become slightly negative. This can be explained by start of massive entrainment of liquid from the disturbance waves, which decreases the height of disturbance waves and their interaction with the gas flow.

The entrainment was studied by both sampling probes and LIF method. The former allowed us to estimate the amount of liquid entrained from an individual disturbance wave and compare it to the deceleration of the waves. The latter was used to study the parameters of entrained droplets at the initial stage of their evolution, since the droplets contain the fluorescent dye and are also detectable in LIF data. It was shown that the initial velocity of the droplet is 1.5-2 times higher than the velocity of the fast ripples, which implies that a droplet gains large momentum in process of ripples break-up. The size of the entrained droplets was found to be much larger than the average size of the droplets in the gas stream; this can be explained by faster deposition of the larger droplets back onto the film and creation of smaller droplets due to secondary entrainment. Impact of depositing droplets causes formation of craters on film surface which travel with the same speed as the slow ripples. The maximum size of the craters was found to be limited by the wavelength of the slow ripples. In some cases - presumably, when the angle between the droplet and the film is small - impacting droplets create bubbles trapped inside liquid film. It was also found that the coalescence of disturbance waves may be accompanied by massive entrainment. Thorough examination of such events shows that entrainment still occurs due to bag and ligament break-up mechanisms. Thus, coalescence of disturbance waves is not a separate mechanism of entrainment, but just a mechanism of entrainment enhancement.