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Stages of luminescence development under intense liquid flows

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Two stages of luminescence development have been established during intense flows of hydraulic oil in a narrow channel: a precursor and the subsequent main luminescence pulse. Luminescence stages are associated with gaped momentum states (GMS) during the formation of collective localized shear modes.

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Luminescence in intense fluid flows can serve as a source of additional information on the mechanisms of momentum transfer and energy dissipation in condensed media. It was noted in [1,2] that fluids, being condensed media, can exhibit shear elasticity and momentum transfer mechanisms similar to those of plasticity in the formation of localized shear. This is accompanied by a qualitative change in the dispersion properties, the spectrum of relaxation times (Frenkel times) defining „gaped momentum states" (GMS [3]). Luminescence caused by hydrodynamic instability of fluid flow (hydroluminescence, HL) was observed in [1,2]. The pulsed character of luminescence in the presence of intense cavitation was observed in [3,4], and pulse distributions in amplitudes and rise times were obtained. The present work focuses on the investigation of HL at relatively low flow rates when cavitation effects are not dominant. The experimental setup is similar to the setup proposed in [4], except for the design of the measuring cell (Fig. 1). HL was investigated in oil (Mobil DTE25, viscosity grade ISO VG 46). The luminescence was observed in a channel of diameter 1 mm and length 20 mm, made in the center of the plate from polymethylmethacrylate (PMMA) with a diameter of 100 mm (*2* in Fig. 1), using a Hamamatsu H6779 photomultiplier tube with a sensitivity range of 300−650 mm and a pulse rise time of 0.78 ns. The photomultiplier was attached directly to a plate with a channel, which was papered around the perimeter with aluminum tape (not pictured in Fig. 1 to show the channel), except for the window for the photomultiplier. The distance from the channel to the photomultiplier tube is determined by the plate diameter and is 49.5 mm. Unlike the [5] setup, the expansion region behind the channel was shielded by a steel flange (*1* in Fig. 1) with a hole diameter also 1 mm and a cylindrical length of 3 mm to cut off the luminescence in the expansion region behind the channel with a significant contribution from cavitation. During assembly, the channels in the flange and PMMA plate were aligned using a 1 mm gauge. The signal from the photomultiplier tube was recorded with a Tektronix digital oscilloscope with a bandwidth of 6 GHz equipped with active probes with a bandwidth of 3 GHz. The sensitivity of the photomultiplier tube made it possible to record pulses at low flow rates when the glow was not detected by the FASTCAM SA-Z video camera, since the camera has a frame rate limitation of 1 kHz and the shutter speed is not sufficient to detect the glow. The average time between pulses at low flow rates was more than 10 s (Fig. 2). At low flow rates (Reynolds number $\mathrm{Re} < 650$), HL pulses have small and almost identical amplitude (12 ± 1 mV) and duration (Fig. 3, *a*) and occur relatively infrequently (Fig. 2). The average intensity of the radiation is so low that it is not recorded by the video camera.

But since the pulses are short enough, the peak luminescence intensity is sufficient to be detected by a fast photomultiplier tube. At zero flow rates, pulses were not recorded for at least 10 min, which rules out a different nature of pulse occurrence.

It was found that as the liquid flow rate increases, the pulse repetition rate increases, their shape and peak am-

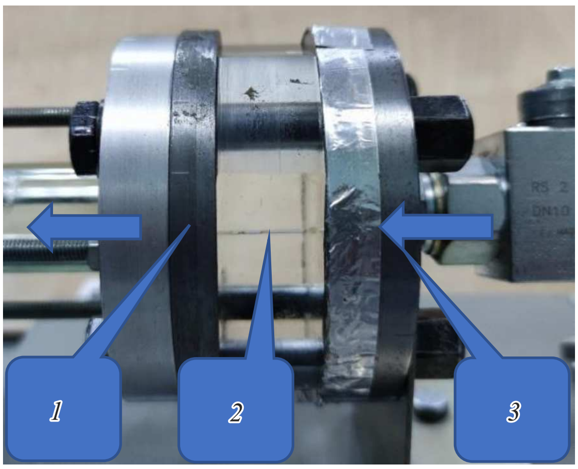

Figure 1. The structure of the measuring cell. *1* — output flange, *2* — measuring channel, *3* — input flange.

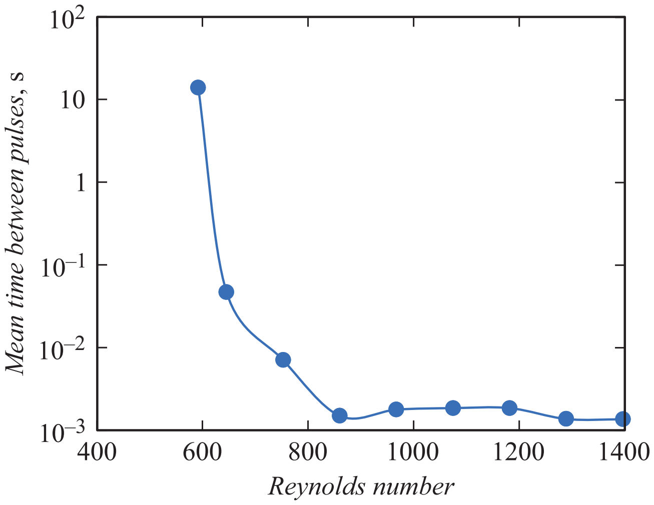

Figure 2. Average pulse interval as a function of Reynolds number.

plitude change, and the luminescence is already registered by conventional methods. At medium (Re $= 800$) flow rates, it is localized closer to the channel inlet edge and then, at Reynolds numbers greater than 900, it is observed throughout the channel. After reaching a certain flow rate (Re ~ 900), the average pulse repetition rate reaches a plateau (Fig. 2) and the luminescence intensity mainly increases due to the increase in pulse energy.

Two stages of development can be distinguished at the transient stage: the precursor pulse, which has the same amplitude 12 ± 1 mV as the pulse at low flow rates (Fig. 3, *b*), and the main pulse. The formation of the main impulse at this stage is still unstable. It may occur 10−100 ns after the precursor and have a rather complex profile (Fig. 3, *c*). In Fig. 3, *c* only one oscillogram is presented. In experiments, different variants of the luminescence evolution were observed. But in each case, there was a precursor impulse first and the development of a more powerful glow followed. At the developed stage of HL, when the glow is visible to the naked eye, the pulses have a much larger amplitude (an order of magnitude larger than the amplitude of precursor pulses), and at this stage it is no longer possible to distinguish the precursor (Fig. 3, *d*). The pulse amplitude at this stage varies considerably in contrast to the nearly constant pulse amplitude at low flow rates, and the pulse amplitude distribution is similar to that obtained in [5]. Similar shapes and durations of the precursor-pulses and luminescence pulses with high costs, apparently, are associated with the time constant determined by parasitic capacitance of the photomultiplier and input resistance of the active probe. The true pulse duration can be much shorter. The future plan is to reduce the resistance and repeat the experiments.

Reynolds pointed out that the non-Newtonian behavior of simple fluids under shear flow can be attributed to a nonequilibrium viscoelastic response with a corresponding spectrum of relaxation times [6]. This allows us to conclude that the spectral range corresponding to relaxation times $\tau \sim 10^{-5}$ s, at realization of collective shear of molecular groups in the presence of elastic shear stresses [7], can appear in liquids as condensed media. The collective effects of such interaction are similar to the scenarios of formation of localized shear modes during plastic deformation and can be accompanied by dissipative effects (in particular, luminescence) in accordance with the established types of collective modes (autosoliton and intensifying) responsible for the effects of hydro- and sonoluminescence and the conditions of cavitation initiation [8]. The conditions of fluid flow in a narrow channel (high intensity of shear deformation in the boundary layer) contribute to the formation of a cavitation center in the form of a localized shear region in which local electrification [9] is possible.

The studies based on the registration of luminescence at intensive liquid flows allowed us to establish the stages of luminescence development: the formation of a precursor corresponding to low-amplitude signals and the main pulse with an amplitude an order of magnitude higher than the amplitude of the precursor pulse. Luminescence staging is associated with the formation of collective shift modes, a sharp change in the relaxation time spectrum corresponding to GMS (gap) states, which determine qualitatively new mechanisms of momentum transfer and energy dissipation [3]. At low flow rates, a cavitation focus is formed in the form of a localized shear region of fixed size, in which local electrification [9] is possible, leading to luminescence up to the stage of collapse. This explains the constancy of pulse amplitude and duration at low flow rates. With further increase of the liquid flow rate through the channel, these areas become centers of cavitation bubbles development, whose collapse forms pronounced luminescence centers. Consequently, the stage development of luminescence can be explained by the stage development of the cavitation bubble itself. At the first stage, a germ is formed in which an initial luminescence pulse is generated due to local electrification, and then an already developed cavitation bubble is formed in place of the germ, generating a more powerful luminescence pulse.

In further studies it is planned to evaluate the effect of temperature on the character of GL at low flow rates, to verify the thermoactivation nature of the formation of microshift regions, and to study the emission spectrum in order to identify possible differences between the stages of luminescence. It is also planned to investigate in more detail the spatial distribution of luminescence in the fluid in order to separate the luminescence caused by the formation of defects in the fluid and possible luminescence caused by electrical breakdown in the near-wall region associated with electrification of the channel walls.

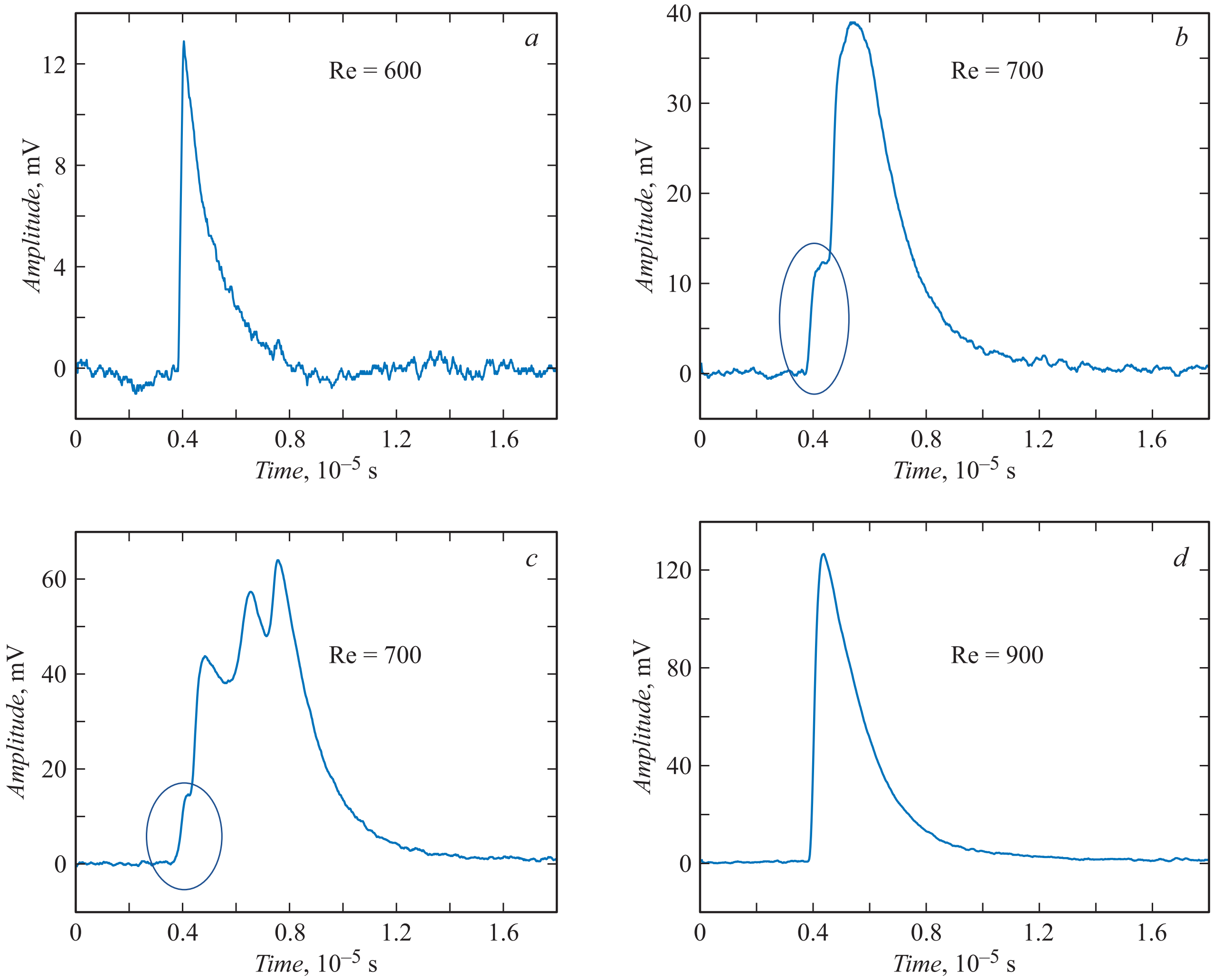

Figure 3. Hydroluminescence pulses at different Reynolds numbers. The initial stage, equal in amplitude to the pulses at low flow rates, is highlighted by the oval.

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Conflict of interest

The authors declare that they have no conflict of interest.

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