*Technical Physics Letters, 2024, Vol. 50, No. 10*

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# Intermittency in separated flows through sudden expansions in axisymmetric channels at subcritical Reynolds numbers

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*Received May 8, 2024*
*Revised June 6, 2024*
*Accepted June 6, 2024*

Flow intermittency in flows through sudden expansions in axisymmetric channels was investigated experimentally at subcritical Reynolds numbers. The intermittency coefficient in the flow reattachment region was shown to depend on the Reynolds number. The study proposes a mechanism behind regular turbulization of flow in the separation region.

**Keywords:** sudden expansion, flow visualization, amplitude of velocity fluctuation, turbulization of flow, intermittency, vortical structures.

DOI: 10.61011/TPL.2024.10.59689.19985

The transition to turbulence is one of the most complex problems in fluid and gas mechanics. Although the first studies into this phenomenon have been performed at the end of the 19th century [1,2], the nature of turbulence remains one of the most formidable mysteries of classical mechanics. Moreover, even an unambiguous scientific definition of the term „turbulence" is lacking [3]. This is the reason why the authors of most classical works focused on this problem limit themselves to listing the properties of turbulent flows [4,5]. One such property is intermittency, which is the alternation of sections of laminar and turbulent flow in oscillograms of velocity (velocity components) [6]. Intermittency is sometimes regarded as one of the successive stages in the process of transition from the laminar flow regime to the turbulent one [6]. Emmons [7] was the first to use intermittency coefficient $\gamma$ (the fraction of time within which the flow is turbulent) to characterize it quantitatively.

At present, the most extensively studied example of emergence of spatiotemporal intermittency in transition to turbulence is the flow in a round pipe. Intermittency is manifested in this case in the emergence of turbulence in the form of localized spots. Reynolds has called them „flashes" [8]. Intermittency has also been observed in the early experiments of Rotta [9]. The following two classes of turbulent spots have been identified later: puffs and plugs [10]. The formation and evolution of these structures has been the subject of a significant number of recent experimental [11] and numerical [12] studies. Intermittency measurements are often used to characterize in more detail the laminar-turbulent transition in the shear layer at the boundary of a separation bubble formed near the leading edge of a plate or airfoil [13,14].

In the present study, we report the results of experimental examination of separated flow downstream of an axisymmetric sudden expansion of a round pipe (Fig. 1, $a$). The Reynolds numbers calculated from the flow-averaged velocity and the diameter of the feed pipe were $\mathrm{Re} = 1407$, 1455, 1540, 1640, and 1700. Flow-averaged velocity $U_b$, which was calculated by dividing the corresponding volumetric flow of the working fluid by the cross-section area of the channel, then assumed the values of $U_b = 0.635$, 0.656, 0.695, 0.74, and 0.767 m/s, respectively. The volumetric flow was determined based on the measured filling time of the measuring container. An intermittent flow pattern was observed in the flow reattachment region in these regimes. A straight pipe section with an internal diameter of $d = 17.4$ mm and a length of $L = 920$ mm was positioned upstream of the expansion. Pipe expansion ratio $(D/d)^2$ was 2.78. Here, $D = 29$ mm is the expanded pipe diameter. An aqueous solution of glycerin was used as the working fluid. The temperature of the working fluid and its kinematic viscosity were checked before each experiment. The flow of fluid through the working section was maintained by the hydrostatic head produced in a head tank with a constant level and was regulated by a dispenser with a nozzle system. Flow visualization in the region of sudden expansion and measurements of instantaneous velocity vector fields were performed using the SIV (smoke image velocimetry) technique [15]. Polyamide particles with a size up to 5 $\mu$m were used as tracers.

The measurement results demonstrated that a developed laminar flow with a velocity profile corresponding to the Poiseuille solution formed upstream of the sudden expansion at all Reynolds numbers probed in our experiment. However, the length of the non-expanded pipe section $(L/d = 52.9)$ was insufficient to dampen completely the disturbances generated at the entrance to this section. Therefore, residual low-frequency (with a frequency of approximately $f = 1$ Hz $(\mathrm{Sh} = fd/U_b \approx 0.023)$) oscillations of the longitudinal flow velocity component were observed

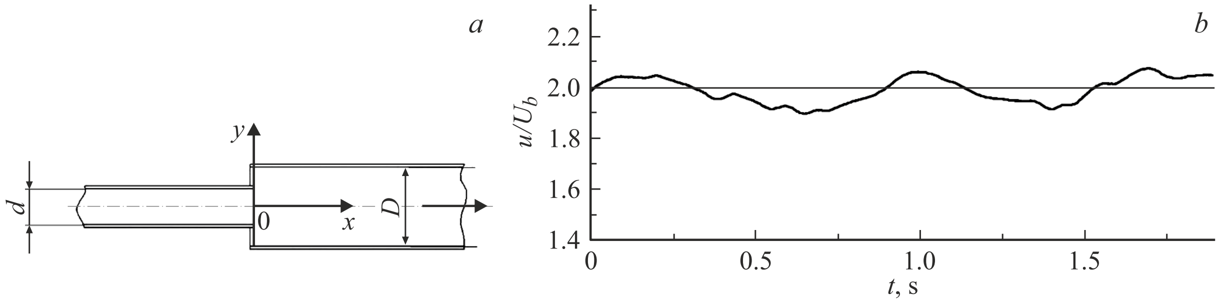


**Figure 1.** Diagram of the experiment ($a$) and oscillogram of the longitudinal component of flow velocity $u$ at the entrance to the expanding channel at $\mathrm{Re} = 1640$ ($b$).

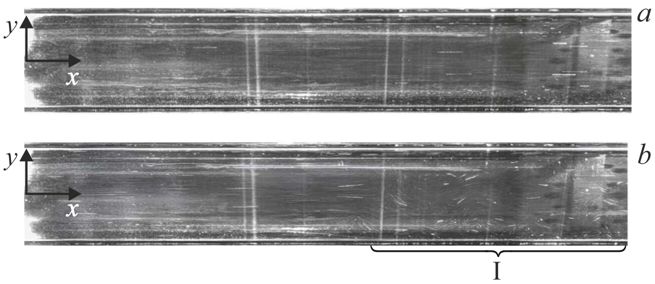


**Figure 2.** Still frames of flow visualization in the region of sudden axisymmetric expansion. $a$ — Period of laminar flow within the entire measurement region; $b$ — emergence of turbulence in the flow reattachment region (I). The flow is directed from left to right.

upstream of the expansion. Their relative amplitude on the channel axis varied from $A_U/U_c \approx 0.11$ at $\mathrm{Re} = 1407$ to $A_U/U_c \approx 0.157$ at $\mathrm{Re} = 1700$. Here, $U_c = U_c(x)$ is the time-averaged flow velocity on the channel axis. Averaging was also performed here over approximately 30 periods of velocity oscillations. An example record of velocity on the channel axis at $\mathrm{Re} = 1640$ with visible oscillations of the discussed type is shown in Fig. 1, $b$.

Flow visualization (tracking of the trajectories of tracers in the laser sheet plane) revealed that periodic loss of stability of flow and its local turbulization occur downstream of the sudden expansion at each fixed value of the Reynolds number (Fig. 2). The loss of stability is initiated in the shear layer in the flow reattachment region and spreads upstream rapidly. Region I, wherein periodic local flow turbulization is observed with the formation of multi-scale vortical structures occupying almost the entire cross section of the channel, is shown in Fig. 2, $b$. It is evident that turbulent liquid flow states are not observed in region I within certain time intervals in one and the same experiment (Fig. 2, $a$). At $\mathrm{Re} = 1640$ and 1700, the flow turbulization region extends approximately to the middle of the recirculation zone ($x/d = 5{-}5.5$). With a reduction in the Reynolds number, the onset of stability loss is also observed in the vicinity of the flow reattachment region, but the upstream extent of the turbulization region gets reduced. Thus, laminar (Fig. 2, $a$) and turbulent (Fig. 2, $b$) flow states alternate in time in the region of stability loss.

Oscillograms of the flow velocity components on the channel symmetry axis in this region, which were obtained by the SIV method within a relatively long time interval (approximately 30 periods of flow velocity oscillations in the cross section of the channel upstream of the sudden expansion), verified the intermittent nature of flow at all the examined Reynolds numbers. Figure 3, $a$ presents an example record of longitudinal $u$ and transverse $v$ velocity components at $\mathrm{Re} = 1640$ on the channel axis in the flow reattachment region for $x/d = 10.3$. The origin of coordinates is in the initial section of the sudden expansion (Fig. 1, $a$). The values of velocity components and their root-mean-square pulsations were normalized to flow-averaged velocity $U_b$ in the feed pipe. The framing frequency in SIV was 2900 Hz at $\mathrm{Re} = 1407$ and 1455; 3300 Hz at $\mathrm{Re} = 1540$; 3500 Hz at $\mathrm{Re} = 1640$; and 4000 Hz at $\mathrm{Re} = 1700$. It turned out that the length of individual periods of occurrence of turbulent flow states at a fixed Reynolds number changed in the course of observations. Intermittency coefficient $\gamma$ was calculated from the $u$ records in accordance with the procedure detailed in [16]. The results demonstrated that the value of $\gamma$ increases with the Reynolds number (Fig. 3, $b$). Average frequency $f_{turb}$ of occurrence of turbulent flow periods also increases monotonically from $f_{turb} \approx 0.6$ Hz ($\mathrm{Sh} \approx 0.016$) at $\mathrm{Re} = 1407$ to $f_{turb} \approx 1.2$ Hz ($\mathrm{Sh} \approx 0.027$) at $\mathrm{Re} = 1700$.

The amplitude of pulsations of the longitudinal flow velocity component $A_U/U_c$ ($x/d = 10.3$) in the intermittent flow region increases with the Reynolds number by a factor of approximately 1.3 at $\mathrm{Re} = 1407$ and 1455 and approximately 6.5 at $\mathrm{Re} = 1640$ and 1700. Thus, flow separation acts like an amplifier of velocity pulsations.

The mechanism of emergence of flow intermittency in the region of flow reattachment downstream of the sudden channel expansion may be presented in the following way.

Low-frequency velocity oscillations in the entrance section of the sudden channel expansion spread throughout the entire flow separation region and, consequently, induce swinging of the shear layer with the frequency of these oscillations. In addition, convective instability in the form

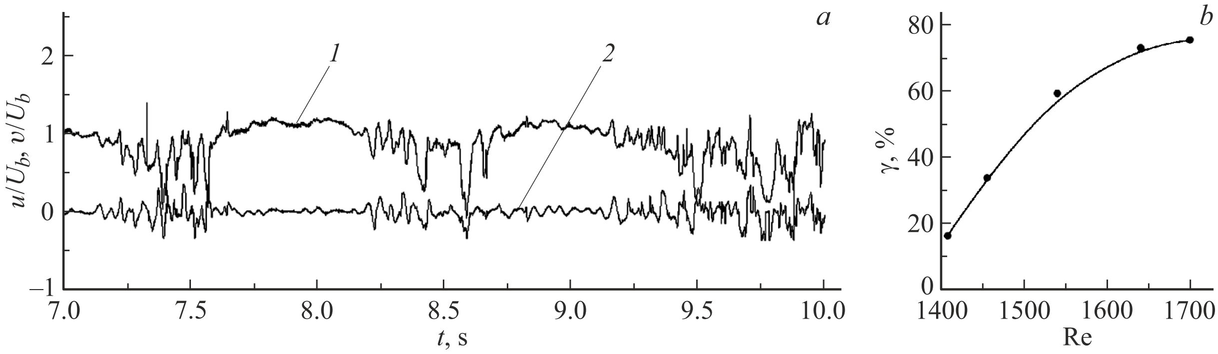


**Figure 3.** $a$ — Oscillograms of longitudinal $u/U_b$ $(1)$ and transverse $v/U_b$ $(2)$ flow velocity components at $\mathrm{Re} = 1640$, $x/d = 10.3$, and $y/d = 0$; $b$ — dependence of intermittency coefficient $\gamma$ in the flow reattachment region on the Reynolds number $(x/d = 10.3, y/d = 0)$.

of Kelvin–Helmholtz vortices develops in the shear layer. Conditions for the maximum enhancement of convective instability are established in the process of swinging of the mixing layer due to disturbances at the entrance to the region of flow reattachment in its deceleration phase. When a certain Reynolds number is reached, this leads to selective intensification of the said instability, which is the most profound in the region of the maximum unfavorable longitudinal pressure gradient (in the vicinity of the flow reattachment point). As a result, an intermittent flow pattern (alternating sections of laminar and turbulent flow observed in the flow velocity oscillograms) is established in this region. A similar potential mechanism was also discussed in [13] in the context of a shear layer at the boundary of a laminar separation bubble formed near the leading edge of a plate (airfoil).

The similarity between the average frequency of occurrence of turbulent flow periods in the intermittency region and the frequency of flow velocity oscillations at the entrance to the sudden expansion speaks in favor of this scenario. Apparently, the deceleration of flow at the entrance to the sudden expansion leads to the emergence of a local (in time) additional unfavorable pressure gradient in the region of flow reattachment. Conditions for the maximum enhancement of convective instability are then established. The laminar flow regime is restored in the subsequent acceleration phase. This pattern was observed in experiments on flow turbulization in a round pipe with forced flow rate oscillations [17]. The validity of the proposed mechanism is also verified by the data of additional experiments with a longer $(L/d = 180)$ straight pipe section upstream of the sudden expansion. The measurement results revealed that low-frequency oscillations of the flow velocity upstream of the sudden expansion are lacking at this value of $L/d$ within the studied range of Reynolds numbers, and intermittency in the flow reattachment region is also not observed.

The obtained new experimental data on the emergence of intermittency in the flow reattachment region downstream of a sudden expansion of an axisymmetric channel may help gain a deeper understanding of laminar-turbulent transition mechanisms in separated flows. In addition, they may be used to test numerical methods of simulation of such flows.


### Acknowledgments

The authors wish to thank V.V. Lemanov (Kutateladze Institute of Thermophysics, Siberian Branch, Russian Academy of Sciences) for fruitful discussions of the results reported above.


### Conflict of interest

The authors declare that they have no conflict of interest.

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*Translated by D.Safin*