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USING SMALL-SCALE TURBULENCE FOR FORMING A SOLID FLUID JET

The technique of solid fluid jet formation with small-scale turbulence is considered. This turbulence is generated by fractal square grids in the area of grid turbulence decay and it moves to a jet. Eddies are impossible in such turbulence flow and consequently, occurrence of small-scale turbulence in the jet can impede strong turbulence and restrain jet breaking. A new procedure can increase the action range of the power water-jet guns and can be applied in those technologies where a solid jet is required. No laminarity in the Fontana Jumping Jet has been found and their exceptional jet stability has been explained by presence of a small-scale turbulence in them. This is what upholds the feasibility of the presented conceptual procedure.

Key words: *jet, turbulent flows, isotropic turbulence, homogeneous turbulence.*

Вступ

Problem statement. Increasing the range and kinetic energy of a submerged fluid jet is a topical problem in fluid jet technologies, in particular, power water-jet guns. The main deterrent to its solving is the unavoidable jet breakup process. There is no common approach to control this phenomenon. Hence, for each process, a technique is chosen to enable using the jet before it breaks up. An effective technique is fluid discharge in an elastic or plastic container. However, each discharge preparation procedure restricts using the technique. Recently, unique fountains have appeared with a solid translucent jet several meters long. Visually, these jets are considered laminar ones; however, as will be shown below, such a view is erroneous. At the same time, the flow in these fountains has interesting features that deserve closer attention.

Jet breakup is caused by interaction of external and internal destructive factors. Fluid turbulence originates as early as in the channel. In the jet, it develops into strong turbulence and creates conditions for jet dispersion and aeration under the effect of the force of gravity and air resistance.

It is impossible to avoid turbulence in a high-velocity flow. However, existing conceptions and prospects enable passing artificially to turbulent flow, which has passed the active phase and does not create large turbulent eddies. Such properties belong to small-scale turbulence (SST) formed within the decaying turbulence. It must be propelled to a jet to delay its destruction.

Analysis of the latest researchers and publications. The basis for choosing SST as a means against eddy formation stems from the energy spectrum of fully developed turbulence at high Reynolds numbers. It was represented by Kolmogorov's phenomenological theory [1], whose statements are a basis for studying all turbulent flows [2–3]. According to them, the kinetic energy of turbulence is cascaded without loss from large to small scales according to the Richardson-Kolmogorov cascade. Energy dissipation occurs at the end of the sequence under the effect of viscosity, with virtually all SST properties being determined by the dissipation rate [4]. According to Kolmogorov [1], SST wave numbers belong to the inertial energy interval, which has no dissipation and local interaction. Such turbulence depends weakly on the mean flow velocity. Hence, a conditional flow with SST will be resistant to influences to a certain degree.

The actual composition and local characteristics of developed turbulence [4] differ from the simplified model presented. In particular, there exists a non-equilibrium turbulence with an appropriate law of non-equilibrium dissipation [5], which co-exists with the common law of equilibrium dissipation in different areas of the same flow. Hence, the complexity of developed turbulence only drives more the need for an experimental search of conditions that produce an intensive SST and its localisation in a flow at high Reynolds numbers.

Purpose of the article. The main purpose of the article is to demonstrate the possibility of using SST for stabilising the flow, due to its properties which impart disturbance resistance to the flow and prevent the emergence of strong turbulence.

Main body

The technique suggested should not only comply with modern concepts in turbulence, but also with the experimental level of generating turbulence and analysing it within the framework of the stated problem.

Extensive experimental research in grid turbulence enabled using SST. It is most effectively generated by injecting energy over a long-scale interval with the help of space-filling fractal square grids [6–7 and references therein]. The turbulence intensity generated by these grids has been found [6] to "build up as the turbulence is convected downstream to a distance x_{peak} from the grid where the intensity peaks and then decays exponentially" $u'^2 = (u'_{peak})^2 e^{-\frac{(x-x_{peak})}{l_{turb}}}$.

Uch a pattern of turbulence intensity change creates a basis for generating SST with the technique presented. Undoubtedly, the values of significant turbulent flow parameters, such as, for instance, x_{peak}, will depend on specific flow conditions. For example, in water-jet guns, we can expect higher Reynolds numbers than in wind tunnels due to differences in the kinematic viscosity of water ~ 10^{-2} cm^2 s^{-1} and air ~ $1.5 \cdot 10^{-1}$ cm^2 s^{-1}.

For SST in the decaying state to be active in a jet, its intensity in the channel must be big. The intensity was generated [8] using a spatial fractal turbulence generator.

A promising tool for investigating turbulent flows is the method of stereoscopic Particle Image Velocimetry (PIV). It provides visual information on the change in the downstream variation of vertical profiles of average velocity, and enables investigating the characteristics of evolution of turbulent structures [9]. Advanced simulation techniques, such as Direct Numerical Simulation (DNS), provide practical information on the decay of a turbulent flow generated by fractal grids. For example, visual information was obtained [10] on the flow acoustical field with the possibility of reducing its noise level with the help of fractal grids.

The existence of SST in a jet is determined by the mean lifetime ф of turbulence fluctuations. A surprisingly rapid increase of ф as a function of Reynolds number Re has been detected [11], virtually as ln ф ~ Re. It turned out that dependence ф is a double exponential function of Re: $ф \sim \exp(\exp(Re)$ [12]. This afforded grounds [4] for considering turbulence as a very long-lived transient state, the behaviour of which is not yet clear.

Papers that investigate the possibility of using grid turbulence in jets are especially valuable for the technique being considered. Turbulence in a free circular jet was investigated by [13] to study the necessary conditions for self-preservation of free turbulent flow with a virtual excitation source. Jet technique applications related to mixing and diffusion in grid-generated turbulence are given in extensive study [14]. Interesting results on turbulence behaviour in a free jet were obtained using direct calculations of three-dimensional Navier-Stokes equations. In particular, a reverse evolution of dimensional scales after a generator of external excitations is shut down has been detected [15]. The authors attribute the observed effect to the action of the Le Chвtelier's principle in turbulence, resulting in consolidation of scales of eddy structures.

When SST moves from the flow channel to the nozzle, and further to the jet, there is a risk of eddy formation because of flow regime changes and abrupt flow cross-section variation. However, local SST isotropy changes the flow response to external action as compared to the response of a laminar flow. A medium with SST can be represented as a finely-structured elastic continuum of turbulent fluctuations, in which the velocity of turbulent transfer and mixing is many orders higher than the velocities of molecular transfer of impulse, heat and matter. Therefore, the critical stress required for formation of a large-scale structure in SST will be higher than in any other flow. Stress relief in a turbulent flow, occurring for instance on wall roughness, will occur faster than in a laminar flow. A bigger excitation caused by a protrusion on the wall channel will multiply into a multitude of small excitations without creating local stress for eddy formation. No doubt, the stability of a flow with SST is restricted by a definite stress, after which an eddy is developed. Unfortunately, even with in-depth research into the behaviour of formation and decay of eddies [16], the issue on stability of a flow with SST did not come up. Apparently, the technique being suggested is the first to pose the problem of using SST to stabilise a flow.

Jet formation should ensure transfer of energy-containing turbulent fluctuations from the flow to the jet. With this in view, in a channel, with the help of space-filling fractal square grids, an area with predominantly small-scale turbulence is formed. The spectrum of wave numbers of fluctuations of the inertial energy interval with high Reynolds numbers encompasses 2–3 orders with different life-time scales and various times of occurrence. As a result, a local array of such fluctuations is formed in the flow with a reserve of turbulent kinetic energy, wherein merely a dissipation process occurs. Part of this array in the nozzle transforms to a jet and prevents the generation of strong turbulence therein. The authors have no technical means to provide experimental proof of the technique principles, therefore it is impractical to discuss the assumed processes in the jet.

With no immediate analogues of the technique being suggested, our attention was drawn to fountains known as Jumping Jet or Laminar Water Jet. They create a solid translucent jet with small kinetic energy. However, the jet appears to be overly long for laminar flow, with which the jet characteristics are associated. The principle of operation and the design of proprietary fountains are protected by patents. However, one can gain some insight into them by using available technical characteristics and the visual parameters of the jet. They allowed estimating the Reynolds number of the initial flow. It turned out to exceed $1 \cdot 10^5$, which does not correspond to laminar flow conditions.

In our opinion, grid turbulence, or probably, even SST account for the unique properties of the jet. Let us present, in our opinion, the most obvious facts in support of this finding.

Certain features of industrial fountain design are apparent during technical maintenance. The flow channel shape and the nozzle profile not only ensure conditions for laminar flow but, undoubtedly, cause turbulence. Moreover, the channels have a mesh or grids with small cells that create grid turbulence.

Consequently, the fountains discussed, in spite of ignoring all requirements to smooth flow, ensure the translucency and stability of jets. These contradicting factors are in accord if SST is present, and they also help understand the features of jets relying on appropriate flow stability. The flow is not disturbed by channel wall roughness, and it is maintained in the nozzle in spite of the inlet ribs. SST also ensures jet translucency and continuity.

The design of amateur fountains with a translucent jet is presented in detail in the Internet with more information about their operation. They virtually copy industrial products and are made to one schematic diagram: the nozzle cylindrical cavity is packed tightly with drinking straws or another material with narrow channels. Apparently, the objective of such design is to ensure a laminar flow. However, the end face of the set of straws forms a peculiar grid to cause turbulence. Hence, there is no reason to consider the jets of Jumping Jet fountains laminar ones.

The light effects demonstrated by the jets are also caused by turbulence. The fine quality of the jet facilitates illumination light propagation therein due to total internal reflection. In absence of impurities – and they are removed with a filter – the laminar jets should not glow; however, the fountain jets do glow. The glow observed can be explained by light scattering on small-scale turbulent fluctuations, which do not create jet opacity.

Proprietary fountains demonstrate a unique effect of light spot transfer by a jet, which is also explained by the presence of turbulence. Apparently, in this case, it is SST that is created by changing the flow velocity. It causes no light scattering and the jet in the dark becomes invisible in spite of the illuminating effect. When impulse turbulent disturbance is created it moves with the jet as a glowing spot. The preservation of the spot shape correlates with the established fact [12] of an unusually long turbulent eddy lifetime in a laminar flow. However, in this case, a stable eddy is observed in the turbulent flow, and this is in agreement with the concept of stability of a flow with SST.

Hence, the special properties of the jets in the Jumping Jet fountains actually demonstrate the feasibility of the concepts of our technique. The technical solutions implemented in these fountains merit the highest appraisal. However, they cannot be used for obtaining a solid jet with big kinetic energy under impulse conditions. These fountains use a continuous flow, which is interrupted by a gate for a given time interval.

Conclusions

Using the technique for water-jet guns poses problems, which can be resolved during experimental research. One of them is related to flow instability at the initial phase of the impulse. Methodically, its solution is straightforward. A more challenging issue is studying the features of SST behaviour at high flow velocities. However, there is no apparent hindrance to solving these problems, and the expected improvement of jet technologies will make up for the spent efforts and invested funds. The authors will appreciate the effort of professionals who will be interested in further development of the concepts presented herein.

Looking at the future, a flow with an artificial SST can be used as a means against eddying in different production processes. Namely, properties of a turbulent flow impart disturbance resistance to the flow and prevent the emergence of strong turbulence.

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ВИКОРИСТАННЯ ДРІБНОСМАШТАБНОЇ ТУРБУЛЕНТНОСТІ ДЛЯ СТВОРЕННЯ СУЦІЛЬНОГО ГІДРОСТРУМЕНЯ

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Запропонована методика отримання суцільної гідрострумінь з використанням струму з дрібномасштабною турбулентністю, що утворюється в області розпаду решіткової турбулентності та відводиться у струмінь. У такій турбулентній структурі неможливо утворення вихорів, та присутність її у струмені буде перешкоджати утворенню високої турбулентності та затримає розпад струменя. Методика дозволить збільшити дальність дії імпульсних водометів, а також буде корисною у технологіях, де потрібна суцільний струмінь. Наведені приклади використання дрібномасштабної турбулентності у каналах та струменях. Показана відсутність ламінарності у струменях фонтанів типу Jumping Jet, а їхня особлива стабільність пояснена існуванням дрібномасштабної турбулентності, що свідчить на користь реальності концепції запропонованої методики.

Ключові слова: *струмінь, турбулентний струм, ізотропна турбулентність, гомогенна турбулентність.*

ИСПОЛЬЗОВАНИЕ МЕЛКОМАСШТАБНОЙ ТУРБУЛЕНТНОСТИ ДЛЯ СОЗДАНИЯ СПЛОШНОЙ ГИДРОСТРУИ

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Предложена методика получения сплошной гидроструи с использованием течения с мелкомасштабной турбулентностью, которая образуется в области распада решеточной турбулентности и отводится в струю. В такой турбулентной структуре невозможно возникновение вихрей, и присутствие ее в струе будет препятствовать образованию сильной турбулентности и задержит распад струи. Методика позволит увеличить дальность действия импульсных водометов, а также будет полезной в технологиях, где требуется сплошная струя. Приведены примеры использования мелкомасштабной турбулентности в каналах и струях. Показано отсутствие ламинарности в струях фонтанов типа Jumping Jet, а их особая стабильность объяснена присутствием мелкомасштабной турбулентности, что свидетельствует в пользу реальности концепции методики.

Ключевые слова: *струя, турбулентное течение, изотропная турбулентность, гомогенная турбулентость.*