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INFLUENCE OF SURFACE FRACTAL MICROSTRUCTURE ON THE CHARACTERISTICS OF A TURBULENT BOUNDARY LAYER

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Abstract

The influence of the surface fractal microstructure on the velocity spectrum and the structure of the turbulent boundary layer were registered in both load and hot-wire experiments. Advantageous change in aerodynamic drag was observed, which indicates the possibility of turbulence control.

1 Introduction

The problem of turbulent flows over a rough surface is one of the most urgent problems of practical importance in aerohydrodynamics. The roughness of a material surface can be different, namely, it can be statistically homogeneous (this case has been considered by many authors since the beginning of the twentieth century) and stochastically structured (this case has recently been discovered in the process of plasma processing of surfaces of different materials) [1]. A viscous incompressible fluid flow over different structured surfaces was studied theoretically and experimentally [2, 3]. As a rule, the topology of rough surfaces after plasma processing possesses properties of scale invariance in a wide range of sizes from several hundred nanometers to several millimeters and is characterized by special properties of self-similarity, i.e., fractality. In the case of the turbulent flow over rough surfaces of this kind with a fractal structure, it is quite natural to expect a certain qualitative variation in the flow properties [4].

Most types of roughness are known to lead to a relationship between the friction coefficient and the Reynolds number, $c_f = c_f(\mathrm{Re})$, which corresponds to the model, based on the consideration of a single-grain and statistically uniformly distributed roughness. However, this results from a number of investigations of turbulence in flows that are bounded by a rough wall, in which for certain types of roughness there is an explicit dependence of the turbulent boundary layer (TBL) characteristics on the type of wall inhomogeneity.

Note that in the general case the stochastic topography of the surface can be of two different types: the simplest type, with a Gaussian function of distribution of irregularities that has an exponential tail; and a statistically inhomogeneous type, with a non-Gaussian distribution function of irregularities. As a rule, this function of distribution has a power tail, i.e., it damps significantly slower than the Gaussian function of distribution.

The second type of structure of a stochastic surface, in contrast to the first type, is characterized by such properties as the generalized scale invariance, long-range correlations, and power-law spectra. The dominant role of these properties, which can specify the TBL transverse momentum transfer owing to a special self-similar symmetry of the surface structure, is discussed in [4]. As far as the authors know, the effect of a fractal microstructure with non-Gaussian function of distribution on the TBL has not been previously investigated.

This paper presents the first results of such experiments in the T-36I wind tunnel at TsAGI. The samples used in the experimental studies were flat plates, obtained by plasma processing. Intensive erosion of a material surface in contact with plasma leads to considerable variation in the shape and structure of the surface in thermonuclear fusion devices with high-temperature plasma in a magnetic field (Tokamak and other types of units). Eroded particles turn into plasma and then deposit once again on the surface. As a result, a surface with a fractal structure is generated. Irregular surface shapes, such as globular, cauliflower, ovoidal, stratified, and columnar shapes are observed. This problem refers to the problems of growth of materials with complex structures that are neither crystals nor amorphous bodies in the classic sense. Not only the plasma energy content but also factors specific to the plasma heat load on the material surface exert an influence on the generation process of such an inhomogeneous surface.

Plasma in thermonuclear facilities possesses complex nonlinear self-organizing and structuring properties in plasma turbulence. Anomalous transport of plasma on a wall across a magnetic field is in general the result of sporadic, large-scale events that are accompanied by long-range correlations, self-organizing, and coherent structures. The trajectories of the particles deposited from the turbulent plasma in electrical fields are not classical Brownian motion but are stochastic Levy flights. Such anomalous diffusion leads to fractal growth of the surface with a specific structure. This growth is known in condensed-matter physics, where the shape of the deposition surface depends on fluctuations in the deposited flow. Even relatively small fluctuations are capable of leading to growth instability, which forms an inhomogeneous surface with three-dimensional (3D) irregular structures of a particular hierarchy.

2 Surface structures of the samples under investigation

2.1 Surface structure generated under the high-temperature plasma effect on the model

The models used in the experiments were supplied from the National Research Centre, Kurchatov Institute, and the State Research Center, Troitsk Institute for Innovation & Fusion Research (TRINITI). The models were 5-mm-wide, 160 × 160 mm^2 flat plates made of 12Cr18Ni10Ti stainless steel. The plates were processed by intense plasma jets in the fusion device QSPA-T (TRINITI). The QSPA-T fusion device is a one-step coaxial high-current plasma accelerator with its own magnetic field. Depending on the energy content of the plasma jet, it is possible to generate a required range of maximum roughness heights on the surface of a plate under processing.

The measurements of the inhomogeneity height profiles were performed by a laser profilometer with a gauge length up to 12 mm and a height resolution from 1 μm to 1 mm. A traditional system of coordinates was chosen. The x axis was the longitudinal distance from the wind tunnel test section start and the y axis was the distance across the boundary layer counted from the model surface. As an example, the rough surface profile in the maximum roughness zone is shown in Fig. 1, where the plasma impact is seen to lead to the generation of stochastic relief.

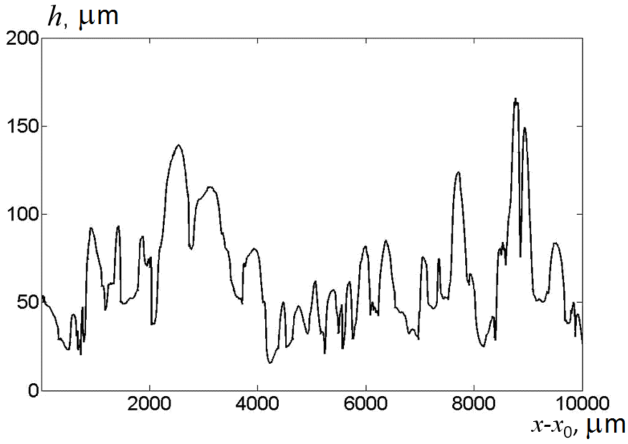

Fig. 1. Profile of the surface of model, obtained using the profilometer (x_0 is the coordinate of the roughness region start)

Fig. 2 shows the Fourier spectrum of the reliefs of the heights for model 1. It turns out that the spectra can be approximated by an algebraic function of spatial scale f (measured in units of 1/mm): $S(f) \sim f^{-\gamma}$. Within the range of scales from ~5 to ~3 ×10^{-2}, the spectrum is approximated by a power law with γ = –1.94.

The investigations of the profiles of the rough surfaces of the two other models also showed a Fourier spectrum power type with values close to the power-law index.

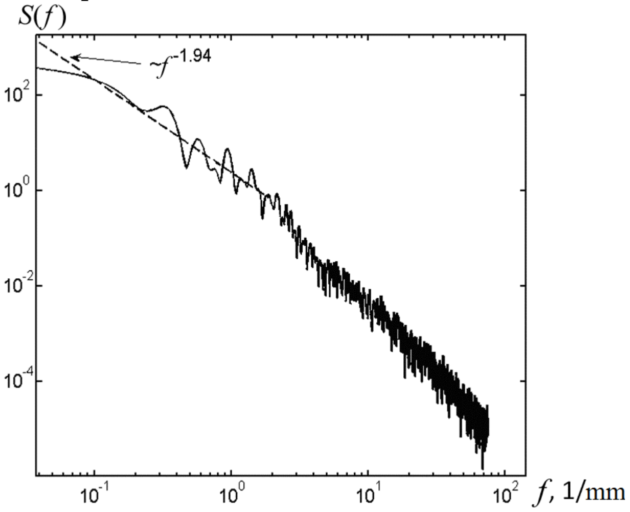

Fig. 2. Fourier spectrum of the relief heights in relative units for model 1 (approximation of the spectrum by a power function with a power of –1.94)

The function of distribution of heights, constructed as a histogram of the series $\left(h_i - \langle h_i \rangle\right)/\sigma_h$, determined from a series of heights h_i by profilometry data, is the characteristic of the stochastic character of the relief; $\langle h_i \rangle = (1/n)\sum_{i=1}^{n} h_i$ is the arithmetic value of the whole series h_i, where h is the height along coordinate y and σ_h is the root-mean-square deviation from the arithmetic value. The function of distribution of the relief heights for all considered samples had heavy tails, which is not described by the Gaussian (normal) law; this points to nontrivial stochastic properties of the topographic relief (Fig. 3).

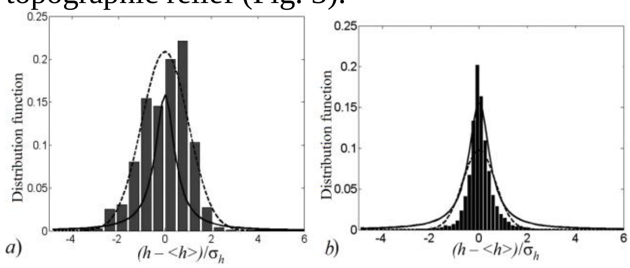

Fig. 3. Probability distribution function in relative units for model 1: (a) surface heights; (b) increments in surface heights (for comparison, the following curves are presented: dashed line, Gaussian distribution function; solid line, Cauchy–Lorentz distribution function)

Remember that the closeness of the distribution to the Gaussian law indicates a trivial stochastic distribution. For a quantitative description of the relief stochastic structure, the concept of self-similarity and fractals is used, which is applied when studying amorphous bodies [5]. This allows focusing attention on the macroscopic aspects of a rough structure and irregular clusterization of inhomogeneities. With the assumption of independence of self-similarity properties from observation scale $h(y)$, H is used (the Hurst parameter is the exponent of the relief irregularity, which is related to the fractal dimension of the surface as D=3-H). The Hurst exponent H is the parameter that characterizes the relief self-similarity; namely, for any $\lambda>0$, profile $\lambda^{-H}h(\lambda y)$ has the same probability distribution function of heights as profile $h(y)$. Here, H=0.5 corresponds to the trivial stochasticity (Brownian relief), and a value within $0.5< H< 1$ corresponds to relief with long-range correlations and structuring [4]. A standard library routine in the *MATLAB* software package was used to determine H. The Hurst parameter that characterizes the surface inhomogeneity of the samples considered takes values from 0.7 to 0.9. This is higher than 0.5, which clearly indicates a nontrivial scale invariance (fractality) and is typical for stochastic systems with long-range correlations and hierarchic structure [5].

2.2 Surface structure of a standard abrasive material

Flat surfaces of 160×160 mm^2, made of an abrasive industrial material (sandpaper abrasive sheets; produced by KLINGSPOR) were also used as samples in the comparative study. These materials have a stochastic surface topography with a random law of distribution of roughness heights with the Gaussian function of distribution. Samples of two types of waterproof sandpaper, P120 and P280, made of silicone carbide with grit sizes of 120 and 280 μm, respectively (this corresponds to the ISO 634 standard designations of abrasive materials), were used in the experiments. The heights measured by the profilometer of the profile of the sample made of the P120 sandpaper varied up to 120 μm (Fig. 4).

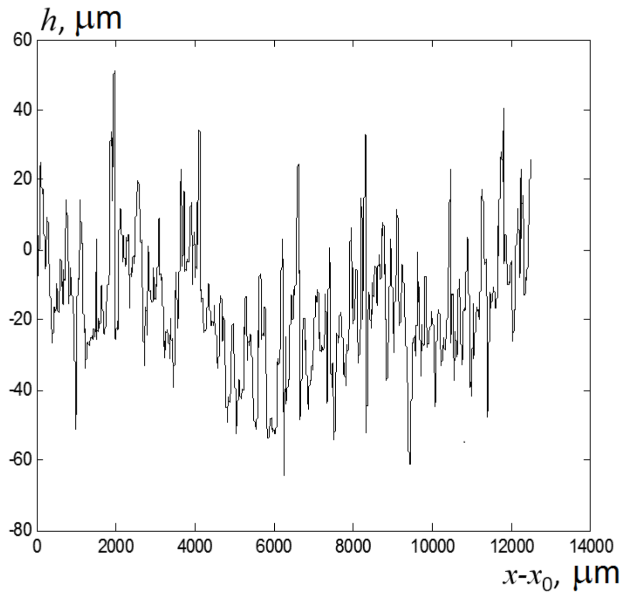

Fig. 4. Profile of the P120 abrasive surface (x_0 is the coordinate of the roughness region start)

The Fourier spectrum of this profile did not depend on the scale within 10^{-5} to 10^{-2} mm^{-1} (Fig. 5).

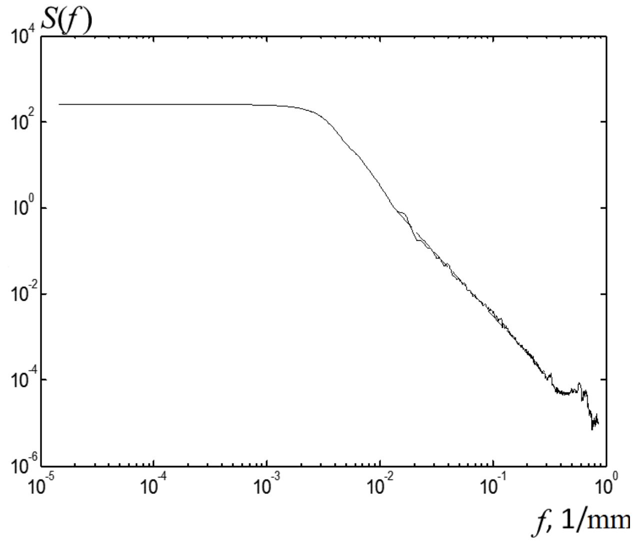

Fig. 5. Fourier spectrum in relative units for the profile of the P120 abrasive surface

The distribution function of heights was close to the Gaussian function, which points to the trivial stochasticity of the relief and the absence of a fractal hierarchy of granularity (Fig. 6). The profile for the P280 sandpaper was similar, with height variations up to 250μm. The Fourier spectrum of this profile did not depend on the scale within 10^{-2} to 2 mm^{-1}, and the distribution function of heights was also close to the Gaussian function.

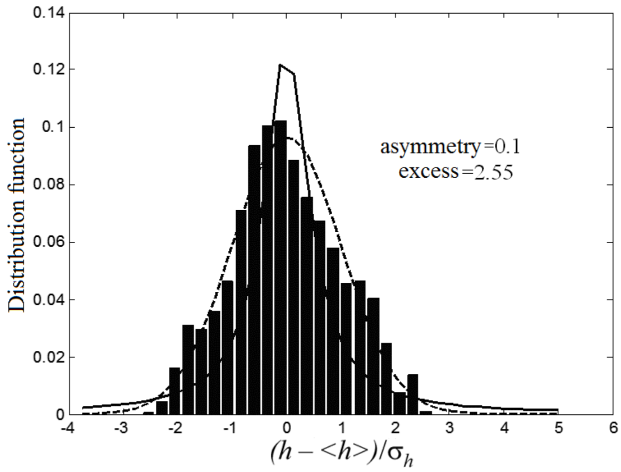

Fig. 6. Probability distribution function of the relief heights in relative units for the P120 abrasive surface (for comparison, the following data are presented: dashed line, Gaussian distribution function; solid line, Cauchy–Lorentz distribution function)

Thus, the models made of abrasive sandpaper sheets significantly differed in the roughness structure from the models with the same average height processed by plasma in the QSPA-T facility.

3 Surface structures of the samples under investigation

3.1 Surface structure generated under the high-temperature plasma effect on the model

The tests were carried out in the low-turbulent aerodynamic T-36I wind tunnel at TsAGI. The test section of 2600 mm had a rectangular cross section of 500×350 mm^2. The free-stream scale of turbulence for a velocity of 8–55 m/s did not exceed 0.06%. Forced turbulization of the boundary layer was implemented by means of a stationary vortex generator installed in front of the test section. The models, in the form of inserts, were installed flush with the bottom polished wind-tunnel wall. The gap between the edges of the model and the wind-tunnel wall was thinner than 0.1 mm, which almost eliminated its influence on the TBL characteristics. The distance from the wind-tunnel test section start to the model leading edge was 1520 mm. Two types of experiments were carried out:

- Determination of drag coefficient *cx* using a balance unit within the range of velocities from 8 to 55 m/s; and
- Measurement of flow velocity and its pulsation component in the boundary layer using the hot-wire anemometer DISA 55M01 for flow velocities of 10, 20, and 30 m/s.

The force effect of the flow on the model was measured by strain-gauge transducers, attached to the bridge block of the 8ANCh-23 equipment. The data obtained were processed using a special software program.

The pulsations of the flow local velocity, measured by the hot-wire anemometer, were registered using a separate system of acquisition with a high-speed ADC. The multifunctional card ADC/DAC L-Card L-783M was used (16 channels, 12-bit ADC, maximum frequency of conversion of 3 MHz, adjustable input range up to ±5 V). The ADC frequency for the registration of velocity pulsations was 10 kHz.

For the qualitative analysis of the turbulent process it is necessary to know the distribution function of the amplitudes of fluctuations in the turbulent flow. Description of experimentally measured probability distribution function by analytical functions is quite a difficult problem. Therefore, to describe the distribution functions, their moments are applied in practice. For turbulent field $u(t)$, the structure function of order q is defined as a statistical average over the assemblage of differences $\delta_\tau(u) = u(t+\tau) - u(t)$, namely, $S_q(\tau) = \left\langle |\delta_\tau(u)|^q \right\rangle$, where τ is a time lag.

The scalings (i.e., the laws of scale invariance) for $S_q(l)$ and for dissipation energy ε_l in the case of an isotropic developed turbulence are [6]

$$S_q(l) \sim \left\langle |\delta_l u|^q \right\rangle \sim l^{\varsigma(q)}, \quad \left\langle \varepsilon_l^q \right\rangle \sim l^{\eta(q)}$$

with interdependent parameters $\varsigma(q) = q/3 + \eta(q/3)$. From considerations of dimensionality, Kolmogorov (1941) derived that $\varsigma(q) = q/3$, which led to the well-known energy spectrum $E_k \sim k^{-5/3}$.

The log-Poisson model of intermittent turbulence was suggested by Dubrulle [7] and became a generalization of the fractal turbulence models, which had been developed previously. These models appeared after a phenomenological observation of an extended self-similarity in hydrodynamic turbulence. In the log-Poisson models, a stochastic multiplicative cascade was considered, in which dissipative structures with different dimensionalities, including the fractal one, could be generated simultaneously. Such a process was described in the probability theory in the framework of the Khintchine–Levy approach.

3.2 Spectral characteristics of velocity pulsations in the turbulent boundary layer

The investigations showed that the velocity pulsations at different flow velocities take different forms depending on the height above the surface. Velocity pulsations have a characteristic structure with the presence of aperiodic bursts of amplitude. Turbulent fluctuations contain bursts of amplitudes of a typical form with abrupt growth and a slow decrease in amplitude. This property of turbulence is called intermittency and is observed in many experiments on the TBL.

To thoroughly describe the signal structure and properties of its self-similarity, the wavelet transform of the signal is applied. The wavelet transform of signal $x(t)$ on the basis of analyzing function $\Psi(t)$ (the Morlet functions are applied) is defined as

$$Y(a,t') = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \Psi^* \left(\frac{t-t'}{a} \right) dt$$

where the asterisk denotes the complex conjugation, t' is the time parameter of the shift, and a ($a > 0$) is the scale coefficient.

A typical spectrum of free-stream velocity pulsations has a complicated dependence on frequency within the range from 0.1 Hz to 10 kHz, with saturation below 100 Hz and decay in the region of high frequencies. Within the range of frequencies from»100 Hz to 1 kHz, the frequency spectrum can be approximated by a power law of frequency $f^{-\gamma}$ with power index

γ=1.97. In other frequency spectra, the dependence is described by other γ indices, which differ from the K41 law (Fig. 7). In the TBL zone after the model, a significant variation of spectrum is observed. In particular, at the height of 0.2 mm in the region of low frequencies, the spectrum intensity decreases 1.5–2 times, while the amplitude of the spectrum increases in the region of high frequencies (Fig. 7); that is, transfer of the spectrum into the range of high frequencies takes place, which can point to the breakdown of low-frequency coherent structures by the model with fractal roughness.

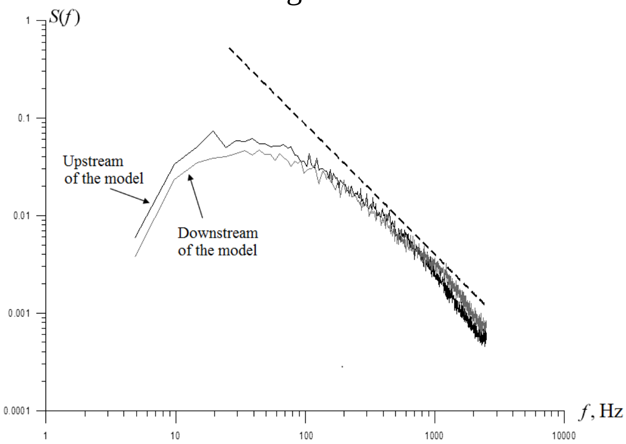

Fig. 7. Spectrum of velocity pulsations in relative units at x = 1515 mm (before model 1) and at x = 1685 mm (after model 1) at height y = 0.2 mm and U = 20 m/s (dashed line, K41 Kolmogorov law)

Asymmetry and excess over the Gaussian curve for large amplitudes (the so-called heavy tails) are observed for a typical function of distribution. Large bursts of amplitude that occur in signals with higher probability than predicted by the law of the classical Brownian process (known as white noise) further contribute to this asymmetry. The presence of large peaks with amplitudes larger than three standard deviations, called bursts, indicates considerable intermittence.

The probability distribution function dependence on height is observed in the TBL. This fact points to the complicated structure of turbulence. To describe the distribution function deviation from the Gaussian law in the first approximation, the asymmetry and excess coefficients are used. The asymmetry coefficient is a value that characterizes the distribution function asymmetry. It is set by formula $A = M_3 / \sigma^3$, where $M_3 = \sum_x x^3 P(x)$ is the third central moment of distribution function $P(x)$ and σ is the standard deviation. The excess coefficient is the criterion of fineness of a distribution function peak. It is set by formula $F = M_4 / \sigma^4 - 3$, where $M_4 = \sum_x x^4 P(x)$ is the fourth central moment of the probability distribution function.

As was mentioned in Section 2.1, the Hurst exponent H, interpreted as an index of the law of diffusion of a particle in a turbulent medium [where the mean square displacement depends on time as $\left(\left\langle \delta x^2 \right\rangle\right)^{1/2} \sim t^H$] is one of the indices of the scale invariance used in the literature to characterize the fractal properties of turbulence. For Brownian motion (classical diffusion), H = 1/2; that is, the law of displacements of particles is $\left\langle \delta x^2 \right\rangle \sim t$. Analysis of the obtained experimental signals of velocity pulsations has shown that the Hurst exponent in the basic zone of the TBL takes the values from 0.6 to 0.8. When approaching a wall, it was observed that this value tended to increase.

3.3 Measurement of the drag coefficient of a turbulent plate

To measure drag coefficient c_x, the model was placed on balances. The scheme enables measuring with high accuracy the variation of force for different free-stream velocities. Two series of measurements were performed. The first series was performed by varying the free-stream velocity from small to large values; the second series was performed by varying the free-stream velocity from large to small values. This enabled verifying the correctness of the measurements. For comparison, similar additional series of measurements were carried out on the following:

- A smooth model made of glass;
- A model made of a plate (unprocessed by plasma); and
- A rough model made of an abrasive industrial material.

An excess of drag coefficient c_x for an abrasive surface over drag coefficient c_x for a fractal surface with the same average roughness was observed in a wide range of Reynolds numbers (Fig. 8).

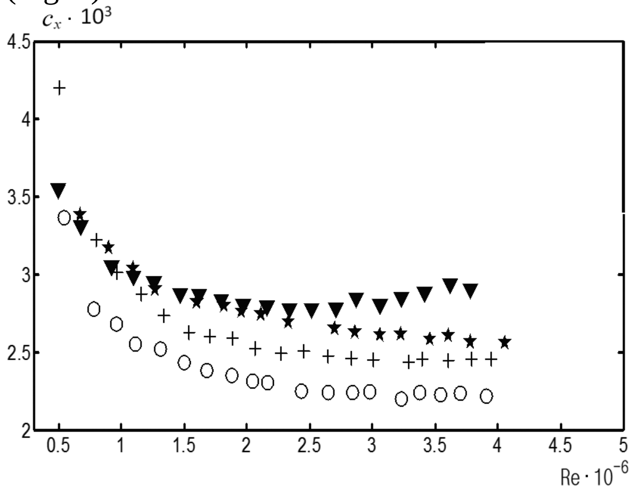

Fig. 8. Drag coefficient c_x as a function of the Re number: open circles, smooth model (glass surface); plus signs, surface unprocessed by plasma; stars, model with a fractal roughness; open triangles, PS 280 (abrasive surface)

The measured drag coefficient was compared with the known theoretical dependences for the friction coefficient of a smooth plate in a turbulent flow within $5\times10^5 < \mathrm{Re}_l<10^7$: $c_f = 0.074(\mathrm{Re}_l)^{-1/5}$. Fig. 9 shows the result of processing of an experimentally measured drag coefficient of a glass surface using a power law [8].

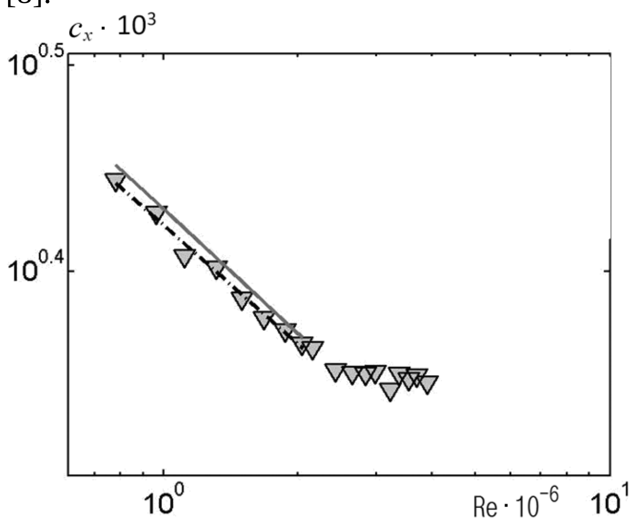

Fig. 9. Drag coefficient as a function of the Re number for a smooth model (open triangles): dashed line, fitted by the law $\left(\sim \mathrm{Re}^{-0.19077}\right)$; solid line, theoretical dependence $\left(\sim \mathrm{Re}^{-1/5}\right)$.

The fitting index of power 0.19 turned out to be close to the theoretical value 1/5.

It can be seen that the models processed by plasma have scaling indices close to the theoretical value for an absolutely smooth surface. For the abrasive surface with an average roughness of ~100μm and the Gaussian statistics of distribution of the relief heights, index ν=0.1, which is considerably deviated from 1/5 for a smooth surface. This experimental fact should be taken into account when analyzing the influence on the turbulent flow characteristics of a fractal surface and a surface with a Gaussian distribution of heights.

4. Conclusions

The non-Gaussian statistics of distribution of roughness heights is a distinctive feature of fractal surfaces, and the forms of the spectrum of the fractal surface profile agreed well with the TBL. This result enabled making the assumption of the existence of a frequency-space selective effect of a stochastic relief of a model on the TBL characteristics.

These results were compared to the one of tests of a model made of an abrasive industrial material with the Gaussian distribution function of heights, as well as with an almost smooth model made of glass.

The measurements of drag coefficient c_x as a function of the Reynolds number revealed the power dependence $c_x \sim \mathrm{Re}^{-\nu}$ with different power indices (scaling) ν for the models with a fractal structure and abrasive surface. The fractal models had $\nu \approx 0.2$, which is close to the theoretical value $\nu = 1/5$ for an absolutely smooth surface. For an abrasive surface with the same mean roughness, the scaling index turned out to be significantly lower, namely, $\nu \approx 0.1$.

Acknowledgments

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