Application of innovative materials with stochastic nano- and microstructure of the surface: control of turbulent flows in plasma and aerodynamics

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Abstract. It is proposed to control plasma turbulence near the LCMS of a tokamak with a system of electrodes made from porous tungsten. We propose to apply the RF modulation at the ion-cyclotron resonance frequency for driving of fluctuations near the LCMS. Porous tungsten plates used as biasing electrodes are the advantage to increase the emissivity of the porous surface and to reduce a surface erosion. To reduce the drag and thermal load on streamlined surfaces at supersonic and hypersonic speeds, it is proposed to cover the aircraft with materials of high porosity. The first experiments were carried by using model with fractal surfaces having non-Gaussian height statistics from ~ 500 nanometers to ~ 200 micrometers obtained by plasma treatment. The advantage of such a surface is the coincidence of the spectral and statistical characteristics of the stochastic topography of the surface with the turbulence characteristics of the flow.

1. Introduction
In recent years, the effects of extreme thermal plasma loads on the material have revealed universal effects of stochastic clustering of a surface with hierarchical granularity and statistical self-similarity - fractality [1-4]. Such a structure of the solid surface is formed in fusion devices after the plasma testing of materials when multiple mechanisms of erosion and redeposition of eroded material, melting and melt movement of surface layers effect simultaneously at scales from tens of nanometers up to hundreds of micrometers. The properties of the unique scale invariance (self-similarity) of the structure of such highly porous materials (see the examples in Fig. 1-3) [1-4] produce hierarchical granularity and the formation of a percolation cluster of defects and dissipative structures over a wide range of scales, starting from submicron scales. Refractory metals with a high-porosity nanostructured surface are in demand for operation under extreme thermal and plasma-beam loads [1-4], in a fusion reactor, to cover the streamlined surfaces of aircraft in order to reduce aerodynamic drag at supersonic and hypersonic speeds, in biomedical applications.

2. Porous tungsten for controlling the plasma sheath layer and the edge plasma turbulence in a tokamak
Edge plasma turbulence near the last closed magnetic surface (LCMS) in a tokamak drives enhanced plasma losses. Plasma flow along magnetic field leads to the narrow width layer (which is of several ion gyro-radiuses) onto the divertor plates. In the ITER, this width is only a few millimetres; extremely high loads are expected in this zone leading to melting and destruction of the divertor plates. To achieve a steady-state operation of a fusion thermonuclear reactor, it is required to develop
effective control of the plasma sheath layer and the edge plasma turbulence in a tokamak with the aim to extend the radial scale of the high-heat load layer.

Figure 1. SEM micrographs of tungsten surface after plasma irradiation: (a) in the T-10 tokamak, (b) in the QSPA-T facility.

Figure 2. SEM micrograph of beryllium surface after plasma irradiation in the QSPA-Be facility.
In this paper, we propose a controlling of plasma turbulence [5,6] near the LCMS with a system of electrodes made from tungsten with stochastic surface and porous structure tungsten, Fig.4. The electrodes biasing forces a modulation of plasma instabilities by a longitudinal electric field. In such a scheme, a driving of ion-acoustic instability is formed under the effect of a longitudinal electric field as considered by the theory of V.P. Silin [8, 9] who predicted the growth of the plasma temperature $T$ with an electric field $E$ as $T \sim E^2$ under developing of ion-acoustic turbulence. The scheme of the experiment proposed for the T-11M tokamak is shown in Fig. 4b. The proposed radial width of the electrodes is of 15 mm; the poloidal width is of 10 cm; the toroidal width is of ~5 cm. The DC biasing voltage $U_{dc}$ between electrodes is proposed to be in the range from -200V to +200V. We propose to apply the RF modulation by $U_{RF}$ voltage amplitude at the ion-cyclotron resonance frequency for driving of fluctuations near the LCMS. In such a scheme, it is expected that the SOL plasma turbulence and related cross-field turbulent plasma transport will be affected locally in the vicinity of the LCMS. This scheme is improved previous biasing schemes used earlier, namely: the biasing voltage is applied between electrodes along the magnetic field with no radial current; in addition, the RF modulation of turbulence and a local change in the cross-field plasma flux near the LCMS are expected. Porous tungsten plates used as biasing electrodes have an additional advantage of increasing the emissivity of the porous surface and reducing surface erosion. A self-sustaining process of maintaining tungsten porosity at the long-term operation in a tokamak fusion reactor is expected [1-4].
3. Control of the turbulent boundary layer of aerodynamic flows

To reduce the drag and thermal load on streamlined surfaces at supersonic and hypersonic speeds, it is required to cover the aircraft with materials of high porosity [10,11]. In the wind tunnel [11], the first experiments (Fig. 5b) were carried by using model (Fig.5a) with fractal surfaces having non-Gaussian height statistics (Fig.6a) from ~ 500 nanometers to ~ 200 micrometers obtained by plasma treatment in QSPA-T facility. The advantage of such a surface is the coincidence of the spectral and statistical characteristics of the stochastic topography of the surface with the turbulence characteristics of the flow, Fig.6b. (it relates with turbulent eddy turn-over time scale of ~ 10^{-4} seconds estimated as scale of velocity fluctuations ~1 m/s over roughness scale of 0.1 mm). A significant attenuation of the low-frequency spectral range and a change in the drag force were observed in experiments with a fractal surface plate [10] as a boundary of a turbulent flow. In a wide range of Reynolds numbers Re, it was registered a decrease in aerodynamic drag over the fractal plate compared to the abrasive surface (with Gaussian height statistics) of the same roughness (Fig.7a). For a fractal surface, the scaling index $\nu$ of the drag coefficient $c_d \sim Re^{-\nu}$ is close to $\nu$ for a smooth plate (made from glass) [11] (Fig.7b). This demonstrates the potential of a fractal surface to reduce aerodynamic drag at supersonic and hypersonic speeds.

Figure 5.  (a) Fractal surface profile formed in fusion device. (b) Velocity fluctuations in the turbulent boundary layer in the wind tunnel experiments.

Figure 6. Probability distribution functions of the fractal surface profile in the Fig. 5a. Gaussian law (dashed line) and Cauchy law (solid line) for the reference. (b) Spectra of velocity fluctuations in the turbulent boundary layer and surface heights fluctuations, experiments in subsonic flows.
Figure 7. (a) Drag reduction $c_x$ vs. Reynolds numbers $Re$; smooth plate (glass) – circles, virgin surface - crosses, fractal surface – black stars, abrasive surface – black triangles. (b) The scaling index $v$ of the drag coefficient $c_x \sim Re^{-v}$ for a smooth and rough plates vs. roughness.

Conclusions

Stochastic clustering of a surface with hierarchical granularity and statistical self-similarity (fractality) is observed in fusion devices after the plasma treatment in fusion device when multiple mechanisms of erosion and redeposition of eroded material, melting and melt movement of surface layers effect simultaneously at scales from tens of nanometers up to hundreds of micrometers. It is proposed to control plasma turbulence near the LCMS of a tokamak with a system of electrodes made from porous tungsten. We propose to apply the RF modulation at the ion-cyclotron resonance frequency for driving of fluctuations near the LCMS. Porous tungsten plates used as biasing electrodes are the advantage to increase the emissivity of the porous surface and to reduce surface erosion. To reduce the drag and thermal load on streamlined surfaces at supersonic and hypersonic speeds, it is proposed to cover the aircraft with materials of high porosity. The first experiments were carried by using model with fractal surfaces having non-Gaussian height statistics from ~ 500 nanometers to ~ 200 micrometers obtained by plasma treatment. The advantage of such a surface is the coincidence of the spectral and statistical characteristics of the stochastic topography of the surface with the turbulence characteristics of the flow. In a wide range of Reynolds numbers, it was registered a decrease in aerodynamic drag over the fractal plate compared to the abrasive surface (with Gaussian height statistics) of the same roughness.

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