Simulating the full-scale sea trials in the towing tanks using polymer drag reduction

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Abstract. We discuss the approach to simulate the experiments with surface and underwater vehicles in towing tanks for Reynolds numbers corresponding to the full-scale ones using discrete injection of polymer additives. Experimental data on velocity profiles and local skin-friction coefficient in turbulent boundary layer of vehicles and their models are given. Results of the simulating tests demonstrate a good agreement with sea trials.

1. Introduction

It is well known that polymer additives to Newtonian fluids reduce turbulent friction drag (e.g., White & Mungal, 2008). This effect is widely used in drag reduction systems including engineering of marine vehicles (e.g., Dimotakis et al., 2003). We extend its practical applications on simulating the full-scale experiments with ships and underwater vehicles by using their models in towing tanks with polymer augmented water (Elyukhina, Kholpanov & Khomyakov, 2010). The problem concerns forecasting the characteristics of flow near hull, including ones in boundary layer and viscous wakes and, in particular, data on frictional resistance under sea trial conditions. This allows to optimize design of vehicles with the required propulsion properties and to estimate tactical and technicoeconomic characteristics.

2. Approach to experiments

Traditionally, studying the such questions in a towing tank is reduced to the methods of partial simulation because of scale effects. It is caused by absence of complete dynamic similarity: in real and model conditions, the equivalence is provided only for Froude numbers $\text{Fr} = U_0/\sqrt{gL}$, but not for Reynolds numbers $Re = U_0L/\nu$, where $g$ is the free fall acceleration, $\nu$ is the kinematic viscosity, $U_0$ is the speed of the moving model or ship. For $Re_0$ corresponding to full-scale experiments, the skin-friction coefficient is substantially less than for model tests in towing tanks. Application of polymer additives allows to decrease this coefficient on ship model to values corresponding to $Re_0$. This fact can be use to develop the method for simulation of
towing tank flows like ones under full-scale $Re_0$, i.e., to reproduce sea trials in terms of these hydrodynamic factors. Some related theoretical aspects are considered by Orlov, Pashin & Sedov, 1997.

We report the selected results of experimental study carried out for the following purposes: to establish validity of velocity defect law, to determine features of diffusion of polymer additives and turbulent drag reduction in boundary layer depending on location and way of their input, to obtain uniform reduction in local shear stress for discrete injection. The special flow facility is designed to study diffusion (figure 1) and the towing tanks at Krylov Shipbuilding Research Institute are used (e.g., figure 2). Experimental conditions provide stable regime of turbulent boundary layer flow and enough amount of viscous flow on the vehicles models (200–500 mm). Reynolds numbers are up to $3.5 \cdot 10^7$. Some data and devices of KSRI, e.g., turbulence rheometer are used. Polymer solutions are ones of polyox WSR-301 with molecular weight of about 3 million g/mol. Size of the models are 5–8 m, the towing tanks are width of 15–17 m, depth of 1.7–7.0 m and length of 150–600 m.

3. Results and discussion

Results for the real and model experimental tests agree well (figures 4, 5) using the discussed approach. In figures 4–10, the parameters are scaled by the following: $\bar{u} = u/U\delta$, $\tilde{u} = (u_0 - u)/u_\tau$, $\bar{U} = u/u_0$, $\bar{y} = 100y/x$, $\tilde{y} = yu_\tau/(\delta^*u_0)$, $\bar{Y} = y/\delta$, $\tilde{x} = x/L$, $\tilde{c}_f = c_f \cdot 10^3$; $c$ is the concentration,
Figure 4. Velocity profiles in boundary layer of Crimea tanker (figure 3): 1 – model tests, water, $Re = 5.3 \cdot 10^6$; 2 – model tests, polyox, $c \sim 6.10^{-4} \%$, DR $\sim 45\%$, $Re = 5.3 \cdot 10^6$; 3 – sea trials, $Re = 1.33 \cdot 10^8$; $\bar{x} = 0.85$.

Figure 5. Change of $\bar{c}_f$ along body of revolution: 1 – in towing tank, water, $Re = 3.3 \cdot 10^7$; 2 – in towing tank, polyox, DR $\sim 30\%$, $Re = 3.3 \cdot 10^7$; 3 – sea trials, $Re = 3.3 \cdot 10^8$.

c$_f$ is the local skin-friction coefficient, DR is the drag reduction, $L$ is the corresponding length, $Re_x$ and $Re_L$ are Reynolds numbers along the surface, $x$ is the current longitudinal coordinate, $y$ is the coordinate orthogonal to the surface, $u$ is the streamwise velocity, $u_0$ is $U_0$ or $U_\delta$ for pipe flow, $u_r$ is the dynamic velocity defined from $U_\delta/u_r = \sqrt{2/c_f}$, $U_\delta$ is the velocity at $y = \delta$, $\delta$ is the boundary layer thickness, $\delta^*$ is the displacement thickness; the curves respond to calculations.

Analysis of mean velocity in different parts of the developed hydrodynamic stand shows that DR $\sim 15$ – 50% does not change character of defect profiles. In acceleration part, velocity $U_\delta$ is varied from 8.54 m/s at $x = 1.6$ m to 9.255 m/s at $x = 4.9$ m. For outer region of turbulent boundary layer, the dependence has the form $\bar{u} = a \ln \bar{y} + b$ (figure 6, polymer solution is injected through nose slot section). Note that DR $\sim 30\%$ corresponds to Reynolds numbers which are more on order of magnitude and to higher powers in law (figure 7) of velocity distribution in turbulent boundary layer (Schlichting, 1955).

Presence of second section with polymer injection slot give uniformity in DR along the layer (figure 8). The case 3 responds to input part of the pipe with gradient of $U_\delta$ and then the flow is weakly differing from one in plane boundary layer. There is typical jump in values of $c_f$ at place of slot section ($\sim 5\%$) that is fast vanishing downstream. We also develop the procedure to determine an optimal location of slot sections on vehicle models for experiments with uniform drag reduction in towing tanks. First slot is close to the place of turbulator on the hull, next ones are defined from empirical formulas linking, in particular, polymer concentration at the wall and local friction stress with and without solution.

The approach is working not only for plane boundary layers but also, e.g., for flow near propeller, i.e., for such 3D gradient boundary layers. Figure 9 shows the dependences of velocity on angle $\theta$ ($\theta = 0$ at the top of disc) for radii $r = 0.3$ (a) and $r = 0.25$ (b) scaled to total radius of propeller. Surface roughness leads to higher skin friction (e.g., Petrie et al., 2003). This fact gives possibility to simulate flows with smaller Reynolds numbers and also to control the required parameters by varying the experimental conditions (figure 10).
Figure 6. Velocity defect profiles in drag reduced turbulent boundary layer. $x = 1600$ mm from the pipe entrance: 1 – water, $u_\tau/u_0 = 0.0345$; 2 – polyox, DR~35%, $u_\tau/u_0 = 0.0274$; 3 – polyox, DR~52%, $u_\tau/u_0 = 0.0236$; $x = 4900$ mm: 4 – water, $u_\tau/u_0 = 0.0334$; 5 – polyox, DR~30%, $u_\tau/u_0 = 0.0272$; 6 – polyox, DR~15%, $u_\tau/u_0 = 0.0307$.

Figure 7. Velocity dependences for the cases with and without polymer DR: 1 – water, $u_0 = 9.255$ m/s, $\delta = 46.3$ mm, $\delta^* = 5.06$ mm; 2 – polyox, $u_0 = 9.06$ m/s, $\delta = 28.8$ mm, $\delta^* = 3.2$ mm, DR~30%; $Re_x = 2.75 \cdot 10^7$.

Figure 8. Values of $\bar{c}_f$ under upstream injection portion: polyox, $c \sim 0.05\%$, injection for the cases: 1 – slot 1, 2 – slots 1 and 2, simultaneously; 3 – water, $Re_L = 3.4 \cdot 10^7$.

Thus, usage of polymer additives allows to provide a hydrodynamic similarity between sea trials and towing tanks experiments and to simulate flows at higher Reynolds numbers.
Figure 9. Velocity in propeller disc of underwater vehicles: 1 – in towing tank, water, \( Re = 3.3 \cdot 10^7 \); 2 – in towing tank, polyox, DR \( \sim \) 30\%, \( Re = 3.3 \cdot 10^7 \); 3 – sea trials, \( Re = 3.3 \cdot 10^8 \).

Figure 10. Full frictional resistance for the model of Prague tanker class: 1 – smooth surface, water; 2 – rough surface, water; 3 – rough surface, polyox, \( c \sim 4.5 \cdot 10^{-4} \% \); 4 – rough surface, polyox, \( c \sim 6 \cdot 10^{-4} \% \).

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