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Experimental studies of water entrance in axisymmetric bodies with a negative pressure gradient

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Abstract

A series of water entrance tests for different special axisymmetric bodies with the negative pressure gradients along the surface was carried out and different flow patterns were revealed. In particular, for the smaller velocities, the flow without a cavity takes place. Increasing the entrance velocity leads to the typical non-steady super cavity flow. The body shape influences significantly the critical entrance velocity at which the flow pattern changes. In particular, an example of a slender body showed the flow pattern without a cavity for the whole range of the available entrance velocities (up to 6 m/s).

Keywords: Axisymmetric bodies; Pressure; Flow pattern; Velocity.

1. Introduction

In order to prevent the adhesion of the adjoining layer, special forms with appropriate static pressure distribution may be used. For example, the negative pressure gradient on the surface provides an irrevocable mode of rotation. The majority of researchers believe that minimal static pressure is achieved in the region of the water body, and the pressure gradient is added after the point of maximum thickness. This was used in the so-called laminarization phenomenon (Schlichting, 1959) obtained by the maximum displacement of the point of maximum thickness downstream.

It was interesting to study the possibility of securing an undivided pressure gradient after a point of maximum thickness. An example of such a body is given in (Goldschmied, 1982), but the irrevocable mapping of the model was only achieved with the use of an extraction of the boundary layer.

In a series of theoretical and experimental studies of the body of a special form was

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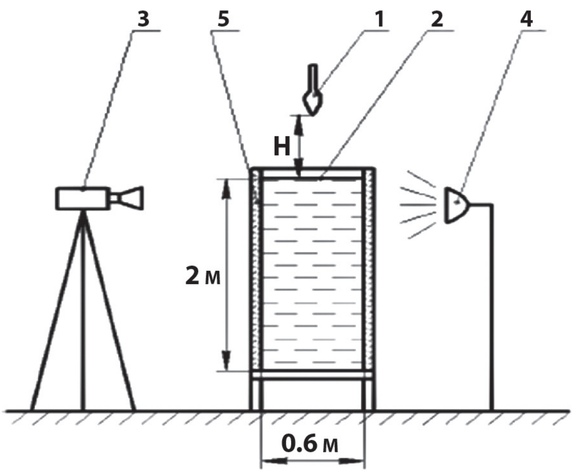

Figure 1. Scheme of the experimental installation

investigated to prevent liquidation and cavitations without using the active methods of controlling the adjacent layer (Nesteruk, 1989; Nesteruk, 1990; Nesteruk, 2000; Nesteruk, 2001; Buraga *et al*., 2001; Nesteruk 2002). For the calculation of axisymmetric bodies and two-dimensional profiles with negative pressure gradients on the surface, a theory of fine body and exact solutions of Euler's equations were used. The results of aerodynamic experiments with the proposed axisymmetric bodies are available in former studies (Nesteruk, 1989; Nesteruk, 1990; Nesteruk, 2000; Buraga *et al*., 2001; Nesteruk, 2002). Some of these forms provide an irresistible flow for relatively small Reynolds numbers.

Since the beginning of the caviation on a smooth surface is bounded to the abrasion, the presented bodies can provide a flow in the liquid without cavitation (Knapp *et al*., 1970; Takahashi, 2003). The foundation of such studies that was a series of experiments on the entrance to the water of the axisymmetric bodies of the special form, are carried out in this work.

2. Materials and methods

2.1. Description of experimental setup and models in axisymmetric bodies

Experiments were carried out in special glass walls with a capacity of 2 m deep and a straight-necked cross-section of 0.6 × 0.8 m. The investigated was located above the free surface of water at altitude H, which determined the velocity of the body when entering the water, since its initial velocity was equal to zero. The picture was recorded by a fast digital video camera with the help of the tiny registration method. The scheme of installation is shown in Figure 1, where, 1-the subject body; 2-free surface of water; 3-digital video camera; 4-four different bodies, V-1, V-3, UA-2, and S, fell vertically into the water. The speed of the entrance to the water ranged from 1-6 m/s.

The forms of the body and the distribution of the body are shown in Figures 2 to5. These forms were studied in an aerodynamic tube in the previous studies (Nesteruk, 2000; Nesteruk, 2003; Nesteruk, 1999). The UA-2 and S bodies provided an invulnerable stationary mode in the Reynolds number range of 100,000 <ReL <300,000 (Nesteruk, 2000; Nesteruk, 2003; Nesteruk, 1999). The vortex appeared on the forms V-1 and V-3, but the use of a small obstacle located on the surface in the region of the maximal radius prevented the freezing at sufficiently large Reynolds numbers (Nesteruk, 2000).

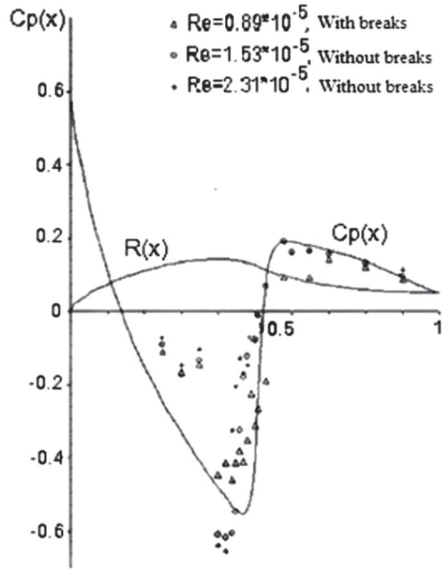

Figure 2. Radius and theoretical distribution of pressure for the body V-3

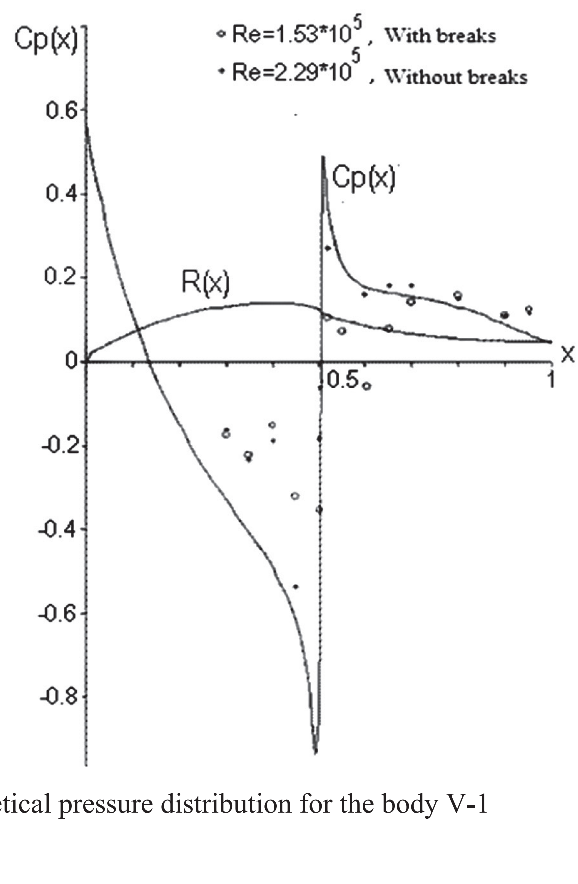

Figure 3. Radius and theoretical pressure distribution for the body V-1

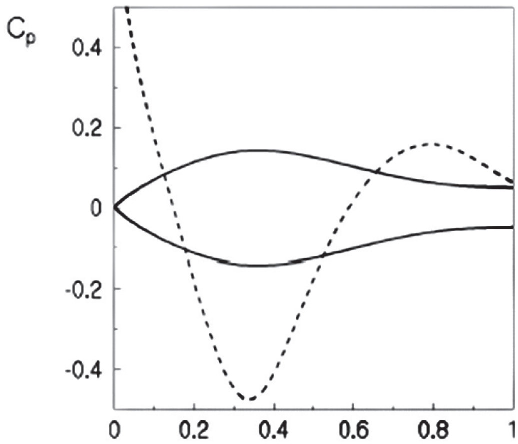

Figure 4. Radius and theoretical pressure distribution for the body UA-2

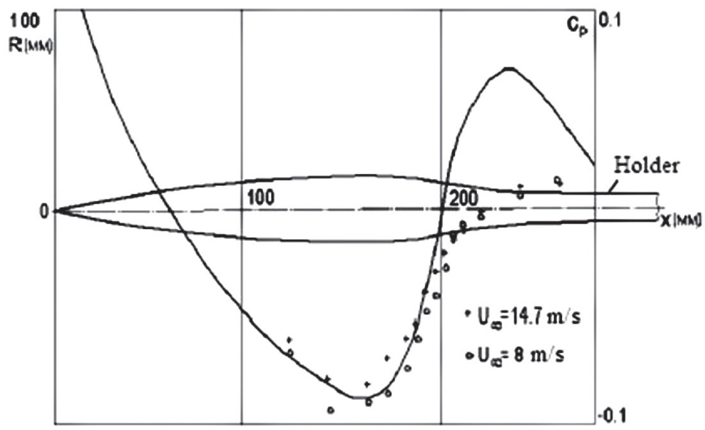

Figure 5. The radius and theoretical pressure distribution for the thin body S

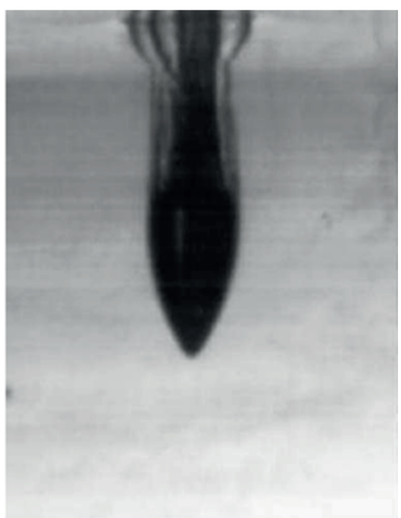

Figure 6. Body V-1, the entrance speed to the water is 3.5 m/s

In experiments, we used a semicircle rubber ring with a radius of 0.5 mm to obtain a non-detachable variant of the V-3 form. This body was designated of V-3-U. The maximum diameter of the V-1 and V-3 models was 56.5 mm, and the UA-2 and S with diameters of 56.76 mm and 30.26 mm, respectively. The bodies V-1, V-3 and UA-2 had the same length of 200 mm. The length of the body S was 280 mm. All models were completed with a cylindrical tube (as shown in Figure 5) in the length of 200 mm for V-1 and V-3; 300 mm for UA-2 and 220 mm for S. Total mass (body + tube) was equal to 0.86 kg for V-1; 0.37 kg for V-3; 0.36 kg for UA-2 and 0.315 kg for S. For the study of the influence of body weight, an additional piece weighing 0.23 kg was used that located inside the body of the V-3. The option model with additional weight marked V-3-H.

3. Results and Discussion

It was found that the nature of the layout of the hall live not only from the initial velocity of the entrance to the water, but also from the shape of the body. To illustrate this fact, Figures 6-8 show the photographs of the entrance to the water of the models V-1, V-3 and UA-2 that approximately the same initial immersion rate was 3.5 m/s.

It is visible that in the regions V-1 and V-3, in the regions of the region, non-constant caverns are formed on the bridge, the form of which in the fixed points of time is plotted in Figures 6 and 7. In contrast to these models, the UA-2 body was cured not only shown in Figure 8 time point, but also during the entire immersion process with an initial velocity of 3.5 m/s. It should be noted that all models have at-same the same maximum diameter; Moreover, the bodies V-3 and UA-2 have almost the same mass.

The pattern of the same models V-1, V-3 and UA-2 with a higher initial rate of immersion, which was approximately the same, 4.5 m/s, as are shown in Figures 9-11. It is obvious that at the higher speed, the super-covariance mode of wavering is characteristic of all three bodies. In this case, the length of the caverns on the models V-1 and V-3 is increasing in comparison with the case of lowering the rate shown in Figures 6 and 7. This fact is easily recognized by the decrease in characteristic numbers of cavities and the following estimates. With an increase in velocity, the evolution of the cavity acquires the forms that are characteristic for the so-called deep closure.

Characteristic of this phenomenon caverns with “throat” that are brightly observed especially for the body V-3-U. Figures 12 and13 show the forms of caverns in this body at two successive times. For the estimation of the coordinates of the closure point of the cavity and the closing time from the beginning of the immersion, we can use the solution obtained in (Nesteruk, 1980) to solve the problem of the vertical entrance to the water with the constant velocity U of a thin axisymmetric cavity:

$$\frac{R^2(x,t)}{R_{max}^2} = \frac{\sigma(t)}{2\ln\epsilon}\frac{x^2}{R_{max}^2} - \frac{1}{3\mathrm{Fr}^2\ln\epsilon}\frac{x^3}{R_{max}^3} + 1 \quad (1)$$

where, R(x, t) is the radius of the non-stationary axisymmetric cavity, R_{max} is the maximum radius of the body, $\mathrm{Fr} = U/\sqrt{gR_{max}}$ is the Froude number, ϵ is the small parameter of the thin body (R_{max} to total length of body and the holders).

Experiments have shown that the opening of the cavity is in the zone of the object body (see Figures 6, 7, 9-13), therefore, the difference from the radius of the cavity in its beginning x = 0, is zero. This fact is taken into account in Equation (1). Assuming that the pressure in the cavity up to the moment of deep closure is atmospheric, then, the current (depending on time t) the number of cavitations is given by the following equation:

$$\sigma(t) = \frac{2gt}{U} \tag{2}$$

By differentiating the Equation (1) along the coordinate x, we can determine the position of the throat of the x_{min} point that corresponds to the minimal radius of the cavity:

$$\frac{x_{min}}{R_{max}} = \frac{\sigma(t)\mathrm{Fr}^2}{3} \tag{3}$$

Then, adding Equation (3) to Equation (1) and considering that during closing, the minimum radius of the cavern is equal to the radius of the R_s holders, we obtain the value of the number of cavitation at the closing time:

$$\sigma_c = \left[-54\left(1 - \frac{R_s^2}{R_{max}^2}\right)\ln\epsilon\right]^{1/3}\mathrm{Fr}^{-4/3} \tag{4}$$

From the Equations (3) and (4), we can find the coordinate by adding the Equation (3) to Equation (1) and taking into account the points of closure:

Figure 7. Body V-3, the speed of body entrance to the water is 3.5 m/s

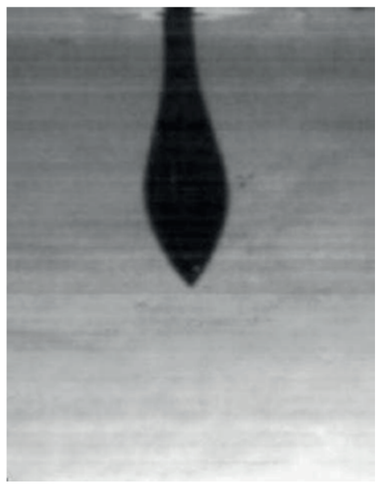

Figure 8. Tile UA-2, the speed of body entrance to the water is 3.5 m/s

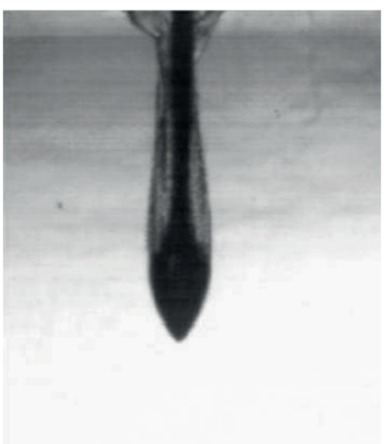

Figure 9. Body V-1, the speed of body entrance to the water is 4.5 m/s

Figure 10. Body V-3, the speed of body entrance to the water is 4.5 m/s

Figure 11. The UA-2, the speed of body entrance to the water is 4.5 m/s

Figure 12. The V-3-U, the speed of body entrance to the water is 4 m/s, 0.08 second after the entrance

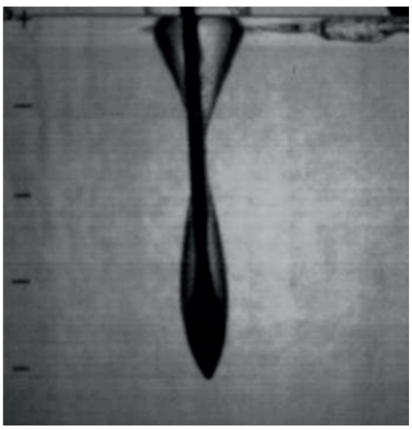

Figure 13. The V-3-U, the speed of body entrance to the water is 4 m/s, 0.1 second after the entrance

$$\frac{x_c}{R_{max}} = \frac{\mathrm{Fr}^{2/3}}{3}\left[-54\left(1-\frac{R_s^2}{R_{max}^2}\right)\ln\epsilon\right]^{1/3} \quad (5)$$

and the Equations (2) and (4) allow to determine the time of deep closure of the cavity:

$$t_c = \frac{R_{max}^{2/3}}{2U^{1/3}g^{1/3}}\left[-54\left(1-\frac{R_s^2}{R_{max}^2}\right)\ln\epsilon\right]^{1/3} \quad (6)$$

From Equation (5), it can be seen that the coordinate of the cavity's momentum increase with increasing immersion velocity. Since the value of this coordinate is an estimate of the length of the body cavity in the depth where the observations were made, it can be argued that the theory agrees with the experimental data on the extension of the caverns with increasing immersion velocity (Figures 6, 7, 9, and 10).
Estimates of the value x_c/R_{max} by the Equation (5) give values in the range from 4.1 to 8.5 with an increase in the rate of immersion from 2 to 6 m/s. The dimensional coordinates of the beginning and end of the holder for bodies V-1 and V-3 are estimated by depreciation of 4.3 and 11.3. Consequently, the theoretical estimates suggest an experimental observation

that the deepening occurred at the state.

Equation (6) indicates that the time of deepening decreases slowly with the growth of the rate of immersion. In particular, by the velocities from 2 to 6 m/s in Equation (6), the time changes from 0.06 to 0.086 second. Experimental data for the time of deep closing are within the range of 0.06 to 0.09 second. Unfortunately, the lack of accuracy of the measurements of this time makes it impossible to make unambiguous conclusions about its decrease in the course of rapid dive.

It is worth noting that for thin bodies of a simple shape (disk or sphere); the time of the deep-seated closure practically does not depend on a constant immersion velocity. This is the result of theoretical calculations (Nesteruk, 1980; Zhuravlev, 1993) and experimental observation (Gilbarg and Anderson, 1948). For the experimental confirmation or negation of a weak velocity dependence (according to Equation (6)), it is necessary to increase the accuracy of the registration of the moment of closure or to increase the speed of the input of models. Furthermore, the Equation (6) is valid only for the steady immersion velocity. Our observations represent that the body motion after immersion was essentially non-stationary (for the smaller ones it is accelerated, for the big ones it is slower).

In order to determine the influence of the body's form and its mass on the critical value of the initiation rate of the immersion, in which the transition from the irreversible to the cavitation mode of rotation takes place, a series of additional experiments with low velocities of water intake for the bodies V-3, V-3-U, and V-3-H. The presence of a ring on the surface of the body V-3 in the zone of its middle (body V-3-U) reduces the critical speed (to a value of about 1.3 m/s), while for the body V-3 and its heavier V- 3-H this value was approximately 2 m/s. For the body UA-2 critical speed was equal to about 4 m/s.

It is worth emphasizing, in particular, that there was no cavitation in the thin body S throughout the range of water entry speeds (up to 6 m/s, see Figure 14). It is worthwhile to estimate the coordinate of the point of a possible deep closure of the cavity for this body under its condition. Assuming that the stall speed of immersion is 6 m/s and the cavity is buried in the region of the die, the evaluation of the value x_c/R_{max} for the body S by the Equation (5) calculated the value of 11.3. The frameless coordinates of the beginning and end of the holder for body S were estimated by the values of 8.6 and 23.1. Consequently, in the very existence of this fact, its deep closure at a rate of 6 m/s immersion could have taken place on the Nazi (as was not the case for all other models). Since the experiments did not reveal the cavities on the body S, this may indicate that the speed of 6 m/s is not sufficient for the caving mode, or this form provides an irrevocable mode of rotation in the entire range of water intake rates. Responses to these important questions can be given by the experiments with higher rates of immersion.

The study of the body of the V-3-U in an aerodynamic tube testifies to an irradiance mode of rotation in the region of 150,000 <ReL<300,000 [5]. Our experiments showed that the ion and cavity in the range of inputs corresponded to the Reynolds numbers in the range of 125,000 <ReL <750,000. Thus, the entrance of the body of V-3-U takes place in the alternate mode, while the stationary flow through the airflow in the same range of Reynolds numbers is invulnerable. Similar dissimilarities can be explained as non-stationary character of the processes of entering to the water, as well as by the influence of the free surface of water. It is also worth noting that the shape of the cavity on the V-3-U significantly differs from the cavities on a very close in the form of V-3 (Figures 7, 10, 12, and 13).

For the evaluation of the resistance of bodies with different forms, the values of the middle acceleration were calculated. The accuracy of this sampling method was rather limited. At the same time, In particular, the value of m (a−g) (here "a" is calculated body resistance) was approximately 5 N at Ue = 4m/s for bodies V-1, V-3, UA-2, V-3-U, and V-3- H and about 2.5 N for thin body S.

If we subtract from these values the average hydrostatic component of the resistance (Archimedes force, which corresponds to half the volume of bodies), then the hydrodynamic resistance can be estimated by 3.6 N for bodies V-1, V-3, V-3-U, V-3-H; 3.1 N for body UA-2, and 2 H for model S. The obtained data allow us to estimate the volumetric coefficients of the resistance of the body, CV (aligned to the full body volume with holders in the degree of 2/3). Simple calculations give the value CV = 0.09 for bodies V-1, V-3, V-3-U, V-3-H; CV = 0.07 for UA-2 body and CV = 0.12 for Model S.

The magnitude of the obtained value is 6-7 times exceeds the values of the volumetric coefficients of the friction resistance of the bodies under a stationary, non-detachable laminar flow, which indicates a significant impact load on the body during their entrance to the water. To determine the forms that reduce these loads, it is necessary to increase the accuracy of the measurements of the current coordinates of the body.

Experiments with different modifications of the body V-3 without a stomach showed a significant instability of its motion. An example of such a body's dynamics is shown in Figure 15. It is remarkable that the use of the extra weights located in the spout of the V-3 model did not stabilize its movement. The problem of stabilization of their motion significantly limits the experimental velocities, since deviations from the vertical trajectory (even for models with grips) can lead to damage the model and its installation.

Conclusions

The body entering to the water with an adverse pressure gradient was investigated along the body surface. The results revealed that the nature of the flow depends on the shape of the body and the speed of entering to the water. In particular, the speed was characterized by lower velocity without meandering and cavitating. The increase in the speed of the input led to the dissipation and super-cavitation. The body shape has a significant effect on the critical velocity, with which the nature of the flow changes. In particular, the thin body was cut around the entire range of speeds (up to 6 m/s). To answer the question about the existence of a super-cavitation mode for a thin body, further experiments with higher input speeds are required. Furthermore, exact calculations of the resistance forces require an increase in the accuracy of measurements of the exact coordinates of the bodies and their stabilization.

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