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GRAVITY WAVES GENERATED BY A BODY FALLING ONTO SHALLOW WATER

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Two aspects of the problem of a body falling onto water are of interest in applied problems: the forces affecting the body itself and the waves generated in the process. Many scientific papers devoted to the study of the forces have appeared in connection with the invention of the hydroplane [1, 2]. Theoretical analysis at that time was performed within the framework of an ideal fluid model ignoring the influence of air. More recently, the necessity for the study of impact loads from waves to a ship or to off-shore structures became another great stimulus. In any problem on impact, the rheological properties of water are of great importance. The properties of air also play a part in momentum and energy transfer. A great number of papers consider these factors. Theoretical analysis of forces is simplified by the fact that some practically valuable information can be derived from analysis of the initial stage of the processes. The contemporary status of this line of investigation is reflected in [3–7].

In the present paper we focus on gravity waves generated by a falling body. The progress in this line of research is stimulated by the necessity of evaluating the consequences produced by falls of meteorites into the ocean or by falls of rock fragments into a fjord, and also by landslides in lakes. Among the numerous publications, we mention [8–10]. An extensive literature is dedicated to tsunami waves. In this regard, paticular attention has been given to the development of effective methods of numerical calculations.

There are difficults, however, in specifying initial conditions for such calculations in which experiment plays an important part. For waves generated by a falling body, the situation is complicated by phenomena such as rupture of the liquid continuity, liquid jet injection into the atmosphere, and wave breaking, which occurs with strong perturbations. Such processes present a serious problem for many theoretical methods of analysis. In this connection, it is pertinent to mention the method in [11], which has been used to predict complicated processes in the neighborhood of the body, which are further illustrated by photographs.

Plane gravity waves generated by a body falling onto water have been studied experimentally in [12, 13]. Similar waves result from displacement of a part of the reservoir bottom. They have been studied, for example, in [14]. Some experimental data on the waves generated by a falling axisymmetric body are contained in [15, 16].

The aim of the present paper is to supplement the available experimental information on plane waves. The experiments were performed in such a way that the effects due to finite liquid depth would be strongly displayed themselves. In this case there is a critical velocity in the system: $c_* = (gh)^{1/2}$ (where g is the acceleration of gravity, h is the liquid depth). Upon attaining the critical velocity, the wave of level elevation can break, and the question arises: what part of the perturbation energy (and in what form) is preserved after the breaking? Along with gravity waves, also the processes in the neighborhood of the body (which were studied earlier, for example, in [17–19]) were registered in the experiments. In particular, information on the relationship between these processes and the gravity waves was obtained.

The formulation of the problem along with the main designations are explained in Fig. 1. A rectangular channel with a horizontal bottom of length $L = 4.3$ m and width $B = 0.2$ m was filled with water to depth h. Initially, the water was at rest. At moment $t = 0$, a solid body began to fall from height H from air onto water. Bodies of two shapes were used: a rectangular parallelepiped with dimensions l, b, and H_1 and a wedge

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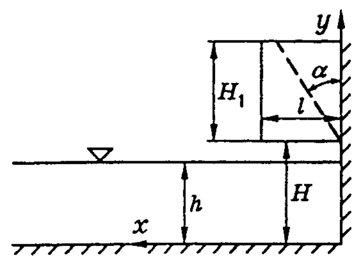

Fig. 1

with parameters α, b, and H_1 (see Fig. 1). The conditions $H_1 > h$ and $b \approx B$ were met. The first condition meant that the upper edge of the body was not submerged in the liquid (this simplified the wave pattern), while the second one meant that the waves were almost plane.

Physical parameters such as gravity acceleration g, liquid density ρ, body density ρ_1, liquid viscosity and compressibility, surface tension, and also the density, viscosity, and compressibility of air, play an important part in the problem discussed. For example, liquid compressibility and surface tension define not only the energy carried away by sonic and capillary waves. The relative portion of this energy was negligible in the experiments. Surface tension and compressibility affect the location of the point at which water separates from the body to carry away a significant part of the energy [20]. Because of liquid viscosity, the objects known as solitary waves in the ideal fluid model cannot be correctly reproduced in experiments. In the model, these waves are stationary. In experiments, they decay because of viscosity.

When comparing theoretical and experimental solitary waves, one may only rely on the following principle of the quasistationary state: if the influence of viscosity is accounted in any parameter of a solitary wave, for example, in its amplitude, then its shape and velocity can be found using the algorithms developed in the ideal fluid model. The validity of this principle was confirmed by the experiments of [21]. The physical properties of air become important when a blunt body approaches a liquid surface at a high speed.

Of all the physical parameters, only density ρ_1 was varied in the experiments and the condition $\rho_1 > \rho$ was met. The other physical parameters can be found in reference books with allowance for the normal laboratory conditions of the experiments. Of the geometric parameters, the values of h, H, H_1, l, and α were varied. Below they are given in dimensionless form:

$$H^0 = H/h, \qquad H_1^0 = H_1/h, \qquad l^0 = l/h, \qquad x^0 = x/h, \qquad \rho^0 = (\rho_1 - \rho)/\rho.$$

The fixed coordinate system shown in Fig. 1 is used.

The law of motion $y_*(t)$ was registered by a rheochord transducer (here y_* is the vertical coordinate of the lower edge of the body). Deviations of the free surface from equilibrium η were registered by wavemeters, whose principle of operation was based on the difference in electrical conductivity between water and air. Paper-tape recorders were used along with a HISTOMAT-S system of data acquisition and processing to record the transducer signal and preliminary processing. Qualitative information was obtained by a photocamera with an exposition time of 1/250 sec. The wave velocity was calculated from signals of two wavemeters spaced $\Delta x < 8h$ apart. All the equipment was tested in processes with characteristics known a priori. For wavemeters, this process was their oscillations in relation to the quiescent liquid, while for a rheochord transducer this was the law of a freely falling body. Using the information thus obtained, along with the results of sample repeated tests under the same conditions, the following estimates for the mean square measurement error were determined: about 2% for the wave amplitude parameters and about 3% for the phase parameters.

The results below were obtained in experiments with bodies falling along one of the side walls of the channel. In addition, proof experiments were carried out in which a parallelepiped of doubled length $2l$ and a wedge with doubled vertex angle 2α fall into the middle of the channel. The wave amplitude charecterictics were found to differ most greatly. In these experiments, this difference did not exceed 7%. In experiments with a body falling into the middle of the channel, the wave amplitudes were larger. This is due to the influence of

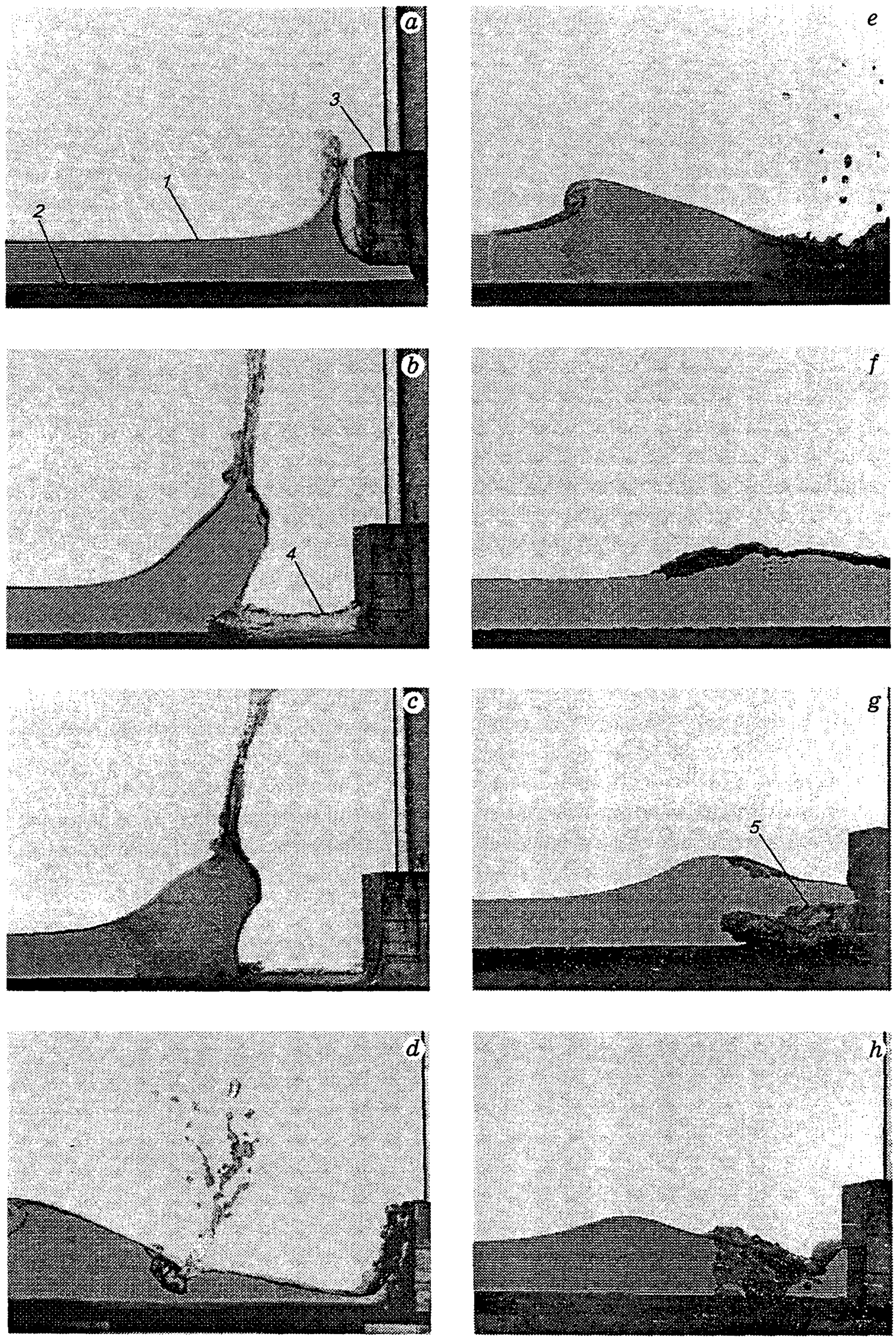

Fig. 2

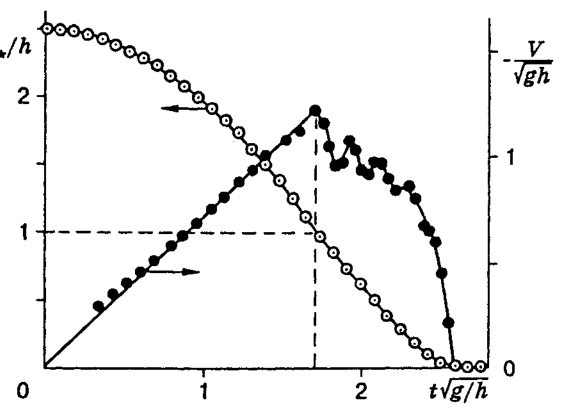

Fig. 3

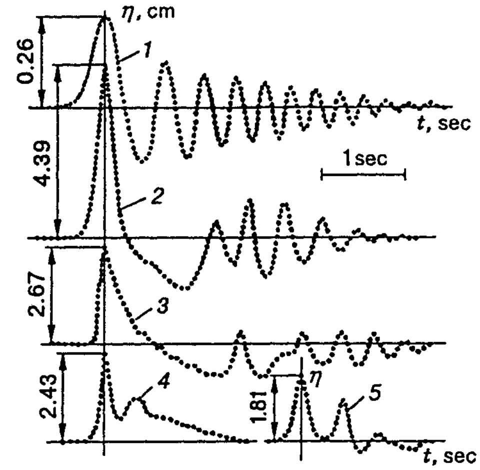

Fig. 4

the gap during the fall along the side wall.

Gravity waves carry away only a portion of the energy that is introduced into the liquid by a body. The stronger the perturbation, the more energy dissipates via complicated processes near the body. These processes are described in detail in the above-mentioned literature. Additional information for the fall of a parallelepiped onto shallow water is given in Fig. 2. Similar photographs were published in [17, 22]. In comparison with them, the photographs in Fig. 2 refer to a longer time interval. Here 1 is the free surface, 2 is the channel bottom, 3 is the parallelepiped, 4 is the horizontal jet, and 5 is the parcel of air. The photographs illustrate the typical perturbation shapes; therefore, the time intervals between individual frames are not equal.

The photographs shown in Fig. 2a–f were taken for $h = 8$ cm, $H^0 = 3.75$, $H_1^0 = 2.26$, $l^0 = 1.15$, and $\rho^0 = 0.215$. The initial stage of development of a cavity and of a spray jet are shown in Fig. 2a. The spray jet is vertical (cf. with [17]). The boundaries of the cavity and of the perturbation's leading edge change monotonically with height. In Fig. 2b, the jet reaches a high altitude; the channel bottom are exposed and the boundaries of the cavity and of the wave leading edge are nonmonotonic. Attention is drawn to the fact that, in addition to the vertical jet, a horizontal jet 4 is ejected from the liquid bulk. The frame in Fig. 2c was taken about 0.1 sec after the frame in Fig. 2b. The velocities within the spray jet decreased. The final stage of cavity collapse and of spray-jet generation are shown in Fig. 2d.

In the example under discussion, intense dissipation of mechanical energy occurs at a considerable distance from the body because of the breaking of the perturbation's leading edge. Three stages of the breaking process of the leading edge are illustrated by the photographs in Fig. 2d–f. The last photograph refers to distance from the body $x = 30h$. Due to lack of energy supply, the breaking process gradually ceases and the waves become smooth. In this example, the leading edge of smooth waves propagated at a velocity that was appreciably higher than the critical velocity and two solitary waves formed at large distances from the body.

The frames in Fig. 2g,h were taken under conditions that differ from the previous conditions only in value $H^0 = 1.0$. In this case, spray jets did not form and the leading edge did not break. The cavity rapidly collapsed and, as a result, a significant parcel of air 5 was captured in the liquid. The pertubation's leading edge in this case also propagated at a supercritical velocity, but only one solitary wave formed away from the body. Under less intense perturbations, a nonstationary dispersing wave train formed which propagates at a subcritical velocity.

The effects illustrated by Fig. 2a–f can be explained qualitatively through an analysis of the nonstationary process of collision of counter jets in a transverse gravitational field [11]. In such a sketchy description, the perturbation introduced by a wedge differs significantly from that introduced by a

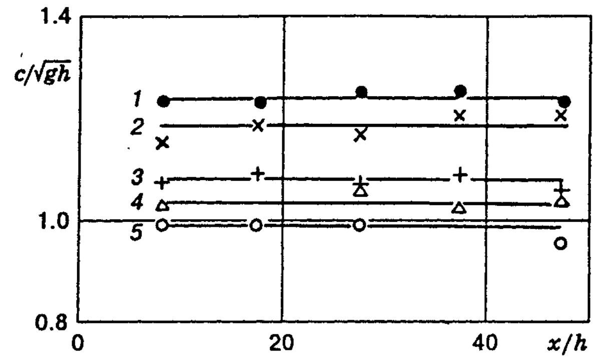

Fig. 5

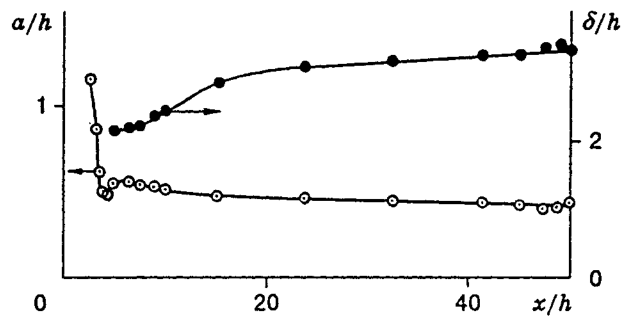

Fig. 6

parallelepiped. In the case of a wedge, the momentum of the moving mass of liquid is directed at an angle to the horizon. As a result, a significant part of the perturbation energy transfers to the spray jets. This explaing why, when a wedge was used, all attempts to obtain waves which would propagate at a supercritical velocity failed.

Figure 3 shows the typical motion of the trajectory $y_*(t)$ and velocity $V(t)$ for a parallelepiped for the following initial parameters: $h = 8$ cm, $H^0 = 2.5$, $H_1^0 = 2.26$, $l^0 = 0.575$, and $\rho^0 = 0.215$. At $t < t_*$ the body moved through air, in good agreement with the law of a freely falling body ignoring friction. At the moment the body touches the water ($t = t_*$), its velocity sharply falls and moderate velocity oscillations are observed. At the instant the body touches the bottom, the velocity decreases practically to zero.

Examples of waves recorded by a fixed wavemeter are shown in Fig. 4. Wave 1 was obtained in experiments with a wedge for $h = 4.5$ cm, $H^0 = 4.3$, $H_1^0 = 4.4$, $\alpha = 26.5°$, and $\rho^0 = 0.4$ and at distance $x^0 = 26$. The propagation velocity c of the first crest is lower than the critical velocity $c = 0.864c_*$. Such waves are typical of relatively weak perturbations. They are nonstationary and disperse with time.

Wave 2 was observed in experiments with a parallelepiped for $h = 8$ cm, $H^0 = 2.9$, $H_1^0 = 2.26$, $l^0 = 0.575$, $\rho^0 = 0.215$, and $x^0 = 16$. There was no breaking of the leading front in this example. The first crest propagated at the supercritical velocity $c = 1.06c_*$. The first crest was followed by a long trough, with an alternating wave train propagating over it with a subcritical velocity. Subsequently, one solitary wave evolves from this perturbation.

Plots 3–5 illustrate the evolution of the same parallelepiped-introduced perturbation for $h = 4$ cm, $H^0 = 4.75$, $H_1^0 = 4.5$, $l^0 = 1.15$, and $\rho^0 = 0.215$. The values of x^0 differ: $x^0 = 31.5$ for plot 3 and $x^0 = 89$ for plot 4. Wave 5 was registered at distance $x^0 = 89$, but after its reflection from the vertical side wall, it was located at distance $x^0 = 108$. In this example the breaking of the perturbation's leading edge occurred at $x^0 < 60$. Nevertheless, some similarity to wave 2 can be traced. A distinguishing feature is the fact that two solitary waves formed in this example after a lapse of time.

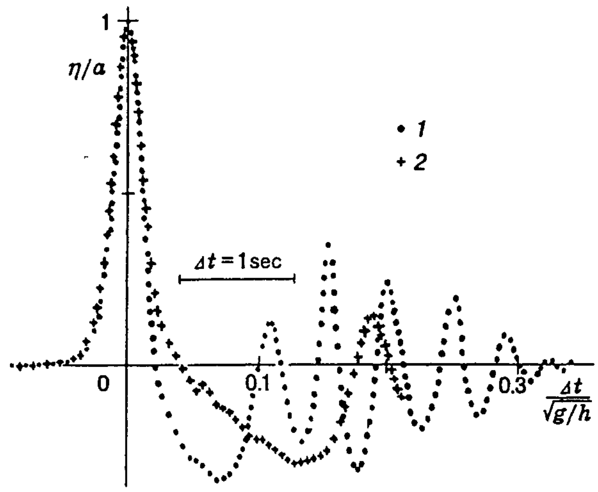

Fig. 7

If the breaking of the first crest has terminated or did not occurr at all, further transformation of the crest proceeds rather slowly. This fact is illustrated by the experimental data shown in Figs. 5–7 and is of great importance for applications since plane waves that are caused by a falling body can have impressive amplitudes and high propagation velocities even at long distances.

Figure 5 shows data on the propagation velocity of the first crest in a series of experiments with a parallelepiped with $h = 8$ cm, $l^0 = 0.575$, $H_1^0 = 2.26$, and $\rho^0 = 0.215$. The parameter H^0 was varied. Curves 1–5 correspond to $H^0 = 3.75$, 2.5, 1.25, 1.0, and 0.63, respectively. It is evident that in the range at hand and within the measurement error, the value $c/(gh)^{1/2}$ does not depend on x^0 for at least $x^0 \geqslant 8.5$.

Figure 6 gives the height of the first crest a and its characteristic width δ as functions of x^0 in experiments with a parallelepiped with $h = 8$ cm, $H^0 = 2.5$, $H_1^0 = 2.26$, $l^0 = 0.58$, and $\rho^0 = 0.215$. The quantity δ is defined as the crest width at a level $y = h + a/2$. Values of a and δ change quickly in this example only at $x^0 < 20$. Their subsequent slower change is partially due to the formation of a solitary wave and also to the influence of viscosity.

The transformation of the first crest under the conditions specified in Fig. 6 is shown in more detail in Fig. 7. Wave 1 was registered at $x^0 = 16$ and wave 2, at $x^0 = 19.8$. One can see that most significant changes take place at the trailing edge. One can also see the rapid lag of the alternating wave train from the leading crest, whose propagation velocity in this example was $1.06c_*$.

A portion of the initial perturbation energy that is carried away by a wave for long distances can be estimated for wave 5 in Fig. 4 from the following considerations. The energy introduced by the body into the liquid is defined by the formula

$$E_0 = \rho_1 l b H_1 (gH - V_0^2/2), \tag{1}$$

where V_0 is the velocity of the body at the moment it reaches the bottom. Using the data of Fig. 3, one can set $V_0 \approx 0$. In the case considered, two solitary waves form at distances well away from the body and contain the greatest portion of the energy that is carried away by waves. According to the theoretical analysis in [23, 24], the energy of one solitary wave can be written as

$$E_s = 8B\rho g(a_s h/3)^{3/2}[1 + 9a_s^0/10 + 21(a_s^0)/40 + (a_s^0)^3/8 + O((a_s^0)^4)]. \tag{2}$$

Here a_s is the solitary wave amplitude; $a_s^0 = a_s/h$. For $a^0 \ll 1$, the Rayleigh formula is obtained [1]. In the literature the following formula is used as well:

$$E_s = 4B\rho g\lambda a^2/3, \tag{3}$$

where λ is the characteristic length of the solitary wave, which can be found by comparing the right sides of (2) and (3).

For the case discussed, calculations using (1) and (2) lead to $[(E_s)_1 + (E_s)_2]/E_0 = 0.024$ (subscripts 1 and 2 correspond to wave number).

This estimation shows, in particular, how difficult it is to describe only theoretically gravity waves, using only information on the body energy if this energy is high enough. Fortunately, this problem has a feature that is important for applications: despite the complexity of the processes near the body, the variety of gravity waves at great distances is not so rich. In predicting catastrohpic consequences, one can hold that finite-amplitude solitary waves constitute the greatest hazard. The theory of finite-amplitude, plane, solitary waves is well developed. According to the Rayleigh theory [1], the ultimate amplitude of a plane solitary wave equals h. One of the latest papers on this problem is [25].

The question of how many solitary waves are formed upon a fall of a body is of importance. In the above-described experiments we could not obtain more than two solitary waves following one another. More solitary waves were observed in experiments with displacement of part of the reservoir bottom [14]. However, when one introduces perturbation in such a way, the energy losses near the body diminish, for example, for lack of spray jets.

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