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THE EFFECT OF PRESSURE CONVECTION AND UNSTEADY FRICTION ON THE STRUCTURE OF A SHOCK PULSE

Unsteady fluid flow refers to those that generate a shock pulse, which is usually called a water hammer. Despite the fact that many works are devoted to this topic, there are still no works that consider such interesting properties of the flow as its self-similarity at the initial moments of time when the shock pulse is formed - taking into account the physical phenomena indicated in the title of the work. This is especially important for the correct physical description phenomena using modern 3-D modeling and calculation tools, since the nonlinearity of the system can become a source of significant deviations of the numerical solution from the exact one. In this work, attention is paid to the influence of unsteady friction of the fluid against the pipe wall (Bruno-Vitkovsky model) and convection of the pressure disturbance field, as well as their combined action. Among the main results of the work, the following should be noted: neither the influence of convection nor the influence of unsteady friction can be neglected; each of the just mentioned physical mechanisms and both together lead to a significant spatial expansion of the region of disturbances from the shock pulse. Another result is that the dimensionless distributions of the shock pulse propagation velocity field and pressure disturbances asymptotically coincide with each other, and without taking into account the convection of the pressure field, these (dimensionless) solutions are equal everywhere.

Keywords: *unsteady flow, water hammer, self-similar solutions, pressure convection, unsteady friction of the fluid against the pipe*

Introduction. In the paper [1], the use of the approach initiated by Riemann [2] was continued. Riemann guessed right that to describe unsteady flows and shock pulse by means of transition from physical coordinates to their combination in the form

$$\eta = z - at\,. \tag{1}$$

In equation (1), z, a, t stand for coordinate, sound speed in fluid and time respectively. If the classical water hammer system is considered only with steady friction (Weisbach-Darcy) [3,4] then system

$$-\frac{\partial p}{\partial z} = \rho_0\left(\frac{\partial V}{\partial t} + \frac{\lambda}{8\,\mathrm{Re}}V^2\right), \tag{2}$$

$$-\frac{\partial p}{\partial t} = a^2 \rho_0 \frac{\partial V}{\partial z} \tag{3}$$

transforms into a dimensionless (bar above) system of two self-similar equations [1]

$$-\frac{d\bar{p}}{d\eta} = -\frac{d\bar{V}}{d\eta} + \theta \bar{V}^2\,, \tag{4}$$

$$\frac{d\overline{p}}{d\eta}=\frac{d\overline{V}}{d\eta}, \tag{5}$$

then the solution to (4)--(5) is only trivial

$$\overline{V}\left(\overline{\eta}\right)=0. \tag{6}$$

In equation (4) θ is non-dimensional parameter that is relation of velocity convection to inertia [1], p and V correspond to pressure disturbances and fluid velocity. The addition of velocity convection to (2)--(3) results into transformation (4)-(5) to

$$-\frac{d\overline{p}}{d\eta}=-\frac{d\overline{V}}{d\eta}+\overline{V}\frac{d\overline{V}}{d\eta}\theta\overline{V}^{2}, \tag{7}$$

$$\frac{d\overline{p}}{d\eta}=\frac{d\overline{V}}{d\eta}, \tag{8}$$

The system (7)-(8) has a non-trivial solution in the form

$$\overline{V}\left(\overline{\eta}\right)=C_1\exp\left(-\theta\overline{\eta}\right). \tag{9}$$

If we fix the observation position (i.e., a point in space) in the self-similar variable, then we have an exponential solution in time, which is consistent with the work [5]. Therefore, the velocity and pressure fields during the origin and propagation of the shock pulse are compact in space and can be described by self-similar solutions.

Problem state. The consideration of unsteady friction within the framework of a one-dimensional (hydraulic) shock pulse model is considered in works [6-11]. In work [6], the problem of hydraulic shock is solved by the method of characteristics and it is shown that the frequency-dependent friction of the liquid against the wall causes the distortion of the traveling waves. The results presented in [6] for positions at a distance from the stopcock clearly indicate an exponential decay and, moreover, they agree well with the experiment [7].

In [9], a model of unsteady friction with local balance is proposed and a comparison is made with the results obtained using $k-\varepsilon$ the turbulence model. The importance of taking into account the convection of the velocity field is indicated in [11]. It is also indicated there that it is unacceptable to neglect unsteady friction.

The convection of the pressure field is taken into account in works [5,6,8]. However, self-similar solutions were found without taking into account the convection of the pressure field [12], or without taking into account the unsteady friction [12--13]. Therefore, the drawback associated with the self-similar description of the origin and initial propagation of the shock pulse, taking into account the unsteady friction of the fluid against the pipe wall and the convection of the pressure field, is a new, still unsolved problem.

Problem formulation. Extend the unsteady fluid flow model by adding unsteady Bruno-Vitkovsky friction and pressure field convection.

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\lambda}{8\mathrm{Re}}V\left|V\right|+kD\left[\frac{\partial V}{\partial t}+C_f\, sign(V)\left|\frac{\partial V}{\partial z}\right|\right]=0, \tag{10}$$

$$\frac{\partial p}{\partial t}+V\frac{\partial p}{\partial z}+a^2\rho_0\frac{\partial V}{\partial z}=0. \tag{11}$$

In (10)-(11) D is inner pipe diameter, k is Vardy coefficient and other ones notations from [9].

The purpose of the work. Obtain self-similar solutions to the problem of hydraulic shock in a homogeneous fluid taking into account unsteady Bruno-Vitkovsky friction and pressure convection, and also find the relationship between the pressure field and the speed of propagation of the shock pulse.

Self-similar solution of the problem of water hammer in a homogeneous fluid taking into account unsteady friction. The unsteady flow of a homogeneous droplet liquid is described by a system of equations [8]

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\lambda}{8\mathrm{Re}}V\left|V\right|+kD\left[\frac{\partial V}{\partial t}+C_f\, sign(V)\left|\frac{\partial V}{\partial z}\right|\right]=0, \tag{12}$$

$$\frac{\partial p}{\partial t}+a^2\rho_0\frac{\partial V}{\partial z}=0. \tag{13}$$

In dimensionless variables system (12)-(13) is

$$\frac{\partial \bar V}{\partial \bar t}+\bar V\frac{\partial \bar V}{\partial \bar z}+\frac{\partial \bar p}{\partial \bar z}+DW\bar V\left|\bar V\right|+Br\left[\frac{\partial \bar V}{\partial \bar t}+sign(\bar V)\left|\frac{\partial \bar V}{\partial \bar z}\right|\right]=0, \tag{14}$$

$$\frac{\partial \bar p}{\partial \bar t}+\frac{\partial \bar V}{\partial \bar z}=0. \tag{15}$$

In equation (14), two non-dimensional parameters are:

$$DW=\frac{\lambda L}{4R},\quad Br=\frac{kD}{L},$$

named after Darcy-Weisbach and Brouno respectively [14].

To solve system (14)-(15), we use the self-similar variable and write

$$-\frac{d\bar V}{d\bar\eta}+\bar V\frac{d\bar V}{d\bar\eta}+\frac{d\bar p}{d\bar\eta}+DW\bar V\left|\bar V\right|+Br\left[-\frac{d\bar V}{d\bar\eta}+sign(\bar V)\left|\frac{d\bar V}{d\bar\eta}\right|\right]=0, \tag{16}$$

$$\frac{d\bar V}{d\bar\eta}-\frac{d\bar p}{d\bar\eta}=0. \tag{17}$$

Adding the equations to each other, we obtain an equation for only one quantity – the dimensionless function of the shock pulse propagation velocity

$$\bar{V}\frac{d\bar{V}}{d\bar{\eta}}+DW\bar{V}\left|\bar{V}\right|+Br\left[-\frac{d\bar{V}}{d\bar{\eta}}+sign\left(\bar{V}\right)\left|\frac{d\bar{V}}{d\bar{\eta}}\right|\right]=0\,. \qquad (18)$$

For the propagation of the shock pulse in the positive direction, we have

$$\bar{V}>0, \quad sign\left(\bar{V}\right)>0, \quad \frac{d\bar{V}}{d\bar{\eta}}<0.$$

So, equation (18) simplifies to

$$\frac{d\bar{V}}{d\bar{\eta}}=-\frac{DW\bar{V}^2}{\bar{V}-2Br}\,. \qquad (19)$$

Equation (19) has an analytical solution in the form and

$$\bar{V}\left(\bar{\eta}\right)=e^{-DW\left(\bar{\eta}+C_1\right)+LambertW\left(-2Bre^{DW\left(\bar{\eta}+C_1\right)}\right)}. \qquad (20)$$

One can also find the inverse function by solving the following equation

$$\frac{d\bar{\eta}}{d\bar{V}}=-\frac{\bar{V}-2Br}{DW\bar{V}^2}\,. \qquad (21)$$

Equation (21) has the following solution

$$\bar{\eta}\left(\bar{V}\right)=\frac{1}{\mathrm{DW}}\left[\frac{2Br}{\bar{V}}-\ln\left|\bar{V}\right|\right]+\mathrm{C}_1\,. \qquad (22)$$

Pressure and velocity distributions according to solution (22) presented at fig. 1. One can see some stretching of the distributions. As it will be clear further this result of convection effect on pulse evolution (see also [1]).

For the inverse shock pulse one has:

$$\bar{V}<0, \quad sign\left(\bar{V}\right)<0, \quad \frac{d\bar{V}}{d\bar{\eta}}<0.$$

In this case, equation (18) is much simplified and takes the form:

$$\frac{d\bar{V}}{d\bar{\eta}}=DW\bar{V}\,. \qquad (23)$$

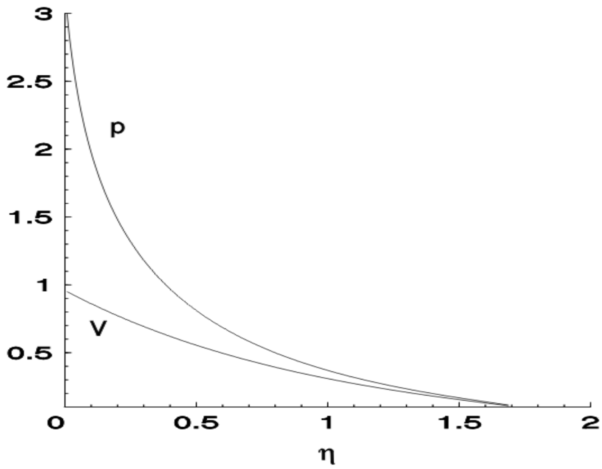

Fig. 1. Dependence of pressure perturbations and shock pulse propagation velocity on the self-similar variable in the presence of Bruno friction (Br =0.03). See (22). $C_1 = 0.02$. $DW = 1$.

Equation (23) has an analytical solution

$$\bar{V}(\bar{\eta}) = C_1 \exp(DW\bar{\eta}). \tag{24}$$

As one can see, (24) coincides with (9) – up to the notation. The only difference is that the self-similar variable has negative values, which ensures the decay of the velocity value and its compact distribution in space. It is also important that in self-similar variables the pressure function has the same distribution as the velocity function. Therefore, the pressure perturbations in the inverse shock pulse also decay and are compact.

Self-similar solution of the problem of water hammer in a homogeneous fluid taking into account the convection of the pressure field. As already mentioned in the introduction, there are works where pressure convection is not neglected [5,6,8]. So, we will obtain self-similar solutions to this problem. The flow is described by the following system of equations

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial z} + \frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\lambda}{8\,\mathrm{Re}} V|V| = 0, \tag{25}$$

$$\frac{\partial p}{\partial t} + V\frac{\partial p}{\partial z} + a^2 \rho_0 \frac{\partial V}{\partial z} = 0. \tag{26}$$

The dimensionless analogue of (25)-(26) is

$$\frac{\partial \bar{V}}{\partial \bar{t}} + \bar{V}\frac{\partial \bar{V}}{\partial \bar{z}} + \frac{\partial \bar{p}}{\partial \bar{z}} + DW\bar{V}|\bar{V}| = 0, \tag{27}$$

$$\frac{\partial \bar{p}}{\partial \bar{t}} + \bar{V}\frac{\partial \bar{p}}{\partial \bar{z}} + \frac{\partial \bar{V}}{\partial \bar{z}} = 0 . \quad (28)$$

Transitioning to a self-similar variable makes it possible to obtain the following system of self-similar equations

$$-\frac{d\bar{V}}{d\bar{\eta}} + \bar{V}\frac{d\bar{V}}{d\bar{\eta}} + \frac{d\bar{p}}{d\bar{\eta}} + DW\bar{V}\left|\bar{V}\right| = 0 , \quad (29)$$

$$\frac{d\bar{V}}{d\bar{\eta}} - \frac{d\bar{p}}{d\bar{\eta}} + \bar{V}\frac{d\bar{p}}{d\bar{\eta}} = 0 . \quad (30)$$

From (29)-(30), by adding equations, we have

$$\left(\frac{d\bar{V}}{d\bar{\eta}} + \frac{d\bar{p}}{d\bar{\eta}}\right) = -DW\left|\bar{V}\right| . \quad (31)$$

Let us now substitute the expression for the pressure gradient from (31) into (29). We have

$$\frac{d\bar{V}}{d\bar{\eta}} = \frac{DW\left(1-\bar{V}\right)\left|\bar{V}\right|}{\bar{V}-2} . \quad (32)$$

For positive values of velocity (32) becomes

$$\frac{d\bar{V}}{d\bar{\eta}} = -DW\left(\bar{V} + 1 + \frac{2}{\bar{V}-2}\right) \quad (33)$$

and for negative values of velocity (32) becomes

$$\frac{d\bar{V}}{d\bar{\eta}} = DW\left(\bar{V} + 1 + \frac{2}{\bar{V}-2}\right) . \quad (34)$$

Their solutions are respectively:

$$\bar{\eta}\left(\bar{V}\right) = \pm\frac{1}{DW}\left[\ln\left|\bar{V}-1\right| - 2\ln\left|\bar{V}\right|\right] + C_1 . \quad (35)$$

In this case, the "+" sign in expression (35) corresponds to the positive direction of the shock pulse propagation, and the "–" sign corresponds to the negative direction. Solution (35) was intentionally obtained in the inverse form – the dependence of the self-similar variable on the velocity, since equation (35) is nonlinear with respect to the velocity and linear with respect to the self-similar variable. Knowing the velocity field, one can easily find the pressure field. Indeed, from equation (30) we have:

$$\left(1-\bar{V}\right)\frac{d\bar{p}}{d\bar{\eta}} = \frac{d\bar{V}}{d\bar{\eta}} ,$$

or

$$\frac{d\bar{p}}{d\bar{V}} = \frac{1}{1-\bar{V}} \, . \tag{36}$$

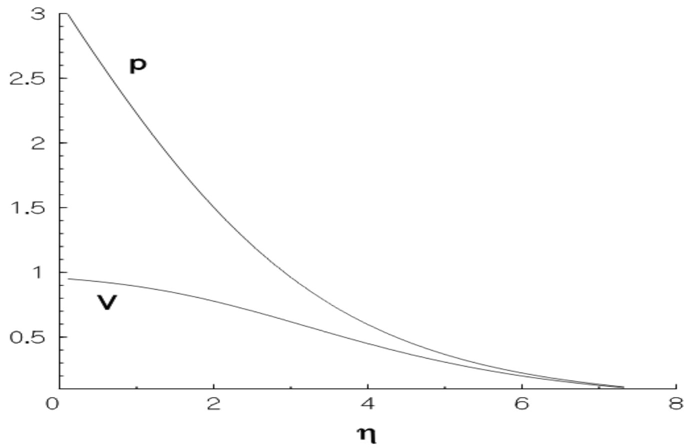

Fig. 2. Velocity and pressure values from the self-similar variable according to solution (35). $C_1 = 3$. $DW = 1$.

It should be noted that the relationship between the pressure perturbation and the velocity of shock pulse propagation, if unsteady friction is not taken into account, does not depend on the direction of shock pulse propagation. The general solution of (36) is:

$$\bar{p} = \text{Const} \cdot \ln\left|1-\bar{V}\right| \, . \tag{37}$$

If we compare this solution with the solution (26) [13], it becomes clear the importance of taking into account the convection of the pressure field, since the corresponding functions are entirely different. Therefore, if we use not only the convection of the velocity but also the pressure in the model, then the relationship between the pressure and velocity fields is already nonlinear. From equation (37) we obtain the dependence of the velocity on the pressure:

$$\bar{V}\left(\bar{\eta}\right) = 1 + \exp\left(\bar{p}/\text{Const}\right). \tag{38}$$

After substitution (38) into (35), we obtain the dependence of the self-similar coordinate on the pressure, and vice versa (see Fig. 4).

Combined effect of unsteady friction and pressure convection on shock pulse propagation in a homogeneous fluid. Now let us consider a more general case -- the combined effect of unsteady friction and pressure convection on the process of shock pulse propagation. The dimensionless analogue of system (1)-(2) is

$$\frac{\partial\bar{V}}{\partial\bar{t}} + \bar{V}\frac{\partial\bar{V}}{\partial\bar{z}} + \frac{\partial\bar{p}}{\partial\bar{z}} + DW\bar{V}\left|\bar{V}\right| + Br\left[\frac{\partial\bar{V}}{\partial\bar{t}} + C_f \, sign\left(\bar{V}\right)\left|\frac{\partial\bar{V}}{\partial\bar{z}}\right|\right] = 0 \, , \tag{39}$$

$$\frac{\partial\bar{p}}{\partial\bar{t}} + \bar{V}\frac{\partial\bar{p}}{\partial\bar{z}} + \frac{\partial\bar{V}}{\partial\bar{z}} = 0. \qquad (40)$$

Therefore, in self-similar variables we have the following system:

$$-\frac{d\bar{V}}{d\bar{\eta}} + \bar{V}\frac{d\bar{V}}{d\bar{\eta}} + \frac{d\bar{p}}{d\bar{\eta}} + DW\bar{V}\left|\bar{V}\right| + Br\left[-\frac{d\bar{V}}{d\bar{\eta}} + sign\left(\bar{V}\right)\left|\frac{d\bar{V}}{d\bar{\eta}}\right|\right] = 0, \qquad (41)$$

$$\frac{d\bar{V}}{d\bar{\eta}} - \frac{d\bar{p}}{d\bar{\eta}} + \bar{V}\frac{d\bar{p}}{d\bar{\eta}} = 0. \qquad (42)$$

It should be noted that for the reversed pulse we have the absence of the influence of unsteady friction (see solution (35)). For a direct shock pulse, we have

$$-\frac{d\bar{V}}{d\bar{\eta}} + \bar{V}\frac{d\bar{V}}{d\bar{\eta}} + \frac{d\bar{p}}{d\bar{\eta}} + DW\bar{V}^2 - 2Br\frac{d\bar{V}}{d\bar{\eta}} = 0. \qquad (43)$$

So, adding (43) and (42), we obtain

$$\bar{V}\left(\frac{d\bar{V}}{d\bar{\eta}} + \frac{d\bar{p}}{d\bar{\eta}}\right) = -DW\bar{V}^2 + 2Br\frac{d\bar{V}}{d\bar{\eta}}. \qquad (44)$$

Equation (44), together with equation

$$\frac{d\bar{p}}{d\bar{\eta}} = \frac{1}{\left(1-\bar{V}\right)}\frac{d\bar{V}}{d\bar{\eta}}$$

makes it possible to obtain a single equation for determining the velocity field:

,

$$\left(\bar{V} + \frac{1}{1-\bar{V}} - 2Br\right)\frac{d\bar{V}}{d\bar{\eta}} = -DW\bar{V}^2 \qquad (45)$$

The solution of equation (45) has a very complicated form. Therefore, it is reasonable to solve it with respect to the self-similar coordinate as a function of velocity:

$$\frac{d\bar{\eta}}{d\bar{V}} = \frac{\bar{V} + \frac{1}{1-\bar{V}} - 2Br}{-DW\bar{V}^2}. \qquad (46)$$

Now, equation (46) has a rather simple analytical solution:

$$\bar{\eta}\left(\bar{V}\right) = \frac{1}{DW}\left[\ln\left|\bar{V}-1\right| - 2\ln\left|\bar{V}\right| - \frac{1}{\bar{V}}\left(2Br-1\right)\right] + C_1. \qquad (47)$$

The shock pulse propagation velocity field (solution (47)) and the pressure field (according to (37)) are presented in Fig. 3.

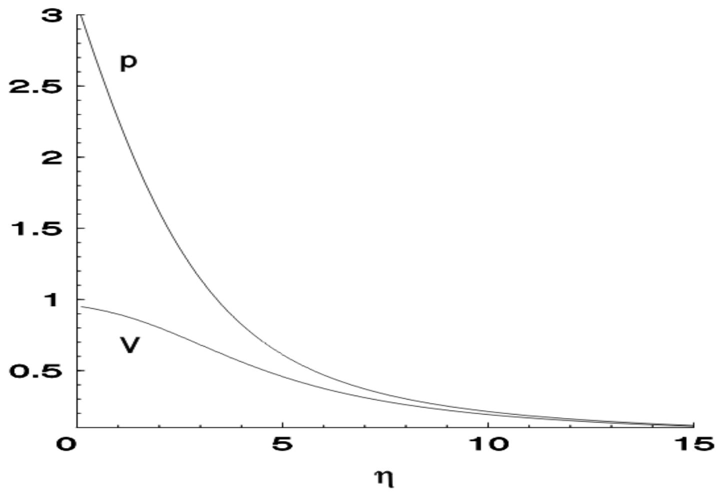

Fig. 3. Velocity and pressure fields according to (47). (Br =0.03). $C_1 = 2$. $DW = 1$.

The curves shown in fig. 4 and fig.5 allow us to draw conclusions that the combined effect of unsteady friction and pressure convection on the propagation of the shock pulse in the positive direction stretches the shock pulse region.

Conclusions. The work takes into account two factors that affect the propagation of the shock pulse: unsteady friction and convection of the pressure field. The novelty lies in the description of the phenomenon by obtaining self-similar equations and their solutions. The self-similar solution describing the inverse shock pulse has the same form as in the model without unsteady friction, and with it. Taking into account the convection of the pressure field made it possible to see how the velocity field depends in this case on the pressure disturbance field, and vice versa. Such dependencies are entirely new. As for the form of the pressure disturbance field as a function of the self-similar variable, this form fully corresponds to classical works [15].

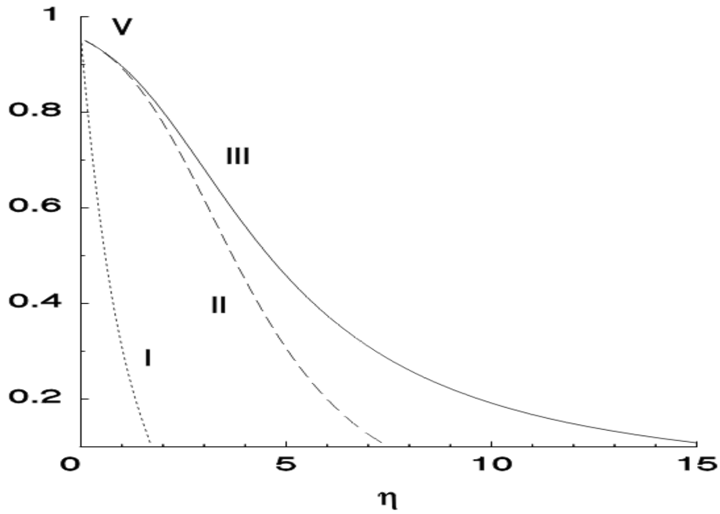

Fig. 4. Distributions of the velocity field according to different models: I—taking into account only unsteady (and steady) friction; II—taking into account only the convection of the pressure disturbance field; III—the joint effect of unsteady friction and convection of the pressure field.

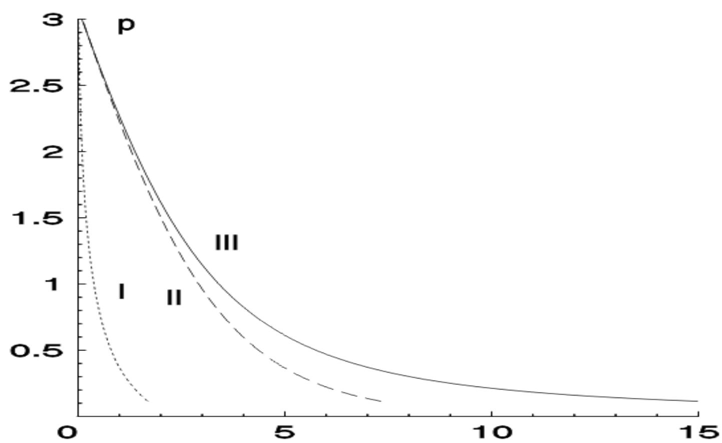

Fig. 5. Distributions of pressure field perturbations according to different models: I—taking into account only non-stationary (and stationary) friction; II—taking into account only convection of the pressure field perturbations; III—joint influence of non-stationary friction and convection of the pressure field.

As future research, the obtained solutions can be used for computer simulation of the propagation and reflection of the formed shock pulse.

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П.В. ЛУК'ЯНОВ

ВПЛИВ КОНВЕКЦІЇ ТИСКУ ТА НЕСТАЦІОНАРНОГО ТЕРТЯ НА СТРУКТУРУ УДАРНОГО ІМПУЛЬСУ

Нестаціонарна течія рідини відноситься до таких, що генерує ударний імпульс, який прийнято називати ударною хвилею. Не зважаючи на те, що цьому питанню присвячено багато робіт, все ж таки відсутні роботи, де були б розглянуті такі цікаві властивості течії, як її автомодельність у початкові моменти часу, коли відбувається формування ударного імпульсу – із урахуванням зазначених у назві роботи фізичних явищ. Це особливо важливо для коректного фізичного опису явища за допомогою сучасних засобів 3-Д моделювання та розрахунку, оскільки нелінійність системи може стати джерелом суттєвих відхилень чисельного розв'язку від точного. В даній роботі увагу приділено впливу нестаціонарного тертя рідини о стінку труби (модель Бруно-Вітковського) та конвекції поля збурень тиску, а також їх сумісної дії. Серед основних результатів роботи слід зазначити такі: ані впливом конвекції ані впливом нестаціонарного тертя нехтувати неможна; кожний із щойно зазначених фізичних механізмів та обидва разом призводять до суттєвого просторового розширення області збурень від ударного імпульсу. Ще одним результатом є те, що безрозмірні розподіли поля швидкості поширення ударного імпульсу та збурень тиску асимптотично збігаються один до одного, а без урахування конвекції поля тиску ці (безрозмірні) розв'язки рівні скрізь.

Ключові слова : нестаціонарна течія, гідравлічний удар, автомодельні розв'язки, конвекція тиску, нестаціонарне тертя рідини о трубу

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