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# Analysis of the mechanism dissipation of mechanical energy flow in adiabatic throttling incompressible liquid

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**Abstract.** The differences arising in the analysis of the throttling process in different reference systems are considered. It is shown that it is convenient to analyze the change in internal energy when throttling a certain volume of gas in a system of counting that is rigidly connected to its center of mass. In this system, gas expansion works, resulting in energy being diverted to the environment. At the same time, energy is transferred from the environment to the gas by the movement of the throttle device. The sign of the increment of the internal energy of the considered volume of ideal gas in the non-equilibrium process adiabatic throttling is determined by the ratio between the two named energy exchange processes. From the first law of thermodynamics, an expression is obtained for the value of the increment of specific internal energy when throttling an ideal gas.

## 1. Introduction

The progress of forestry engineering is inseparable from the successes of general engineering. The development of the engineering industry and the improvement of technology directly depend on the depth and accuracy of the physical description of the processes implemented in various devices. The process of adiabatic throttling of an incompressible fluid is often implemented in various machines. A more accurate description of energy exchange during throttling can improve the efficiency of the equipment where this process occurs.

When an incompressible liquid flows through a channel with a barrier, the thermodynamic characteristics of the flow change. This is due to a change in the flow pattern caused by the barrier. In particular, the trajectories of elementary liquid particles that make up the flow become curved in the area of the barrier. In general, the throttling process is irreversible.

The relevance of practical application and research related to the throttling process is reflected in a number of works [1-8].

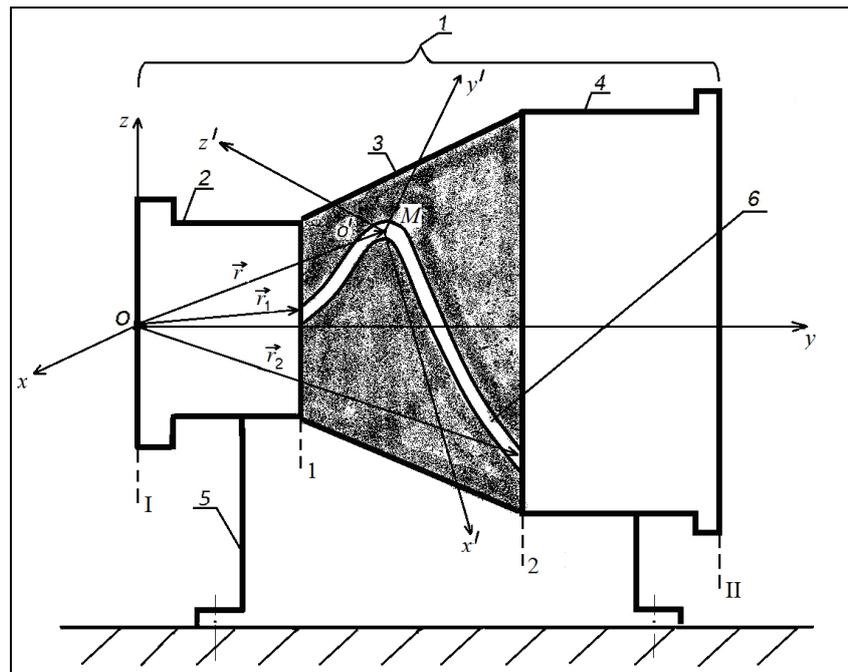
## 2. Methods and Materials

The aim of this work is to examine in detail the process of energy exchange, in which there is an irreversible dissipation of mechanical energy in the flow of an incompressible liquid. To reveal the mechanical nature of irreversibility, consider the diagram in figure 1. Figure 1 shows a diagram of the throttle device 1. It consists of an inlet section with an inlet pipe 2, a flow part 3, an outlet section with an outlet pipe 4, and a support frame 5 rigidly fixed to a fixed surface. This surface is non-mobile in the laboratory coordinate system  $S$  with the coordinate axes  $x, y, z$  and the beginning of the counting at



the point  $O$ . In general, the flow part 3 has a variable cross-section and is made in the form of a washer with through channels 6, which have a complex spatial configuration (figure 1 shows only one of the channels for clarity).

In the throttle device 1, the liquid flow enters through the section of the inlet pipe 2. After the inlet section, the liquid enters the channels 6 of the flow part 3. Inside the channels 6, the elementary liquid particles that make up the flow move along complex curved trajectories. From the channels 6, the liquid enters the outlet pipe 4, through the outlet section of which it exits the throttle device 1.



**Figure 1.** Diagram of throttle device: where 1 – throttle device; 2 – inlet pipe; 3 – flow part; 4 – outlet pipe; 5 – support frame; 6 – channel.

For clarity, we will consider the process of adiabatic throttling.

Strictly speaking, the trajectories of elementary liquid particles are curved not only in the flow part itself, but also in some areas of the flow that are directly adjacent to it. For clarity, we will assume that the width of the flow section in figure 1 includes these areas. In other words, we assume that significant changes in the parameters of the liquid occur only inside the flow part.

Let's denote the sections of the input and output pipes as I and II, and the sections at the entrance to the flow part and exit from it as 1 and 2, respectively. From the above, it follows that the parameters of the liquid flow do not change in parts I-I and 2-II of the throttle device model shown in figure 1.

Let's isolate an elementary liquid particle in the flow and trace its movement in the flow part. The point  $M$  in figure 1 indicates the location of the center of mass of the selected part in the passage channel. This point  $M$  in figure 1 coincides with the point  $O'$ , which is the reference point of the coordinate system  $S'$  with the axes  $x'$ ,  $y'$ ,  $z'$ , which is rigidly connected to the center of mass of the considered elementary particle of the liquid. In the coordinate system  $S'$ , the liquid particle, as a whole, is at rest. It is in this coordinate system that the internal energy of an elementary hot particle is determined. The position of the selected elementary liquid particle in the flow is characterized by a radius vector  $\vec{r}$  drawn from point  $O$  to point  $M$ . The position it occupied at the entrance to the flow part characterizes the radius vector  $\vec{r}_1$  that will occupy the radius vector  $\vec{r}_2$  at the exit.

Consider an elementary liquid particle isolated in the flow as a thermodynamic system. Its thermodynamic state is characterized by thermodynamic state parameters: absolute temperature  $T$ ,  $K^\circ$ ,

and absolute pressure  $p$ , Pa. Strictly speaking, the values  $p$  and  $T$  can only be measured in a coordinate system that moves together with an elementary liquid particle, that is, in one in which the liquid particle, as a whole, rests, that is, in the coordinate system  $S'$ . Let's consider the thermodynamic process that occurs with the selected particle in the section of its trajectory from the entrance to the flow part (section 1) to the exit from it (section 2). Since the liquid is incompressible this process will occur without performing the work of expansion or compression. For clarity, we assume that this process corresponds to the average change in the internal energy of the flow in the flow part. The first law of thermodynamics for such a process is written as:

$$u_2 \cdot dm - u_1 \cdot dm = q_{fr} \cdot dm,$$

or, after dividing by  $dm$ :

$$u_2 - u_1 = q_{fr}, \quad (1)$$

where,  $dm$  is the mass allocated to elementary particles of the fluid, kg;  $u_1$  and  $u_2$  are the average for sections 1 and 2 the values of specific internal energy of the fluid, respectively, J/kg;  $q_{fr}$  – specific heat of friction released by the motion of the fluid in the flow path of the throttle device due to the irreversible transition of mechanical energy of the flow into internal energy, J/kg.

Next, as a thermodynamic system, consider the flow part of the throttle device (figure 1) from the input section (section 1) to the output section (section 2). When the throttle device operates in a static mode, the internal energy of the flow part will remain constant. The first law of thermodynamics in this case can be formed as follows: the total specific energy introduced by the liquid flow through section 1 will be equal to the total specific energy taken out by the liquid flow through section 2:

$$u_1 + K_1 + P_1 = u_2 + K_2 + P_2, \quad (2)$$

where,  $K_1$  and  $K_2$ ,  $P_1$  and  $P_2$  are the average values of the specific kinetic and potential energies of the liquid in sections 1 and 2, respectively, J/kg.

Converting (2) to the form:

$$(u_2 - u_1) + (K_2 - K_1) + (P_2 - P_1) = 0. \quad (3)$$

Equality (3) means that when throttling, the total energy that the input stream has is redistributed between three components: internal, kinetic, and potential energy. Moreover, changes in the components in (3) occur so that the sum of these changes is zero. Exactly how the components change is determined by the flow pattern in the flow part of specific throttle devices.

From (3), taking into account (1), we get:

$$(P_1 - P_2) = q_{fr} + \frac{\bar{c}_2^2 - \bar{c}_1^2}{2}. \quad (4)$$

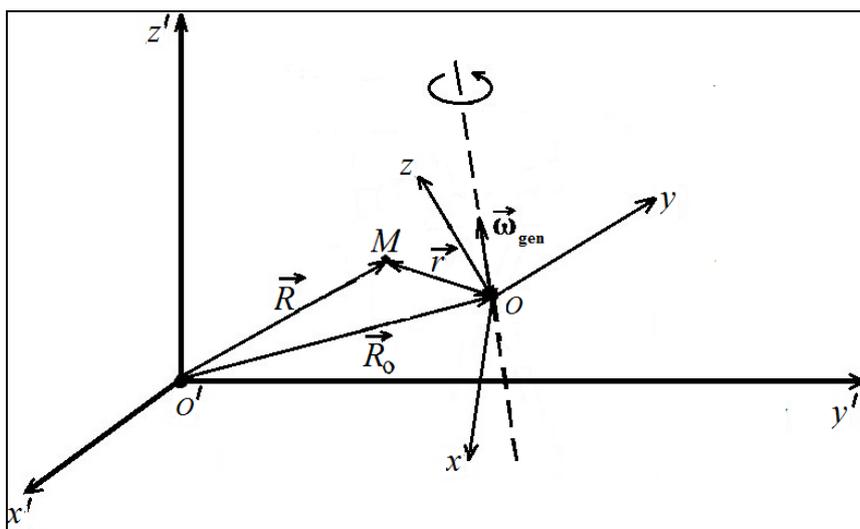
where,  $\bar{c}_1$  and  $\bar{c}_2$  are the fluid velocities averaged over sections 1 and 2 observed in the laboratory coordinate system  $S$ , m/s.

The difference  $(P_1 - P_2)$  is a decrease in the specific potential energy of the liquid when passing the flow part of the throttle device. For clarity, we assume that sections 1 and 2 are at the same height, that is, there are no changes in the potential energy in the field of gravity. In the flow part of the throttle device, the trajectories of elementary liquid particles that make up the flow are curved. With a curved trajectory, any body is known to have acceleration. In the case of elementary liquid particles moving inside a stream with a steady flow, these accelerations form a stationary vector field of the density distribution of mass forces acting inside this stream. The decrease in the potential energy of an elementary liquid particle in the section from section 1 to section 2 is equal to the work performed by the resulting force acting on it on the path of its movement from section 1 to section 2. Thus, the

difference  $(P_1 - P_2)$  is determined by the specific work of this force. We can say that performing this work is necessary for the movement of liquid particles along their trajectories (for pushing them through the flow part).

As you know, in mechanics, two types of problems are solved: by known forces acting on an object, its movement is found, or by known movement, forces are found. In the latter case, it is possible to determine the forces acting on the elementary liquid particle from general ideas about the nature of movement in the flow part of the throttle device. To do this, we consider the general case of arbitrary relative motion of the coordinate systems  $S$  and  $S'$  in figure 1. In fluid mechanics, it is known [9], a basic aqueous liquid volume can be considered as a sum of two movements: quasi-solid, consisting of translational, together with a selected pole (in this case, the pole is the point  $M$ ) and rotation around this pole and deformation. This means that in figure 1, the coordinate system  $S'$  generally rotates around an instantaneous axis passing through the origin  $O'$ . Accordingly, if while in the system  $S'$  we observe the movement of the system  $S$ , the latter in its relative motion will also rotate around its instantaneous axis passing through the origin  $O$ , with a certain angular velocity  $\vec{\omega}$ , rad/s. In this case, the value  $\vec{\omega}$  will generally change in both modulus and direction. Due to the relativity of all motion, one of the coordinate systems  $S$  and  $S'$  can be selected as the base – fixed. Let us choose as a stationary system  $S'$ , in which the motion of an elementary liquid particle is known, since in this system the coordinate of the particle as a whole is at rest: its speed and acceleration in this system are equal to zero.

Motion in the base-fixed coordinate system  $S'$  of some material point  $M$  is defined as absolute motion. Consider the general case of arbitrary motion of any two coordinate systems  $S_{gen}$  and  $S'_{gen}$  relative to each other, shown in figure 2. We assume that one of them  $S'_{gen}$  is given the motion of a material point  $M$  (for example, the speed and acceleration of the point  $M$  are given as functions of the coordinates  $x', y', z'$  and time). Due to the relativity of all motion, we will choose  $S'_{gen}$  the base – stationary. In general, the movement of the coordinate system  $S_{gen}$  is relatively  $S'_{gen}$  decomposed into two: a rotational movement with the speed of the origin of coordinates  $O$ , and a rotational movement around the instantaneous axis passing through this origin, with an angular velocity  $\vec{\omega}_{gen}$ , rad/s, which can change both modulo and in the direction. Figure 2 also shows a general diagram of the movement of a certain material point  $M$  in the systems  $S_{gen}$  and  $S'_{gen}$ .



**Figure 2.** General case of arbitrary movement of any two coordinate systems relative to each other.

The position of a material point  $M$  in a fixed coordinate system  $S'_{\text{gen}}$  is determined by the radius vector  $\vec{R}$ , and in a mobile  $S_{\text{gen}}$  one by the radius vector  $\vec{r}$ . The vector  $\vec{R}_0$  denotes the radius-vector  $\vec{O'O}$  drawn from the fixed reference point  $O'$  to the moving beginning  $O$ . The vectors  $\vec{R}$ ,  $\vec{R}_0$  and  $\vec{r}$  are connected at each time by the relation:

$$\vec{R} = \vec{R}_0 + \vec{r}. \quad (5)$$

The speed of absolute motion  $\vec{V}_{\text{abs}}$  of a material point  $M$  in the coordinate system  $S'_{\text{gen}}$  can be represented as [10]:

$$\vec{V}_{\text{abs}} = \vec{V}_{\text{rel}} + \vec{V}_{\text{por}}, \quad (6)$$

where,  $\vec{V}_{\text{rel}}$  and  $\vec{V}_{\text{por}}$  is the relative and portable velocity of the material point  $M$ , m/s.

The value  $\vec{V}_{\text{por}}$  is calculated using the formula:

$$\vec{V}_{\text{por}} = \vec{V}_0 + \vec{\omega}_{\text{gen}} \times \vec{r}, \quad (7)$$

where,  $\vec{V}_0$  is the absolute velocity of the origin  $O$ , m/s.

The value  $\vec{V}_{\text{rel}}$  can be measured by an observer at rest in the  $S_{\text{gen}}$  coordinate system.

The acceleration of the absolute motion  $\vec{a}_{\text{abs}}$  of the material point  $M$  in the coordinate system  $S'_{\text{gen}}$  can be represented as [10]:

$$\vec{a}_{\text{abs}} = \vec{a}_{\text{rel}} + \vec{a}_{\text{cor}} + \vec{a}_{\text{por}}, \quad (8)$$

where,  $\vec{a}_{\text{abs}}$  is the relative acceleration of the point  $M$  (it can be measured by an observer who is in the  $S_{\text{gen}}$  system and does not suspect its movement), m/s<sup>2</sup>;  $\vec{a}_{\text{cor}}$  – coriolis acceleration, m/s<sup>2</sup>;  $\vec{a}_{\text{por}}$  – portable acceleration (only this acceleration would be experienced by the point  $M$  if it were at rest in the  $S_{\text{gen}}$  system), m/s<sup>2</sup>.

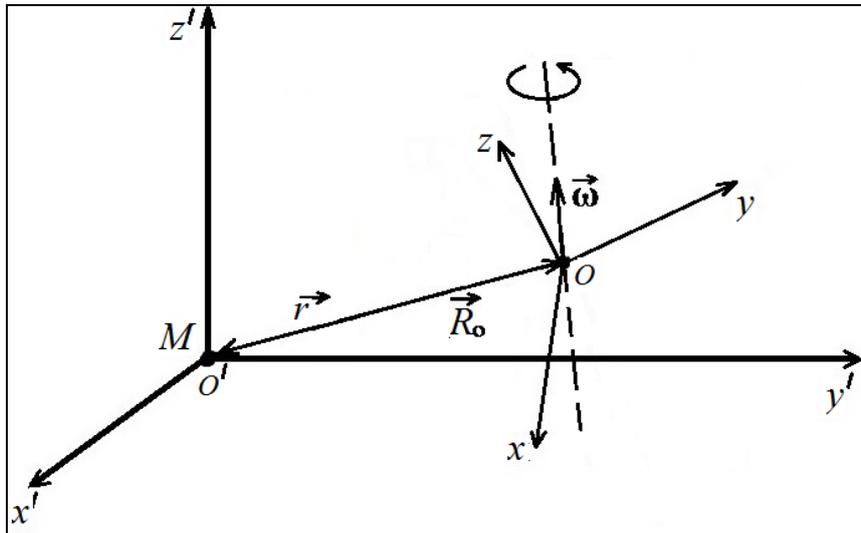
The values included in (8) are calculated using the following formulas:

$$\vec{a}_{\text{cor}} = 2 \cdot \vec{\omega}_{\text{gen}} \times \vec{V}_{\text{rel}}, \quad (9)$$

$$\vec{a}_{\text{por}} = \dot{\vec{V}}_0 + \dot{\vec{\omega}}_{\text{gen}} \times (\vec{\omega}_{\text{gen}} \times \vec{r}) + \dot{\vec{\omega}}_{\text{gen}} \times \vec{r}, \quad (10)$$

where,  $\dot{\vec{V}}_0$  is the absolute acceleration of the origin  $O$  of the  $S_{\text{gen}}$  system, m/s<sup>2</sup>;  $\dot{\vec{\omega}}_{\text{gen}}$  is the time derivative of the angular velocity  $\vec{\omega}_{\text{gen}}$ , rad/s<sup>2</sup>.

Let's compare the movement of the center of mass point of an elementary liquid particle-the material point  $M$  in figure 1, with the general case of considering the movement of a material point in two arbitrarily moving coordinate systems (figure 2). In the comparison shown in figure 3, system  $S'$  is assumed to be the base-fixed, and system  $S$  is assumed to be mobile. The motion of the system  $S$  is decomposed into translational, with the velocity of the reference point  $O$ , and rotational around the instantaneous axis passing through this beginning, with the angular velocity  $\vec{\omega}$ , rad/s. Figure 3 shows that the velocity  $\vec{V}_{\text{rel}}$  and acceleration of the center of mass  $\vec{a}_{\text{rel}}$  of the considered elementary liquid particle in the laboratory coordinate system are equal (figure 1).



**Figure 3.** Comparison of the movement of the point  $M$  in figure 1 with the General case in figure 2.

The feature that distinguishes the movement of the material point  $M$  in figure 3 from the general case considered in figure 2 is that in figure 3  $\vec{r} = -\vec{R}_0$ , since the center of mass of the elementary liquid particle-the point  $M$  is located at the starting point  $O'$ . Consequently, for the motion considered in figure 3, at the point  $M$   $\vec{V}_{\text{abs}} = 0$  and  $\vec{a}_{\text{abs}} = 0$ . Consequently, from (6) and (8) for the motion considered in figure 3, we obtain:

$$\vec{V}_{\text{rel}} = -\vec{V}_{\text{por}}, \quad (11)$$

$$\vec{a}_{\text{rel}} = -\vec{a}_{\text{cor}} - \vec{a}_{\text{por}}. \quad (12)$$

Expressions (11) and (12) describe the relative motion of the center of mass of an elementary liquid particle in the coordinate system  $S$ , i.e. in the laboratory coordinate system. The angular velocity vector, denoted in figure 2 as  $\omega_{\text{gen}}$ , is denoted in figure 3 as  $\omega$ .

When the flow of liquid through the throttle device is steady, acceleration  $\vec{a}_{\text{rel}}$  forms a vector field in the flow part. In physical terms, this vector field corresponds to the distribution density  $\vec{f}$ ,  $\text{m/s}^2$ , of the resulting mass force acting on an elementary liquid particle in the flow:

$$\vec{a}_{\text{rel}} = \vec{f}. \quad (13)$$

In this case, an elementary liquid particle with mass  $dm$  will be affected by an elementary resultant force  $d\vec{F}$ , N:

$$d\vec{F} = \vec{f} \cdot dm. \quad (14)$$

The decrease in the potential energy of such an elementary liquid particle in its relative motion is equal to the work performed  $d\vec{F}$  on the path of moving the particle from section 1 to section 2 (figure 1) along its trajectory:

$$P_1 \cdot dm - P_2 \cdot dm = \int_{r_1}^{r_2} d\vec{F} \cdot d\vec{r} = \int_{r_1}^{r_2} (\vec{f} \cdot dm) \cdot d\vec{r}. \quad (15)$$

where  $r_1$  and  $r_2$  are modules of vectors  $\vec{r}_1$  and  $\vec{r}_2$ .

After dividing both parts of equality (15) by  $dm$ , we get:

$$P_1 - P_2 = \int_{r_1}^{r_2} \vec{f} \cdot d\vec{r}. \quad (16)$$

From (16), taking into account (12) and (13), we get

$$P_1 - P_2 = \int_{r_1}^{r_2} (-\vec{a}_{\text{cor}}) \cdot d\vec{r} + \int_{r_1}^{r_2} (-\vec{a}_{\text{por}}) \cdot d\vec{r}. \quad (17)$$

The vector  $\vec{a}_{\text{cor}}$  is perpendicular to the vector  $\vec{V}_{\text{rel}}$ . Therefore, when the relative motion of the coriolis force does not work, and, accordingly, the first integral in the right part (17) is equal to zero.

To calculate by (10) from (7), taking into account (11), we get:

$$\vec{V}_o = -\vec{V}_{\text{rel}} - \vec{\omega} \times \vec{r}. \quad (18)$$

From (18) we get an expression for the absolute acceleration of the origin of coordinates  $O$  (figure 3)  $\dot{\vec{V}}_o$ :

$$\dot{\vec{V}}_o = -\dot{\vec{V}}_{\text{rel}} - \dot{\vec{\omega}} \times \vec{r} - \vec{\omega} \times \dot{\vec{r}}, \quad (19)$$

where  $\dot{\vec{V}}_{\text{rel}}$  is the time derivative of the relative velocity vector,  $\text{m/s}^2$ ;  $\dot{\vec{r}}$  – the time derivative of the radius vector  $\vec{r}$  (in figure 3  $\vec{r} = -\vec{R}_o$ ),  $\text{m/s}^2$ .

The radius vector  $\vec{r}$  can be represented as the sum of two vectors:

$$\vec{r} = \vec{r}_{\parallel} + \vec{r}_{\perp}, \quad (20)$$

where  $\vec{r}_{\parallel}$  and  $\vec{r}_{\perp}$  are the components of the radius vector directed along the axis of rotation of the system  $S$  (figure 3) and perpendicular to it, respectively, m.

Taking into account (20), as a result of transformations, it can be obtained that the second term in (10) is equal to the centripetal acceleration  $\vec{a}_{\text{ca}}$  directed to the instantaneous axis of rotation

$$\vec{\omega} \times (\vec{\omega} \times \vec{r}) = \vec{\omega} \times (\vec{\omega} \times \vec{r}_{\perp}) = -\omega^2 \cdot \vec{r}_{\perp} = \vec{a}_{\text{ca}}. \quad (21)$$

Substituting (19) and (21) in (10) we get:

$$\vec{a}_{\text{por}} = -\dot{\vec{V}}_{\text{rel}} - \vec{\omega} \times \dot{\vec{r}} - \omega^2 \cdot \vec{r}_{\perp}. \quad (22)$$

Substituting (22) in (17) we get:

$$P_1 - P_2 = \int_{r_1}^{r_2} \dot{\vec{V}}_{\text{rel}} \cdot d\vec{r} + \int_{r_1}^{r_2} (\vec{\omega} \times \dot{\vec{r}}) \cdot d\vec{r} + \int_{r_1}^{r_2} \omega^2 \cdot \vec{r}_{\perp} \cdot d\vec{r}. \quad (23)$$

The first integral in the right part (23) is equal to the change in the specific kinetic energy of the liquid when passing through the flow part of the throttle device ( $K_2 - K_1$ ):

$$\frac{|\vec{V}_{\text{rel } 2}|^2 - |\vec{V}_{\text{rel } 1}|^2}{2} = (K_2 - K_1), \quad (24)$$

where  $\vec{V}_{\text{rel } 1}$  and  $\vec{V}_{\text{rel } 2}$  is the velocity of the liquid in the laboratory coordinate system at the inlet and outlet of the flow part of the throttle device,  $\vec{V}_{\text{rel } 1} = \vec{c}_1$  and  $\vec{V}_{\text{rel } 2} = \vec{c}_2$ , m/s.

The second integral on the right side (23) is zero, since the vector  $(\vec{\omega} \times \vec{r})$  is perpendicular to the vector  $d\vec{r}$ .

The third integral in the right part (23) is physically equal to the specific work of the centrifugal-forces  $l_{\text{cf}}$ , J/kg, the appearance of which is caused by the rotation of the system  $S$  with angular velocity  $\vec{\omega}$  in its relative motion (figure 3):

$$l_{\text{cf}} = \int_{\vec{r}_1}^{\vec{r}_2} \omega^2 \cdot \vec{r}_\perp \cdot d\vec{r}. \quad (25)$$

It can be shown that the value of the  $l_{\text{cf}}$  is always positive and can only be zero in two cases. When  $\vec{\omega}$  equal to zero. This movement is vortex-free. When vectors  $\vec{\omega}$  and  $\vec{V}_{\text{rel}}$  are collinear. This movement is called a screw. It is obvious that in the flow part of the throttle device, in general, these conditions are not required to be met.

Finally, from (23), taking into account (24) and (25), we get:

$$P_1 - P_2 = (K_1 - K_2) + l_{\text{cf}}. \quad (26)$$

Comparing (26) and (4) we get:

$$q_{\text{fr}} = l_{\text{cf}} = \int_{\vec{r}_1}^{\vec{r}_2} \omega^2 \cdot \vec{r}_\perp \cdot d\vec{r}. \quad (27)$$

Accordingly (26) can be written as:

$$q_{\text{fr}} = (K_1 - K_2) + (P_1 - P_2). \quad (28)$$

Expressions (27) and (28) reveal the mechanical nature of the irreversible process of re-distribution of the total mechanical energy of the incompressible fluid flow when passing through the throttle device. Due to the vortex nature of the flow during throttling, a part of the specific mechanical energy of the flow, equal to the sum of  $[(K_1 - K_2) + (P_1 - P_2)]$ , necessarily inevitably passes into internal energy. Thus, the mechanical energy of the flow is dissipated during adiabatic throttling.

It should be noted that in accordance with (28), the  $q_{\text{fr}}$  value during throttling is determined only by the nature of the fluid movement.

### 3. Results and Discussion

The mechanism of mechanical energy dissipation in the throttling process associated with the vortex nature of the flow in the flow part of the throttle device is determined. An analytical expression is obtained for the part of the mechanical energy of the flow that passes into the internal energy of the liquid during throttling.

#### 4. Conclusion

The proposed method can be used to analyze the irreversibility of throttling a compressible fluid. The disclosure of the mechanical nature of irreversibility during adiabatic throttling of an incompressible fluid can ultimately make it possible to increase the efficiency of the equipment in which this process is applied.

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