Investigation of water-air flows in nozzles

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Abstract. The undoubted importance of these problems allows us to conclude that the research aimed at creating and using a simple model of the flow of a two-phase medium is relevant and of interest not only from a scientific, but also from a practical point of view. Two approaches to their description can be distinguished: the study of flows of two-phase media taking into account relaxation processes between phases with a microscopic description of the interaction between phases, or the study of flows of two-phase media with a macroscopic description of the medium in the form of a one-speed one-temperature continuum. However, sometimes, when calculating, it is possible to ignore the structural two-phase medium and consider the medium as a one-speed one-temperature continuum. This proposal allows us to calculate the averaged flow parameters of a two-phase medium, which is required for engineering calculations. In this paper, the calculation of the flow of the gas-drop flow in the Laval nozzle is given. The method is described, which is based on integral energy equations for two-phase dispersed currents. In the calculations, the two-phase flow is considered as a single-speed, single-temperature continuum. When modeling in the ANSYS Fluent software package, a package of Euler equations is used to compare with analytical results obtained from integral energy equations.

1. Introduction

The study of various two-phase media movement is currently of great interest in aircraft construction, machine engineering, when designing the water circuit for nuclear reactors. Due to the complexity of phase interaction processes, it is rather difficult to formulate a general approach for calculating these types of two-phase mixtures. Gas-droplet systems have been studied in a number of papers [1-4], moreover, in [3,4], the propagation of sound waves in various media with heat and mass transfer processes is considered.

Sound propagation is an oscillatory motion with small amplitudes in a compressible medium. A number of authors have shown this sound wave propagation theory from the two-component medium compressibility point of view [4]. It should be noted that when the mass content is equal to zero and one, there is a discontinuity in sound velocity when going over "liquid – gas" or vice versa. The transition over "liquid-gas" phase does not affect the velocity of sound with superresonance frequencies, but their attenuation depends on this transition intensity. As a result, when the mass content is equal to zero or one, the sound linearity theory becomes inapplicable even at small amplitudes of acoustic waves. If no opposite, then there would be a violation of the local thermodynamic equilibrium principle and it turned out that the wave would completely ignore the drops in the medium.

Two approaches to the description of a two-phase flow can be distinguished: the study of flows taking into account the relaxation processes between phases in the microscopic description of the interaction between the phases or the study in the macroscopic description of the medium in the form of a single-velocity and one-temperature continuum [4]. However, sometimes in calculations it is possible to
neglect the structure of a two-phase medium and consider the medium as a single-velocity and one-temperature continuum. The undoubted importance of the listed problems allows us to conclude that studies aimed at creating and using a simple model of the two-phase medium flow are relevant and of interest not only from a scientific but also from practical point of view.

2. Problem statement
The paper poses the problem of studying the stream of a gas-droplet flow in a Laval nozzle and identifying the features of this flow, which distinguishes it from a single-component one. It is important to note that the study of such systems should be based on general integral equations of energy, taking into account that different temperature, pressure and velocity values for the gas and liquid phases are possible. Based on the data obtained, it is necessary to specify the concept of the sound velocity as a characteristic of adiabatic elasticity, which is applicable only to homogeneous media and is not applicable to two-phase (multiphase) media.

3. Study results
A two-phase water-air mixture with finite particle sizes of the condensed phase is discrete with all parameters discontinuity at the interfaces, so that at different points the medium is characterized by different pressure, temperature, and density values, which change abruptly at the interfaces. With the air pressure increase, the calculated sound velocity changes significantly at constant sound speeds in the liquid and gas phases, and at sufficiently high pressures, its minimum disappears, which can be seen in Figure 1.

![Figure 1. Dependence of the change in the sound speed for a water-air mixture depending on the volumetric air content at different pressures](image)

It is considered that the predominant factor determining the gas-liquid mixture compressibility is a high rate of phase transitions that maintain thermodynamic equilibrium with changes in pressure. In this case, two types of flows should be reviewed: equilibrium and stagnant. The frozen flow is available in short nozzles with sufficiently large droplets, and the equilibrium flow is in long nozzles with small particle sizes. In a frozen flow, the droplet component temperature does not change, and the heat exchange between the gas and droplet phases can be neglected, the gas flow is adiabatic with a changing temperature; for an equilibrium flow, there is heat exchange between the phases, which is characterized by the equality of temperatures between the gas and condensed phases. The real flow in the nozzles is in the interval between the frozen and equilibrium flows.

It should be noted that the equilibrium velocity depends significantly on pressure and increases with its growth. Since both frozen and equilibrium sound velocities refer to two limits representing different mechanisms of the gas-liquid medium compressibility, it is really possible to assume the simultaneous existence of both mechanisms [5, 6].

With certain properties, superheated or saturated steam can be considered as a homogeneous medium, but applicability of basic thermodynamic equations is violated at high supersonic velocities. Therefore, it is worth pointing out that a similar picture of applicability of thermodynamic relations for
an ideal gas will be the same for vapor-gas media with the condition that this medium does not contain dispersed inclusions in the form of droplets. When simulating the flow in ANSYS Fluent software package, we will use the package of Euler equations. The working fluid is superheated steam with the initial parameters: $P_0 = 605\text{kPa}$, $T_0 = 399\text{K}$ and $M_0 = 0.2$. Condensation is taken into account. Changes in the parameters along the nozzle contour length are shown in figure 2.

![Figure 2](image)

**Figure 2.** Variation of parameters along the entire dimensionless length of a Laval nozzle for superheated steam with the small amount of moisture 0.001 kg / kg, where $x$ is the length in each nozzle section, and $L$ is the length of the entire nozzle

In figure 2, one can observe condensation surges formed after the minimum section, and since moisture is added in the converging part of the nozzle, there are visible temperature graph distortions, which disappear after passing through the minimum section of the nozzle. It is also worth noting that even such a slight addition of the condensed phase to the convergent part slightly distorts the Mach number variation graph.

When simulating the water-air flow, ANSYS Fluent software package with the package of Euler equations was also used. For the calculation, the working fluid is air and droplet medium. The velocity coefficient changes, condensation and heat exchange between phases are taken into account - such a flow is close to real. The initial parameters of a two-component medium: $P_0 = 343\text{kPa}$, $T_0 = 399\text{K}$ and $M_0 = 0.19$. The change in the velocity coefficient shown in Figure 3 is the ratio of condensed to gas velocities. Changes in the parameters along the nozzle contour length are shown in Figure 3.
Figure 3. Pressure variation along the entire dimensionless length of a Laval nozzle for a two-phase air-droplet flow; the velocity coefficient changes, where x is the length in each nozzle section, and L is the length of the entire nozzle the dashed line shows the parameters for the condensed phase; the density is averaged over the entire two-phase medium.

The calculations have shown that the critical sound speed of the gas phase in the minimum cross section is 304 m/s. For the condensed phase, the velocity of 300 m/s is achieved only at the exit from the nozzle, while in ANSYS Fluent, the change in the Mach number was obtained over the entire nozzle profile; the temperature of the condensed phase drops to 350 K, while for the air phase - to 378 K. It can be seen that this value is averaged - this can be seen from the comparison of the speed graphs of different phases (Figure 3). ANSYS Fluent software package plots the graph of the Mach number change of the water-air flow in the form of a trend line, while it was indicated that the movement of a two-phase flow (multiphase) shall be considered separately and the sound speed concept for the condensed phase is unacceptable. The sound speed concept as a characteristic of adiabatic elasticity is applicable only to homogeneous media and is inapplicable to two-phase (multiphase) media, and the analysis of a two-phase discrete flow should be based on general integral equations of energy, taking into account that the gas and condensed phases can have different temperatures, pressures and velocity using a two-fluid flow.
model representing the flow as the sum of flows of the gas and condensed phases with their own parameters.

4. Conclusions

The gas-droplet flow in the nozzle differs from the one-component flow and has its own peculiarities. The study of such systems should be based on general integral equations of energy, taking into account that the gas and condensed phases can have different temperatures, pressures, and velocities. Based on the data obtained, it can be seen that the concept of the sound velocity as a characteristic of adiabatic elasticity is applied both to homogeneous media and to two-phase (multiphase) media, which is unacceptable. Based on the research of a water-air flow in ANSYS Fluent software package, the Mach number is considered as an average value - which is inapplicable to two-phase (multiphase) media, since the structure of a two-phase medium can be neglected only if it is considered as a single-speed and one-temperature continuum. As a result, the study of two-phase (multiphase) media flows should take into account the processes of interaction between phases, and rely on general integral equations of energy.

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