Mathematical modeling of the generation of acoustic waves in a two-channel system

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Abstract. The purpose of this study is to determine the influence of the diameter of a subsonic conical nozzle on the generation of acoustic waves in a two-channel system. Three-dimensional numerical simulation of flow in the duct of an actual device was performed. A complete picture of the flow generated in the acoustic-convective drying system of the Institute of Theoretical and Applied Mechanics, SB RAS, was obtained. The results of the study show that to maintain the amplitude-frequency characteristics of the workflow with increasing diameter of the subsonic conical nozzle, it is necessary to reduce the settling chamber pressure. The numerically simulated amplitude-frequency characteristics of the acoustic flow generated in the working section of the drying system are in satisfactory agreement with the results of physical experiments.

1. Introduction

In modern industry, there are various technologies for drying capillary-porous materials, the most popular of which is the thermal-convective method [1]. However, there is a promising method of acoustic-convective drying of porous materials, which, according to a series of studies [2-5], has several advantages over the thermal-convective method, including the possibility of drying materials at room temperature.

The amplitude-frequency characteristics (AFCs) of oscillations in the duct of the acoustic-convective dryer (ACD) during its operation have been obtained in previous physical experiments [3, 6]. Previously, parametric studies of the jet generating self-oscillations with varying length of the resonator have been performed [7, 8] under the assumption of plane and axial symmetry. A three-dimensional numerical simulation has been carried out [9], showing that the AFCs of the unsteady flows formed in the ACD duct are in qualitative agreement with those obtained in full-scale experiments with a conical nozzle diameter of 8 mm.

The present study aims to determine the effect of the diameter of the conical nozzle on the physical stream flow in the ACD duct by mathematical modeling.

2. Physico-mathematical formulation of the problem

The ACD geometry can be represented as two perpendicular channels. The first channel consists of a cylindrical settling chamber with a subsonic conical nozzle and a cylindrical resonator with a closed end which is located coaxially to the nozzle at a certain distance from it. The cylindrical channel crosses the second channel with a square cross section and conventionally divided it into two sections:
To study the effect of the diameter of the conical nozzle on the dynamics of the formation of acoustic-convective flow, we used subsonic conical nozzles of diameter 8, 10.5, and 12 mm.

For the numerical description of the gas-dynamic flow, we used an approach based on solving the Reynolds-averaged Navier-Stokes with the $k-\omega$ Wilcox turbulence model \cite{10} having the following form:

\begin{equation}
\rho U \frac{\partial k}{\partial x} + \rho V \frac{\partial k}{\partial y} = \rho_0 \left( \frac{\partial U}{\partial y} \right)^2 - \beta \rho \omega + \frac{1}{y} \frac{\partial}{\partial y} \left[ y \gamma \rho \sigma \cdot \rho \frac{\partial k}{\partial y} \right]
\end{equation}

\begin{equation}
\rho U \frac{\partial \omega}{\partial x} + \rho V \frac{\partial \omega}{\partial y} = \alpha \frac{\partial \omega}{k} \rho_0 \left( \frac{\partial U}{\partial y} \right)^2 - \beta \rho \omega^2 + \frac{\partial}{\partial y} \left[ y \gamma \rho \sigma \cdot \rho \frac{\partial \omega}{\partial y} \right]
\end{equation}

\begin{equation}
v = \frac{k}{\omega}
\end{equation}

The working gas was air with the standard thermal conductivity $\lambda$ and specific heat $C_p$.

Pressure was calculated by the ideal gas equation of state, and viscosity by the three-coefficient Sutherland formula:

\begin{equation}
\mu = \mu_0 \left( \frac{T}{T_0} \right)^{3/2} \frac{T_0 + S}{T + S}
\end{equation}

where $\mu_0$ is the reference viscosity in kg/m·s, $T_0$ is the static temperature in Kelvin, and $S$ is the Sutherland constant.

3. Numerical simulation

The ANSYS Fluent software was used for the numerical simulation. A symmetric three-dimensional geometric model of the ACD was constructed taking into account the features of the internal duct of the dryer. The grid area was divided into small segments to improve the accuracy of the solution in complexly described units of the model and improve the quality of the solution. The region of the intersection of the channels was discretized by a tetrahedral computational grid, which can be modified to a polyhedral grid by means of Fluent in order to improve the quality of the cells. The remaining segments of the computational domain are covered by a multi-block structured hexahedral grid which was refined toward the walls of the model.

For each nozzle diameter, we specified the corresponding static and total pressures in the settling chamber observed in field experiments \cite{3, 6}. For a nozzle diameter of 12 mm, the total pressure was 458 kPa and the static pressure was 451 kPa, and for nozzle diameters of 8 and 10.5 mm, the total pressure was 789 kPa and 616 kPa, respectively, and the static pressure was 769 kPa and 601 kPa, respectively.

4. Results and Discussion

The numerical simulation resulted in the self-oscillating process of filling/emptying the cylindrical resonator with the air jet accelerated by the subsonic conical nozzle. The AFCs and the flow pattern of the acoustic streaming developed in the ACD duct were obtained.
Consider the flow pattern (see figure. 1) formed in the ACD duct with a nozzle diameter of 12 mm. At the initial time, the jet accelerated by the subsonic conical nozzle issues into the working space of the dryer, reaches the sound speed at the nozzle exit, and is accelerated to supersonic speed, resulting in the formation of a barrel-shaped structure terminated by a Mach disk. Behind the Mach disk, the flow is decelerated to subsonic speed in the central part of the jet, and at the periphery of the jet, the flow remains supersonic. The stream flowing from the settling chamber fills the cylindrical resonator; at the beginning of the inflow phase, the resonator pressure is 130 kPa. A new pressure field of 250 kPa is formed behind the compression wave moving into the resonator. The compression wave reaching the closed end of the resonator is reflected by a compression wave of greater amplitude and moves in the opposite direction. The medium behind the reflected wave has a total pressure of about 350 kPa, and the pressure at the wave front is 500 kPa. Reaching the free end of the resonator, the reflected compression wave encounters the jet flowing out of the conical nozzle and begins to interact with it. The interaction results in deformation of the “barrel”, and a pressurized jet enters the second channel with a square cross section, thus emptying the resonator. When most of the gas has issued from the resonator, the pressure in it decreases and a rarefaction wave with a total front pressure of about 200 kPa moves into the resonator. After reaching the closed end, the rarefaction wave is reflected by a rarefaction wave, behind which a uniform low-pressure field of 130 kPa is formed. The wave reaches the free end of the resonator, and the resonator is again filled with the jet flowing from the nozzle. This periodic process is a source of high-intensity acoustic oscillations that underlie the operation of the ACD.
Figure 2. Pressure fields in the ACD duct for a nozzle diameter $d = 8\text{mm}$ (a), $d = 10.5\text{mm}$ (b), and $d = 12\text{mm}$ (c).

Figure 2 shows the total pressure fields in the working channel of the ACD at the same time for nozzles with a diameter of 8, 10.5, and 12 mm. The total pressure in the settling chamber with a conical nozzle of 8 mm diameter is about 7.9 bar, and for diameters of 10.5 and 12 mm, it is 6.2 and 4.6 bar, respectively. The gas jet flowing out of the settling chamber fills the resonator, into which a compression wave propagates; the speed of propagation of the generated wave does not depend on the diameter of the nozzle. The total pressure magnitude behind the compression wave is 2.6 bar for all nozzle diameters. The front of the total-pressure compression wave has a pronounced dispersion character. Increasing the nozzle diameter and hence the greater length of the barrel leads to a partial closure of the neck of the resonator, which complicates the outflow from the resonator; as a result, in the rarefaction phase, the resonator pressure was 0.9 bar for a diameter of 8 mm, 1.3 bar for 10.5 mm, and 1.4 bar for 12 mm.

For these diameters of the conical nozzle, we determined AFCs which show that increasing the diameter of the conical subsonic nozzle and appropriately decreasing the settling chamber pressure provide similar frequencies and intensities. Figure 3 presents the results of comparison of the AFCs for the three diameters of the conical nozzle obtained by numerical simulation and in physical experiments. As can be seen, varying the nozzle diameter leads to a negligible change in the resonating frequency of acoustic oscillations, within a dozen hertz, but, at the same time, the amplitude of the workflow in the working section remains almost unchanged.

Figure 3. AFCs of the flow in the ACD duct.
The numerically calculated AFCs of the workflow in the ACD duct are almost the same as the results of physical experiments. Verification of the AFCs showed satisfactory agreement between the results of numerical calculations for a flow intensity of 171-175 dB at a frequency of 250-310 Hz and the data obtained in physical experiments in which the flow intensity was 178-179 dB at a frequency of 280-290 Hz.

5. Conclusions
The numerical studies have provided a complete picture of the acoustic streaming formed in the working section of the ACD for the corresponding diameters of the conical nozzle.

The relationship between the increase in the diameter of the conical nozzle and the decrease in the settling chamber pressure at constant AFCs of the workflow was obtained.

Validation of the numerical simulation against the results of field experiments showed satisfactory agreement between the simulated and experimental AFCs of the workflow.

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