The subsonic velocity blocking effect for an aerodynamic vortex chamber

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Abstract. The experimental data are presented for the velocity in the slits of guiding apparatus for the classic open vortex chamber as well as for the Ranque tube. In both cases at the linear rise of the mass flow rate with increasing of overpressure level, the essential slowdown was observed for the growth of the slit velocity. At that the ratio of the slit to the critical sound velocities (the velocity coefficient) either tends to an asymptotic limit that is less than unity, or becomes equal to unity at a certain overpressure level and no more changes.

1. Introduction

The open vortex chamber is described in [1-5]. The common pattern with circulating reverse flow is shown in Figure 1. The tangential slits of guiding apparatus serve for the entrance of the air. A thin annular domain, adjacent to the edge of central orifice in the top cover serves for the air exit from the camera, the rest cross section of the orifice belonging to the circulation zone. The ratio \( \xi \) of the circulation zone radius to the radius of the top cover orifice \( a \) is defined in [2] by two parameters: the value of \( \Omega = G / (\pi \rho_0 \Gamma a) \) and the overpressure at the entrance, \( \Delta P \). In the limit of incompressible fluid \( \Omega \) becomes equal to the well known geometric parameter of centrifugal sprayer \( \Omega = Q / (\pi \Gamma a) = nbh / (\pi Ra) \) [1]. Here \( G \) and \( Q \) denote the mass and volume gas flow rates, \( \Gamma = VsR \) is proportional to the velocity circulation at slit exit radius \( R \), \( \rho_0 \) is the stagnation gas density. In [1, 4-5] the connection between the turbulent Reynolds number value and the circulation zone relative radius \( \xi \) is proved. This concept gives reasonably good quantitative description for the velocity profiles inside the vortex chamber in the framework of the constant turbulent viscosity model.

As far as the exit cross section value \( S = \pi a^2 (1 - \xi^2) \) is regulated by the flow parameters, it is not clear in advance if the vortex chamber considered as a nozzle would be blocked with the rise of overpressure \( \Delta P \). From the other hand, the Ranque tube data are usually presented with no focus on pressure dependence of velocity coefficient at the entrance, whereas the comparison of that data with the open vortex chamber experiments could probably clear up the flow behavior inside the tube.

In this work the main attention for both devices is focused on the experiments showing the behavior of slit velocities and mass flow rates with respect to the growth of the overpressure at the entrance. The experimental data are presented for the velocity at the exit from the slits of guiding apparatus for the open classic vortex chamber [1-5], as well as for the Ranque tube described in [6]. It is shown that with the rise of overpressure level at the entrance of vortex device the mass flow rate increases linearly, whereas the growth of velocity at the exit from the slits slows down essentially. In
addition the behavior of temperature difference at the hot exit of the Ranque tube is similar to the character of velocity rise.

2. Experimental setup
The experiments were made on the vortex chamber described in [2-5] with the flow scheme and geometric parameters for the camera shown in figure 1. The investigation was performed in the camera of 67 mm inner radius R, 25 mm height h and the radius of the orifice in a top end cover a of 15, 25, 30 and 45 mm. The number of tangential entrance slits varied from n=1 to n=4. Although the most results are presented for the camera with the exit orifice in one of the top covers, as in figure 1 (k=1), some of experiments were made on the camera with two identical orifices in both top covers (k=2). The overpressure value at the entrance varied from 0.05 to 0.4 MPa.

The other series of experiments was made in the Ranque tube described in [6], with 34 mm tube diameter (figure 2). The air entered the tube through the vortex chamber with two slits guiding apparatus and two orifices in its top covers, one being of 34 mm and the other of 10 mm diameter. The inner diameter of guiding apparatus was 67 mm. The working channel of the Ranque tube was adjusted to the camera exit of 34 mm diameter. The tube of 10 mm diameter for cold air exit passed through the smaller orifice. The hot exit was arranged as a radial diffuser with 1.5 mm clearance. It was packed in a buffer volume connected to the atmosphere by a valve that regulated the cold to total flow rate ratio $\mu$. The overpressure at the entrance was varied from 0.1 to 0.7 MPa.

3. Experimental method
The air flow rate for both devices was measured by means of calibrated orifice plates with the accuracy of 2.5…5 percent. For the slit velocity measurement in the vortex chamber the Pitot tube for total pressure ($P_0$) was placed in front of the slit exit, and a static pressure (P) probe was adjusted at a drain orifice in one of the top covers at the slit exit radius. The coefficient $\lambda$ defined as the ratio of the slit and the critical sound velocities was calculated by the formula for isentropic flow of non-viscous perfect gas ($\kappa$ denotes the adiabatic index that is equal to 1.4 for air):

$$\lambda = \frac{\kappa + 1}{\kappa - 1} \left[ 1 - \left( \frac{P}{P_0} \right)^{\frac{\kappa - 1}{\kappa}} \right]$$

(1)

Another way to define the slit velocity coefficient $\lambda$ is to solve the equations system for the mass flow rate passing through the slits cross section $S$, with uniform velocity, Poisson adiabatic and Bernoulli integral for compressible gas at given flow temperature, resulting in the equation (2),

$$\lambda = \left( \frac{1}{\kappa} \right) \left( \frac{P}{P_0} \right)^{\frac{\kappa - 1}{\kappa}} \int \left[ P \right] dS$$

(2)
connecting $\lambda$ with the measured value of mass flow rate $G$, total slits cross section $S_s$ and critical sound velocity $a*$:

$$\lambda = \frac{G}{S_s \rho_0 a^*} \left(1 - \frac{\kappa - 1}{\kappa + 1} \lambda^2 \right)^{1/(\kappa - 1)}$$

(2)

The comparison of calculations by formulas (1) and (2) is shown in figure 3 for the vortex chamber experiments. The results differ no more than in 2.5%. Both formulas (1) and (2) are used below for the vortex chamber, and only formula (2) served for the Ranque tube investigation.

The temperatures at the inlet ($T_0$), and at the cold ($T_c$) and the hot ($T_h$) exits of the Ranque tube were measured via digital thermometers DS18B20 with uncertainty not exceeding 0.1 K.

4. Results and discussion

In figures 4-9 a series of experiments is demonstrated in the vortex chamber with one, two and four inlets, one or two central orifices in the top covers with the radii of 15, 25, 35 or 45 mm. The data show that at the overpressure level greater than 0.1 MPa the mass flow rate $G$ grows linearly with overpressure. At that, the growth of velocity coefficient at the exit from the slit of guiding apparatus, $\dot{\lambda} = V_s/a^*$, at a certain value of overpressure $\Delta P$ essentially slows down as the value of $\lambda$ asymptotically tends to a limit that in figures 4-8 is less than unity.

Comparing of Figures 4 and 5 shows that at decreasing of inlets number $n$ from 4 to 1 the flow rate decreases only by the factor of 1.9, the value of $\lambda$ being increased by 2.42. From the other hand, if additional central exit is opened (figure 6, $k = 2$), the flow rate and velocity coefficient almost do not change as compared to figures 4 and 7.

Thus, it is demonstrated that not only the slit cross section influences the flow rate value. The near axis circulating zone radius, depending on actual flow parameters, such as velocity circulation and mass flow rate, also influences it, making the flow self consistent [1-2].

Figure 7 shows the velocity coefficient dependence on slits number $n$. Figure 8 shows the influence of a central orifice radius on the velocity coefficient. The sound velocity in the slit ($\lambda = 1$) was reached at the orifice radius $a = 45$ mm at a single slit inlet, $n=1$ (figures 8, 9).
It should be noted that after the sound velocity is reached at the slit exit, at further increasing of the entrance overpressure value, the slit velocity no more increases, whereas the mass flow rate continues to increase linearly. This demonstrates the essential difference between the observed phenomenon of velocity blocking in the vortex chamber and the sound chocking of a simple one dimensional slit nozzle, at which the mass flow rate stops growing.
Figure 8. $n = 1, k = 1$

In the Ranque tube experiments the behavior of the inlet slit velocity coefficient and mass flow rate appeared analogous to the behavior of the similar vortex chamber parameters at cold flow ratios $\mu$ of 0.3 and 0.6. The sound velocity at the exits of guide apparatus slits was not reached in the investigated overpressure range. Figure 10 shows the behavior of velocity coefficients and mass flow rates with respect to overpressure at cold flow ratios $\mu$ of 0.2, 0.3 and 0.6. Figure 11 presents the corresponded temperature differences at the hot and cold exits of the tube: $T_h-T_0$ and $T_c-T_0$. The noticeable qualitative correlation is observed for the temperature differences and velocity coefficient.

Thus, the possibility is presented for the especial subsonic velocity blocking of vortex apparatus, connected with a circulation zone formation in the vortex chamber or with the reverse flow area in the Ranque tube.

5. Conclusions
The experimental data presented for the velocity coefficient in the slits of guiding apparatus for the classic open vortex chamber and for the Ranque tube demonstrate a similar behavior with the pressure change. In both cases at the linear rise of the mass flow rate with increasing of overpressure level, the essential slowdown is observed for the growth of the slit velocity coefficient. The velocity coefficient either tends to an asymptotic limit that is less than unity (vortex chamber and Ranque tube with cold fraction greater than 0.3) or becomes equal to unity at a certain overpressure level and no more changes (vortex chamber). After the sound velocity is reached at the slit exit, at further increasing of the entrance overpressure value the mass flow rate continues to increase linearly. This demonstrates the essential difference between the observed phenomenon of velocity blocking in the vortex chamber and the sound choking of a simple one dimensional slit nozzle. The similarity of the effects observed in the open vortex chamber and in the Ranque tube encourages that the knowledge obtained in vortex chamber flow analysis, namely the velocity and pressure calculations [1-5], will appear useful in further attempts to calculate the flow parameters in the Ranque tube.
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