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Technical note

INFLUENCE OF NOZZLE GEOMETRY ON FLUID FLOW PARAMETERS

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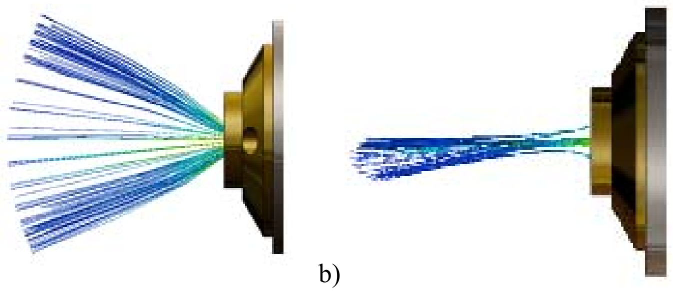
The article discusses ways for optimization of a standard nozzle cup design to achieve a narrower paint flow. The analysis of a standard nozzle cup shows that distribution of air pressure is critically uneven both along the nozzle axis and in the radial direction. A decrease in pressure is about *45*% at the distance of *2 mm* from the front surface of the nozzle cup. Air pressure decreases about *40*% at the distance of *2 mm* from the nozzle axis in the radial direction. Air velocity decreases about *52*% at the distance of *4 mm* from nozzle surface but then the velocity stabilizes and decreases is about *59*% at the distance of *10 mm* from the nozzle surface in comparison to its magnitude on the nozzle surface.

Six extra holes and a circular rim were added to the standard nozzle cup to obtain paint stream as narrow as possible. Also was modified inner surface of the nuzzle cup. Totally, four different components were analysed. The results show that with increasing the nozzle cone by fifteen or more degrees, the pressure distribution decreases. Most optimal solution has six small holes around the nozzle hole and a small rim covering all holes. In this case, pressure decreases only *3*% in the axial direction and *4*% in the radial direction at the distance of *2 mm* from the front surface of the nozzle. Distribution of air velocity is still significant but its magnitude is about *35*% … *45*% less than at the standard nozzle cup.

Key words: fluid flow simulation, nozzle geometry, optimization.

1. Introduction

Spray painting is widely used in industry, art, cosmetic and other fields. Painting technique consists of mixing of air and paint and pushing it through a narrow nozzle. The fluid flow has different shapes depending on the air pressure and nozzle geometry. Usually, it is necessary to spray the paint widely and fluid flow has a cone shape (Fig.1a), but sometimes a narrow flow should reach the painting surface and make only a small dot (Fig.1b). In this case, the fluid flow looks like on arc spray.



a) b)

Fig.1. Types of flow: a) cone flow, b) dot flow.

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Industrial applications [1, 2] require strong and precise solutions and many researchers have considered flow shapes and influence of different parameters on jet and heat transfer. Bernoulli equation [3] is used for calculation of air velocity and pressure distribution along the streamline

$$P_0 = P + \frac{\rho \cdot V^2}{2} .$$

It is known [4 – 6] that air velocity influences the stream shape and painting results. Four different nozzle configurations and their influence on the stream shape are considered in [3]. It is shown that gas velocity can be optimized by nozzle design. Analyses [7] show the gas velocity can be increased by *~20*% and kinetic energy by *~40*% if during the design of nozzle geometry more optimal solutions will be found. Geometrical parameters of the nozzle and kinetic parameters of the liquid and gas have a critical influence on the structure of the mixture [8 – 10]. Some researchers propose extra design components to obtain uniform blend, for example a cylindrical tube from the nozzle [11, 12].The rates of operating liquid flow influencing nozzle size on air-to-liquid ratio are considered in [13], where mixture components are calculated by the following equation [14]

$$U_S = \frac{1}{\sqrt{\left[\alpha\rho_g + (1-\alpha)\rho_l\right]\left(\frac{1-\alpha}{\rho_l c_l^2} + \frac{\alpha}{\rho_g c_g^2}\right)}} .$$

Kinematic and kinetic parameters of fluid and gases flows are usually analyzed by using Computational Fluid Dynamics (CFD). This software offers many opportunities and precise results [15 – 17]. Modelling in this research is also done by help of CFD. The main purpose is to analyze ways for creation a flow to be able to paint a dot in diameter of ten millimeters at the distance *10 – 20 mm*. This will be done by designing the nozzle cup (Fig.2, pos.5), and four different geometrical solutions will be considered.

2. Work principle and experimental model

Usual principles of nozzle work are used in system modelling: the paint is drained from the tank and air is supplied from the compressor. The simulations were made based ona typical spray gun of AeroGrafo ES series [18]. Standard components (Fig.2) and typical conditions were used for modelling: the nozzle hole is equal to *0.5 mm*, general temperature is *20*°C and pressure *1.0* atm (~ 1.01 bar).

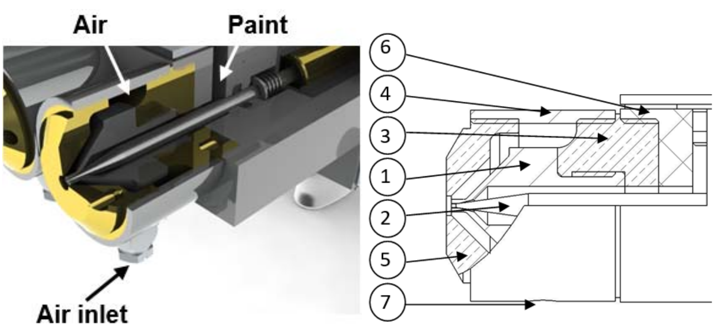


Fig.2. Experimental model.1 – asturomec nozzle, 2 – asturomec needle, 3 – spray camera mount, 4 – air camera,5 – nozzle cup, 6 – body, 7 – air inlet.

CFD simulations were made with SolidWorks Flow Simulation software. Air is fed through the hole with a diameter of *1.6 mm* (air inlet) with the pressure of 2.5 bar. The paint drains from the tank to the nozzle (Fig.2, pos.1) and the compressed air is goes from the air inlet (pos.7) to the air camera (pos.4). When the needle (pos.2) moves back, the paint is mixed with air and compressed air pushes the mix from the hole of the nozzle cup (pos.5).

3. Flow optimization

3.1. Standard nozzle cup

The first experiment series was done on the basis of the most typical nozzle cup geometry (Fig.2). Simulation results show (Fig.3a) that flow velocity is about *340 m/s* near the nozzle front surface. Then the velocity decreases drastically. At the distance of *4 mm* from the nozzle surface the air velocity is about *52*% less (~*160 m/s*). With subsequent motion, the velocity stabilizes and it will decrease only *12*% (~*140 m/s*) at the distance of *10 mm*. About the same decrease in velocity is observed on the whole analyzed distance.

Distribution of air velocity in the radial direction can be divided into two areas with high and low values. The high velocity flow is located near the nozzle axis and is about *7 mm* wide. The air velocity is equal to about *1 m/s* at the distance of *15 mm* from the nozzle front surface and at the distance of *7 mm* from the nozzle axis.

a) b)

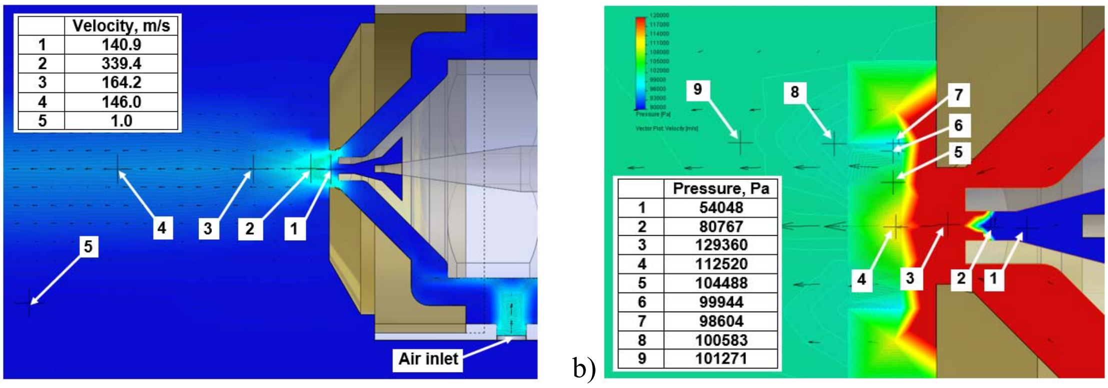


Fig.3. First experiment. a) velocity distribution, b) pressure distribution.

Distribution of air pressure is shown in Fig.3b. High air pressure will push the paint from the nozzle due to low pressure at points 1 and 2. This pressure will decrease after passing the nozzle hole (points 5, 6 and 7) and due to this fact the paint stream will be expanded. High-pressure area on the front surface of the nozzle cup has a diameter about *5 mm*. Pressure distribution with increasing the distance from the nozzle front surface is more even than velocity distribution. The pressure decreases only *1*% at the distance of *4 mm*in comparison to the pressure at the distance of *1.5 mm*.

Pressure distribution in radial direction depends on the width of the high-pressure flow on the nozzle front surface. For creation of a narrow paint stream, it is necessary to concentrate high air pressure at the nozzle axis. This can be obtained by special designs of the nozzle cup and four different solutions will be considered, including the above discussed nozzle cup geometry. Spectral equivalents of magnitudes of air pressure and velocity are presented in Fig.4 for all simulations.

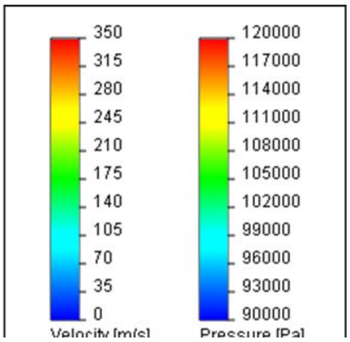


Fig.4. Magnitudes of air pressure and flow velocity.

3.2. Nozzle cup with increased angle of cone

The angle of cone of the inner surface of the nozzle was increased by thirty degrees in the second series of simulations (Fig.5).

In this case, the pressure distribution on the front surface of the nozzle cup is more uniform (about *30*% less than in the first experiment) but pressure streams are still widely spread: pressure at the distance of *3 mm* from the nozzle axis is about *10*% less than the pressure on the nozzle axis. High velocity stream is about *7 mm* in width and unevenly distributed – the velocity decreases about *57*% at the distance of *10 mm* from the front surface of the nozzle cup.

a) b)

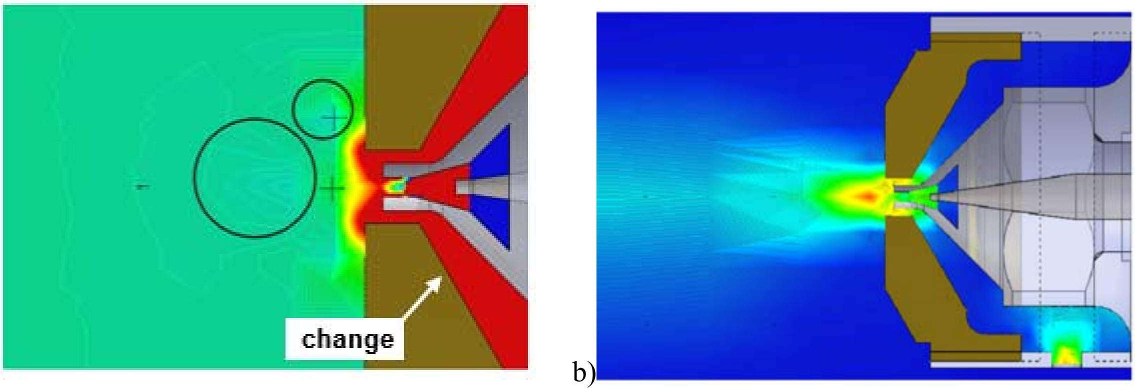
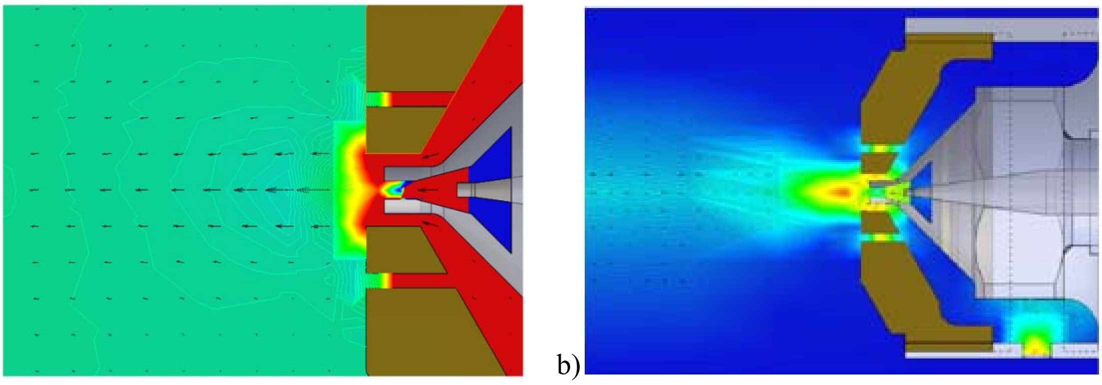


Fig.5. Second experiment. a) pressure distribution, b) velocity distribution.

3.3. Nozzle cup with extra holes

Six holes (Fig.7a) with a diameter of *0.5 mm* were made around the hole of the nozzle cup to concentrate high pressure of air at the nozzle axis. Air pushed through these holes keeps the paint stream near the nozzle axis. Results of this simulation are presented in Fig.6.

It can be seen that pressure distribution is still uneven but there are no more flows in the radial direction. Air flow concentrates at the nozzle axis. The pressure decreases about *3*% at the distance of *1 mm* from the front surface of the nozzle and the pressure decreasing is about *4*% at the distance of *2 mm*. High velocity stream is wider than in the previous simulations and is approximately *10 mm*. This disadvantage can be compensated by the fact that an airflow is created around the paint stream and keeps the paint near the nozzle axis.

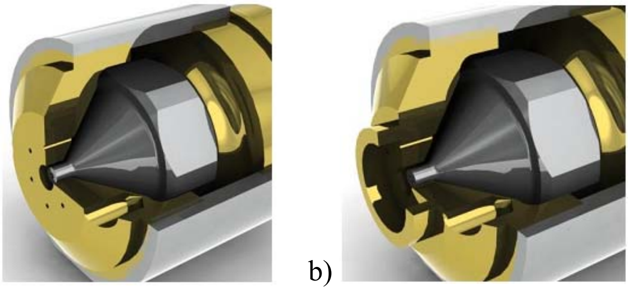


a) b)

Fig.6. Third experiment. a) pressure distribution, b) velocity distribution.

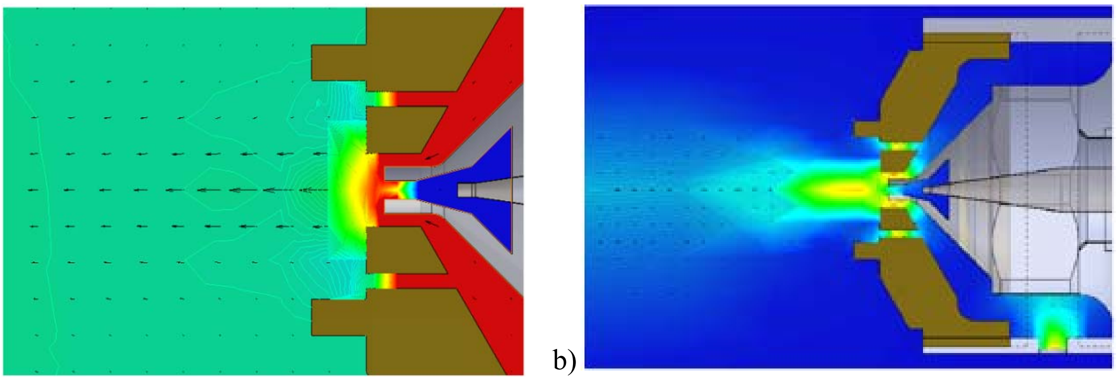
3.4. Nozzle cup with circular rim

Another nozzle cup under analysis had a circular rim on the front surface with an inner diameter of *6 mm* and depth of *1.5 mm* (Fig.7b). Simulation results are presented in Fig.8.



a) b)

Fig.7. Nozzle cup design. a) third experiment, b) fourth experiment.



a) b)

Fig.8. Fourth experiment. a) pressure distribution, b) velocity distribution.

It can be seen from Fig.8 that due to the circular rim airflow is pushed to the nozzle axis and pressure distribution levels. A decrease in pressure is about *1*% at the distance of *0.5 mm* from the front surface of the nozzle cup and about *1.5*% on the distance of *2 mm*. High velocity stream near the cup surface has width about four millimeters and its gradient is along the nozzle axis. The stream width is about *10 mm* and magnitude of the air velocity is about *70 m/s*at the distance of *20 mm* from front surface of the nozzle cup.

3.5. Nozzle cup with circular rim and tilted holes

The last series of simulations was done on the basis of the fourth experiment model but six small holes were tilted at fifteen degrees to the nozzle axis (Fig.9). The results of flow analysis do not differ from the results of previous series more than *1*% but technology of small holes manufacturing is more difficult.

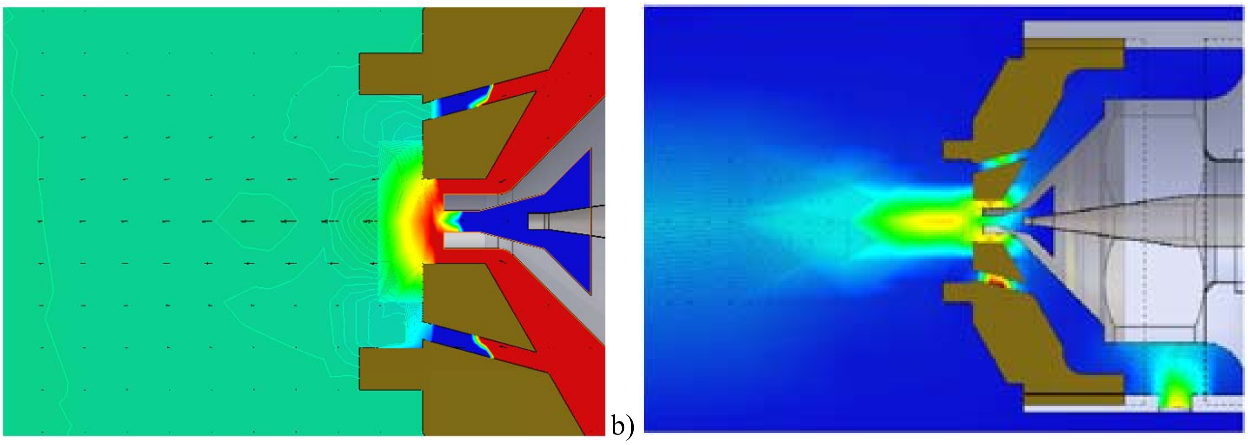
a) b)


Fig.9. Fifth experiment. a) pressure distribution, b) velocity distribution.

4. Results and discussion

Results of all simulations were compared and presented in Figs 10 – 11. It can be seen that all analyzed designs influence significantly on airflow parameters. The maximum air velocity in the typical nozzle design is about *53*% more than the average maximum velocity in other cases under consideration. After a decrease, the velocity stabilizes at the distance of six millimeters from the nozzle cup surface but even in this case the velocity in the standard nozzle is about *90*% more than in other designs. The difference between maximum and nominal velocities in a standard nozzle is about *55*% and in other analyzed cases about *65*%. The difference between absolute values of maximum and nominal velocity is about *120 m/s* and *170 m/s* accordingly in nozzles with changed design and in a standard nozzle. Air velocity influences the shape of the paint stream and more even velocity distribution leads to a narrower paint stream.

Distribution of air velocity in all considered non-standard designs is very similar. The maximum velocity is observed at the distance of *1.5 mm* from the front surface of the nozzle cup and the difference between magnitudes of the maximum velocity is about *7*%. Then the velocity decreases and stabilizes at the distance of *8 mm*. Velocity decreasing is insignificant at the distances from *8 mm* to *20 mm* and average velocity magnitude is about *80 m/s*. The difference is about *15*%.

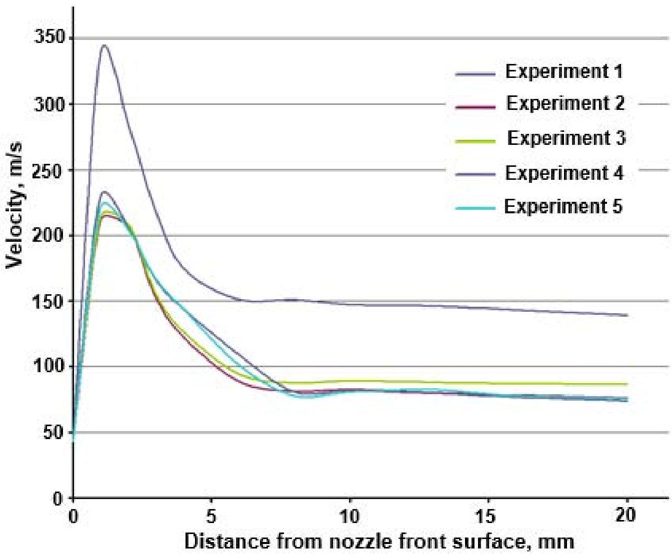


Fig.10. Distribution of air velocity.

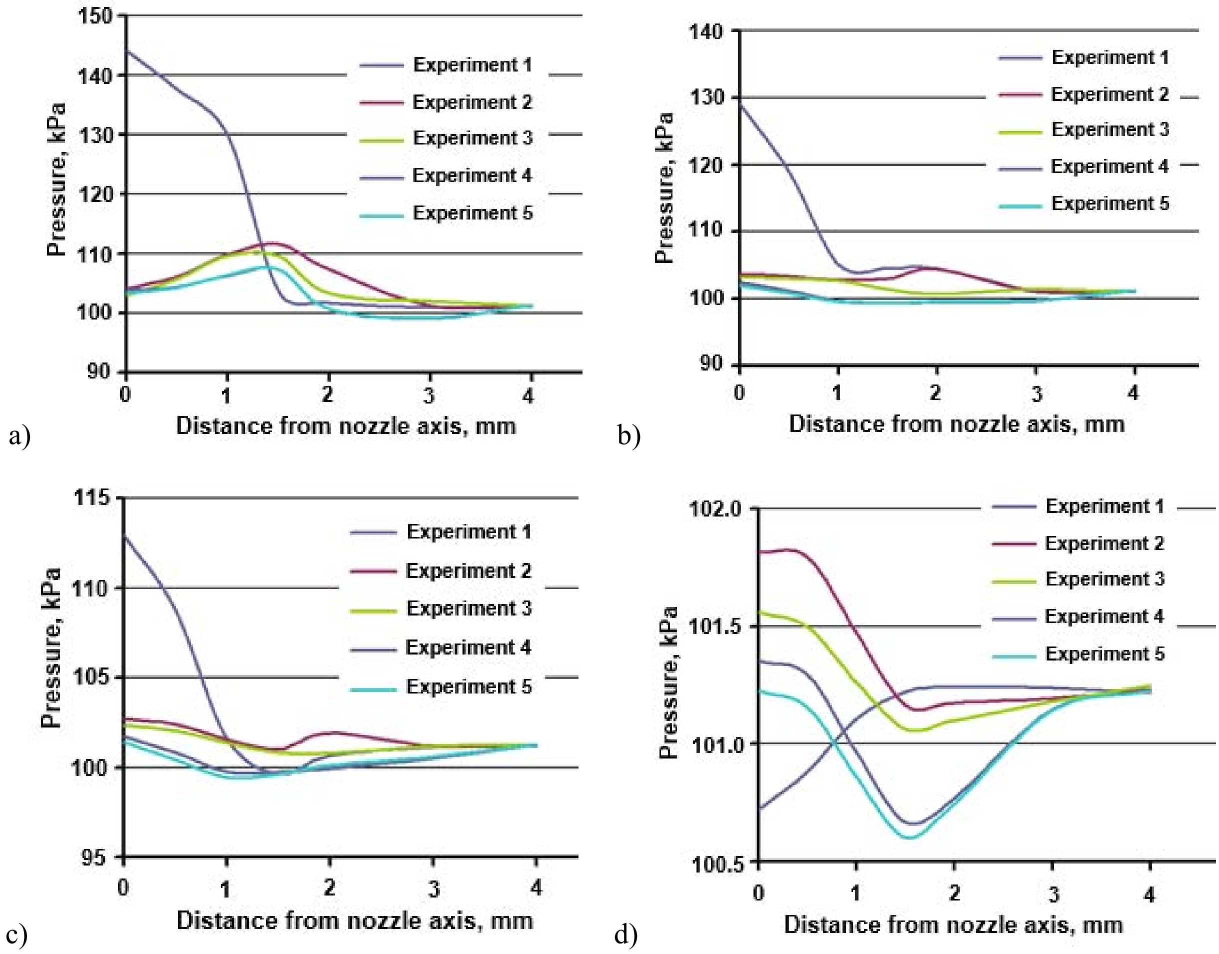


Fig.11. Distribution of air pressure in the radial direction of the nozzle. a) on the front surface, b) at the distance of *0.5 mm* from the front surface. c) at the distance of *1.0 mm*, d) at the distance of *2.0 mm*.

Distribution of air pressure in the radial direction of the nozzle is presented in Fig.11. Pressure is calculated at different distances from the front surface of the nozzle cup. There is a significant difference between standard and modified nozzle cups for all simulations. The pressure is *38*% more on the cup surface of the standard nozzle cup than in other designs. This difference is *25*% on the distance of *0.5 mm* and only *10*% at the distance of *1.0 mm*. At the distance of *2.0 mm* from the front surface of the nozzle cup, the pressure in the standard nozzle decreases and is less than the average pressure in non-standard nozzles (about *1*%).

With increasing the distance from the nozzle axis in the radial direction, the pressure levels in all considered designs of the nozzle cup. The pressure is practically identical for all analyzed cases at the distance more than three millimeters from the nozzle axis. The difference is less than *6*% even on the nozzle cup surface.

Pressure distributions on the nozzle axis and at the distance of *1.5 mm* from the nozzle axis are presented in Fig.12. A significant decrease in pressure can be seen at the first two millimeters from the front surface of the standard nozzle cup. This fact causes wide paint distribution in the first analyzed design in comparison to the fourth case. The pressure distribution has no strong decreases at the distance of *1.5 mm* from the nozzle axis due to the influence of outside air pressure and the pressure is equal for all nozzle cup designs at the distance more than *2 mm* from the cup front surface.

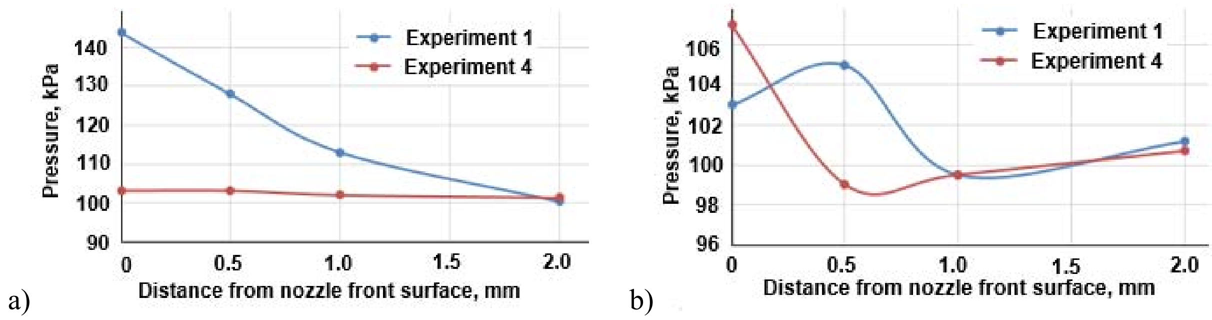


Fig.12. Distribution of air pressure in the axial direction of the nozzle. a) on the nozzle axis, b) on the distance of *1.5 mm* from the nozzle axis.

5. Conclusions

Analysis of paint stream in a standard nozzle shows that air pressure spreads widely after passing through the hole of the nozzle cup and the paint stream will also be widely spread. High pressure moves to the nozzle axis with increasing the distance from the front surface of the nozzle cup and its magnitude degreases significantly: pressure decrease is about *45*% at the distance of *2 mm*. Pressure distribution in the radial direction is also uneven: pressure decreases about *40*%at the distance of *2 mm* from the nozzle axis.

Paint stream depends on the air velocity that is about *340 m/s* in a standard nozzle cup and decreases significantly with increasing the distance from the front surface of the nozzle cup. This decrease is about *52*% at the distance of *4 mm* from the nozzle surface, but then the velocity stabilizes and the decrease is only *59*% at the distance of *10 mm* in comparison to the first magnitude.

Four design changes were analyzed to obtain a paint stream as narrow as possible. All considered designs show significant improvement in the distribution of air pressure and velocity but most optimal solution has six small holes around the hole of the nozzle cup and a small circular rim covering all holes (experiment 4). A decrease in pressure is only *3*% in the axial direction and *4*% in the radial direction at the distance of *2 mm* from the front surface of the nuzzle cup. Distribution of air velocity is uneven: about *52*% at the distance of *4 mm* from the front surfaces of the nozzle cup and *63*% at the distance of *10 mm* but the velocity magnitude is significantly less than in the standard nozzle cup, by *35*% … *45*%.

Nomenclature

c_l – speed of sound in the liquid phase
c_g – speed of sound in the gas phase
P – static pressure at a point in the flow where the velocity is V
P_0 – stagnation pressure
U_s – velocity of sound of the gas-liquid flow
α – volumetric fraction occupied by the gas
ρ, ρ_g – gas density
ρ_l – liquid density

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