

Research Article

Numerical Evaluation of the Influence of the Outlet Nozzle Diameter of a Piezoelectric Gas Injector on Its Flow Properties

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The paper presents the results of flow analyses of a piezoelectric gas injector with pulse action. The conceptual solution, due to the use of a piezoelectric actuator, is characterized by shorter opening and closing times. This promotes the precision of fuel dosing. It also meets current trends in environmental protection. The innovation in the injector under study is the use of a beam actuator comprising three layers, two active and one passive. The electromechanical characteristics of the converter were determined based on the method in which the actuator is treated as a bent beam with a locally implemented piezoelectric segment. Based on such assumptions, the deformation shape of the actuator and, as a result, the opening degree of the injector valve were determined. Flow studies were carried out using Computational Fluid Dynamics (CFD) in the ANSYS Fluent environment. The RANS (Reynolds-averaged Navier–Stokes) approach and the $k-\omega$ SST turbulence model were adopted. The solution was sought based on the standard SIMPLE scheme and polyhedral mesh. It allowed the determination of the flow characteristics of the analysed injector, with variable valve lift and outlet nozzle diameter.

1. Introduction

Further use of fossil fuels (petrol and diesel) significantly affects the volume of oil reserves in the ground. Therefore, it is justified to work on the use of alternative fuels as well as diversification of fuel production and its components. The most widely used alternative fuels in transport are liquefied petroleum gas (LPG) [1] and compressed natural gas (CNG) [2]. These fuels, depending on the complexity of the classical engine supply system, are supplied using new-build fuel systems, which in most cases are universal [3], although dedicated installations for the type and model of the engine are required for the latest designs [4]. LPG and CNG are also used to power off-highway machinery [5, 6]. There is also growing interest in hydrogen (H₂) power in transport [7].

Some hopes are also placed on further research into the use of vegetable oil, where pure vegetable oil (PVO) [8] and fatty acid methyl esters biodiesel (FAME) [9] can be distinguished. In the case of the recently presented fuels, the

costs incurred for ancillary charges like excise tax are decisive, as the production process itself has already been mastered and implemented. In energy applications where the aim is to generate electricity (generators), biogas is largely used [10]. An important aspect of biogas, just like with vegetable oil, is the purification process. This process generates additional costs, but the use of fuel without adequate purification compromises the combustion process [11], which can eventually lead to damage to the power unit.

Piezoelectric transducers have found widespread use in recent years in the automotive industry, where great emphasis is being placed on reducing CO₂ emissions. In transport vehicles, this can be achieved, among other things, by reducing vehicle weight, engine displacement, turbocharging, and the use of lower carbon fuels. In gas supply systems based on LPG in the vapour phase or CNG, sequential injection systems are most commonly used. Their integral parts are low-pressure gas injectors whose task is to deliver a specific dose of fuel to the combustion chamber at

the right time. The existing design solutions of injectors in fuel metering systems usually use electromagnetic circuits that induce movement of the valve's working element, such as a piston, disc, diaphragm, or flap.

The aim of the study is to determine numerically the influence of the outlet nozzle diameter of the conceptual piezoelectric gas injector on its flow properties. The knowledge of such characteristics is essential for the appropriate configuration of the fuel system. It also becomes useful in engine energy calculations. As a result, the appropriate configuration of the fuel system favours the reduction of exhaust gas toxicity. The introduction should be succinct, with no subheadings. Limited figures may be included only if they are truly introductory and contain no new results.

2. Materials and Methods

2.1. Object of the Analysis. The piezoelectric injector analysed (Figure 1) is a conceptual solution developed on the basis of a work of Szpica et al. [12]. A piezoelectric converter is fixed in the rear part of the injector, between upper and bottom casings. This type of fixing identifies the converter with a beam element fixed on one side.

The injector housings are sealed between each other and connected using a screw connector. In the state without electrical supply, the gas flowing through the inlet fills the injector internally. The appearance of electric power in the electrical connection results in the deformation of the piezoelectric converter and the opening of the valve. Gas flows in the direction of the outlet. At this stage, the gas flow can be adjusted by the degree of opening of the valve and the inner diameter of the nozzle. The degree of opening of the valve results from the limiter setting, which can be changed. The limiter setting is determined for the maximum diameter of the injector outlet (without nozzle). Then, in order to adjust the injector output to the engine demand, it is necessary to use a nozzle with an appropriate internal diameter. This type of injector belongs to the low-pressure gas-phase injector group. Its characteristic feature in relation to solutions with the electromagnetic drive is, in addition to the speed of operation, the fact that the piezoelectric converter works not only during the opening but also during the closing of the injector valve.

2.2. Calculation Methods. The electromechanical characteristic of the actuator was determined based on the method proposed in works [13, 14]. In this method, the actuator is treated as a bending beam, in which the so-called piezoelectric segment PS is locally implemented (Figure 2).

PS consists of three components—two piezoelectric (active) layers and one passive layer. The heights and thicknesses of the individual layers are identical, and their values are t and b , respectively. In the transducer (Figure 2), the left side is fixed while the right side can move freely. In the actuator, two characteristic ranges can be determined, related to the change of load and stiffness. In the range $0 < x < x_1$, there is a PS (generating an electrical load Me ,

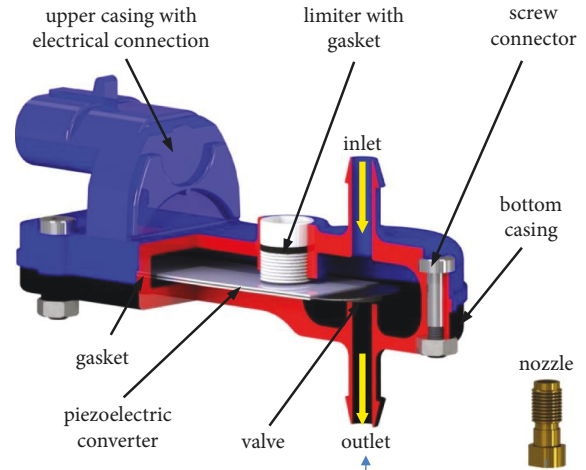


FIGURE 1: The CAD model of the piezoelectric gas injector.

caused by an applied voltage v), with a flexural stiffness $E_p J_o$. The second interval is a homogeneous beam with stiffness $E_b J_b$. In the latter, the force F due to the gas-intake manifold pressure difference is applied (at a distance of x_2 from the transducer fixed side). The force F causes reactions in the fixed support, which are, respectively: $R_y = F$; $R_x = 0$; $M_F = F x_2$.

In order to simplify the mathematical model of the actuator, the following assumptions were made:

- (i) Component bending occurs according to Euler's hypothesis, and the radii of curvature of the deformed components are equal
- (ii) In the plane of connection of the components, there is no intermediate layer and there is no slipping
- (iii) There is a transverse piezoelectric effect 1–3 in the piezoelectric layer, causing pure bending

Taking into account the above assumptions, the differential equation for actuator deflection was written as follows:

$$\frac{\partial^2 y}{\partial x^2} = \frac{M(x)}{E_b J_b} + Me \gamma (H[x] - H[x - x_i]), \quad (1)$$

where $H[x - x_i]$ —Heaviside's function [15], $\gamma = (E_b J_b (Me + M(x)) - E_p J_o M(x) / E_b J_b E_p J_o Me)$ —a coefficient to take account of the change in stiffness at the location of the PS, E_p , E_b —Young's moduli of piezoelectric and passive elements, $J_b = (bt^3/12)$ —moment of inertia of the beam element, $J_o = (b(E_b t^3 + 26E_p t^3)/12 E_p)$ —moment of inertia of PS segment [14], $M(x) = -Fx_2 + Fx - F(x - x_2)H[x - x_2]$ —bending moment due to mechanical load, $Me = (vd_{31}E_p t(E_b + 26E_p)b / E_b - 22E_p)$ —bending moment due to electric load [14], and d_{31} —piezoelectric constant.

After double integration of formula (1), taking into account the following boundary conditions: $(\partial y / \partial x)(0) = 0$, $y(0) = 0$, a close form solution describing the electro-mechanical characteristics of the transducer has been obtained as the following formula:

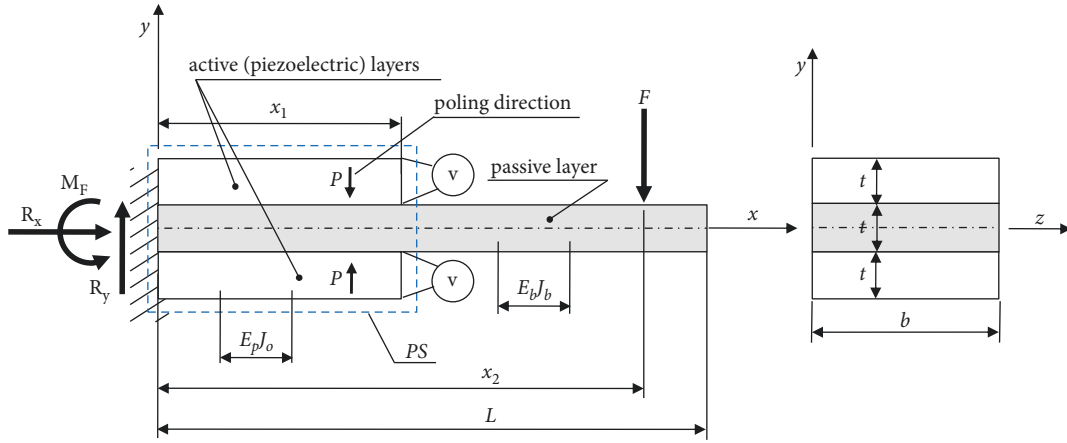


FIGURE 2: Piezoelectric actuator with PS segment implemented from the fixed side.

$$v(x) = A_1 v + B_1 F, \quad (2)$$

where $A_1 = (6d_{31}E_p(x^2H[x] - (x-x_1)^2H[x-x_1])/t^2(E_b + 22E_p))$, $B_1 = -(2/b\beta E_b t^3)$

$$\left(\begin{array}{l} (x-x_2)^3(26E_p(H[x-x_1, x-x_2] - H[x, x-x_2]) + \beta H[x-x_2]) + \\ 26E_p x^2 H[x](x-3x_2) - 26E_p(x-x_1)^2 H[x-x_1](x+2x_1-3x_2) \\ -\beta x^2(x-3x_2) \end{array} \right),$$

and $\beta = E_b + 26E_p$.

In the electromechanical tests, the geometrical dimensions of the piezoelectric converter were assumed to be constant and were, respectively: passive layer length: $L = 46$ mm, passive/active layers width: $b = 15$ mm, active layer length: $x_1 = 41$ mm, layers thickness: $t = 0.25$ mm, and coordinate of the point at which force F is applied: $x_2 = 44.5$ mm.

As for the materials used for the individual transducer layers, it was assumed that the active component is made of PTZ5H soft piezoelectric ceramics ($E_p = 62.1$ GPa and $d_{31} = -320$ pC/N, [16]), whereas the passive layer is silicon oxide ($E_b = 73$ GPa [17]). The use of such materials guarantees the lowest energy consumption of the fuel dosing process [18]. Using the obtained analytical solution formula (2), the electromechanical characteristics of the transducer

were developed for different values of the effective valve opening h_{eff} (Figure 3(b)).

In order to obtain characteristics with the desired h_{eff} parameter, we determined at a distance x_2 from the fixed end of the transducer (Figure 2), and the value of the applied voltage v and the force F had to be changed in formula (2). The applied electric voltages v for different h_{eff} levels are shown in Table 1.

Force F , generated by the pressure difference between gas and intake manifold, occurs only in the closed state of the injector (at the moment of valve unsealing $h_{\text{eff}} \leq 0.01$ mm [19]). Thus, at the assumed opening levels of the effective valve, it was always assumed that $F = 0$ N. The obtained electromechanical characteristics (Figure 4) were used in flow tests to accurately reproduce the shape of the transducer.

In the numerical analysis of the flow, the Ansys Fluent software based on the RANS (Reynolds-averaged Navier-Stokes) approach was used [20]. The Navier-Stokes equations were supplemented in this case with a Reynolds distribution model. Finally, the continuity and momentum formulas (3) and (4) were obtained for incompressible flow:

$$\frac{\partial u_i}{\partial x_i} = 0, \quad (3)$$

$$\rho \left(\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left(u \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right) + \frac{\partial}{\partial x_i} (-\rho \overline{u'_i u'_j}), \quad (4)$$

where u_i and u_j —mean velocities, u'_i and u'_j —the fluctuating part of the velocity, p —dynamic pressure, δ_{ij} —Kronecker delta, and ρ —fluid density.

The member $(-\rho \overline{u'_i u'_j})$ of formula (4) represents the Reynolds stress. Due to the openness of the equations, it was necessary to use the Boussinesq approximation formula:

$$-\rho \overline{u'_i u'_j} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left(\rho k + \mu_t \frac{\partial u_k}{\partial x_k} \right) \delta_{ij}, \quad (5)$$

where μ_t —turbulent viscosity and k —kinetic energy of turbulence.

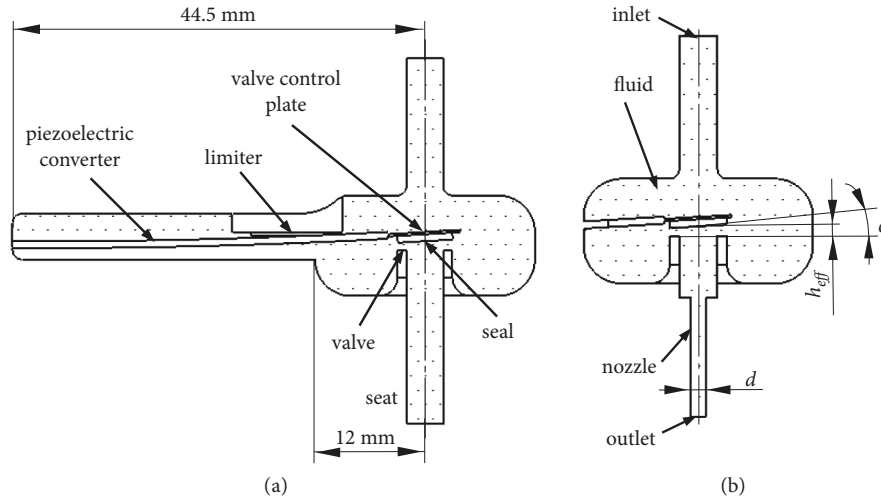


FIGURE 3: The piezoelectric gas injector. (a) The accurate fluid model; (b) the simplified fluid model. Note: h_{eff} , opening range; d , outlet nozzle outlet diameter; α , control plate rotate angle.

TABLE 1: Electrical voltage values required to achieve the assumed effective opening of the valve.

h_{eff} , mm	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
v , V	19.17	38.33	57.5	76.67	95.83	115	134.17	153.34	172.5	191.67

The study uses the k - ω SST turbulence model combining the k - ε and k - ω models [21], for which the basic transport equations are of the form formulas as follows:

$$\rho \left(\frac{\partial}{\partial t} k + \frac{\partial}{\partial x_i} (k u_i) \right) = \frac{\partial}{\partial x_j} \left(\Gamma_k \frac{\partial k}{\partial x_j} \right) + \widetilde{G}_k - Y_k, \quad (6)$$

$$\rho \left(\frac{\partial}{\partial t} \omega + \frac{\partial}{\partial x_i} (\omega u_i) \right) = \frac{\partial}{\partial x_j} \left(\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega, \quad (7)$$

where $\widetilde{G}_k$ and G_ω —production terms of k and ω , Y_k and Y_ω —dissipation terms of k and ω , Γ_k and Γ_ω —effective diffusivity of k and ω , and D_ω —cross-diffusion term.

For the numerical analysis, a solid model of the fluid inside the injector was created in Ansys Geometry (Figure 3(a)). Ultimately, the model was restricted to the part located in the area of the injector valve (Figure 3(b)), omitting remote parts, which should not fundamentally affect the flow process. The opening degree of the injector valve was determined as the value of h_{eff} in the axis of the outlet hole. This corresponded to the α angle formed between the valve seat and the seal fitted to the part of the piezoelectric converter located outside the converter's operating area. The value of the α angle was determined on the basis of the characteristics shown in Figure 4.

Table 2 shows the valve swing angles determined from Figure 4. A linear approximation of a 12 mm section from

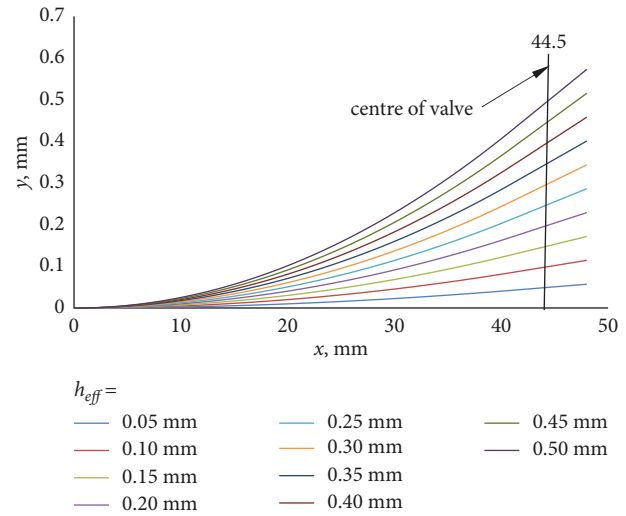


FIGURE 4: Electromechanical characteristics of the transducer obtained for different values of the effective valve opening h_{eff} .

the valve centre was used (Figure 3). It was assumed that the valve is always on axis because the swing angles are small.

In further steps, a tetrahedral finite element mesh was created in Ansys mesh for each case analysed. The main parameters adopted were as follows: normal curvature angle 10 deg, min size 8×10^{-4} mm, max face size 0.2 mm, max element size 0.4 mm and growth rate 1.2, and inflation with

TABLE 2: Values of the valve angle depending on the degree of valve opening.

h_{eff} , mm	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
α , deg	0.11	0.22	0.34	0.45	0.57	0.68	0.80	0.91	1.02	1.14

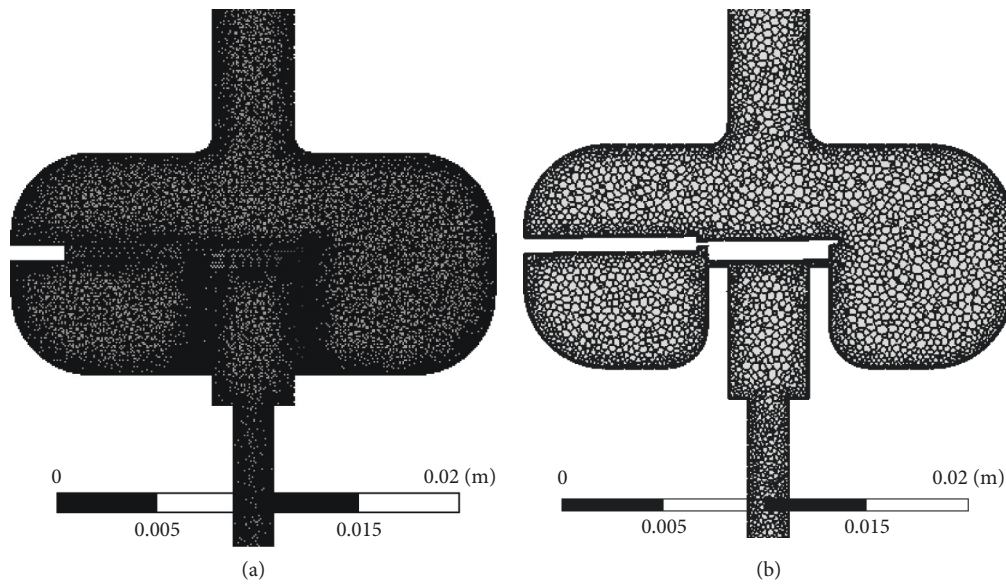


FIGURE 5: Example next steps in fluid model preparation at $d = 2$ mm, $h_{\text{eff}} = 0.3$ mm, and $\alpha = 0.68$ deg. (a) Tetrahedral mesh in fluid; (b) polyhedral mesh in the longitudinal plane.

following parameters: max layers 4, growth rate 1.2, and no-slip variant on the walls. Comparing the obtained values of the mesh quality parameters such as skewness oscillating around 0.21 and orthogonal quality close to 0.88 with the declarations contained in [22], they should be considered satisfactory. Prior to Fluent calculations, the tetrahedral mesh was transformed into a polyhedral mesh, which essentially reduces calculation time with acceptable results [23–26].

A standard SIMPLE scheme was used in the calculations with control residuals specified at 1×10^{-4} . The discretization of the continuity and momentum equations was carried out using a pressure-based solver. Air was used as the fluid because the low-pressure gas-phase injectors are experimentally studied in this way.

3. Results and Discussion

The analyses took into account the following (according to Figure 3(a)):

- (i) Variation of the valve opening degree defined as h in the range (0.05...0.5) mm in 0.05 mm steps
- (ii) Range of diameters of the outlet nozzle opening d in the range (1.5...3.0) mm in 0.5 mm steps and without nozzle (4 mm)
- (iii) Degree of opening h and the diameter d were constant in the given calculation variant

The boundary conditions were defined as

- (i) Injector inlet pressure as a relative of $1 \text{ e } 5$ Pa
- (ii) Pressure at the injector outlet as a relative of 0 Pa

The thickening of the tetrahedral mesh in the wall layer and in the vicinity of the injector valve, as shown in Figure 5(a), is reflected in the polyhedral mesh (Figure 5(b)).

The deflection of the valve plate results in a higher concentration of the stream flowing through the valve gap in the part without the piezoelectric converter (A in Figure 6(a)). The significant influence of the injector nozzle on the flow velocity and jet shape (B in Figure 6(b)), which determines the flow properties, becomes visible.

For individual variants, the flow value at the given boundary and initial conditions was read from the injector outlet surface as volumetric flow rate Q and converted to L/min. As a result of the performed calculations, the flow characteristic presented in Figure 7 was obtained. It shows a gradual increase in Q value as the injector opening degree increases. In the case of the smallest of the analysed nozzle diameters, $d = 1.5$ mm, the maximum Q value stabilises at $h_{\text{eff}} = 0.2$ mm, while at $d = 2$ mm, at about $h_{\text{eff}} = 0.35$ mm. In other cases, it increases as the degree of opening increases, although above $h_{\text{eff}} = 0.4$ mm, the gradient is smaller. Also shown is the difference in the values obtained from those presented in [18], where the plate seal was positioned parallel to the valve seat.

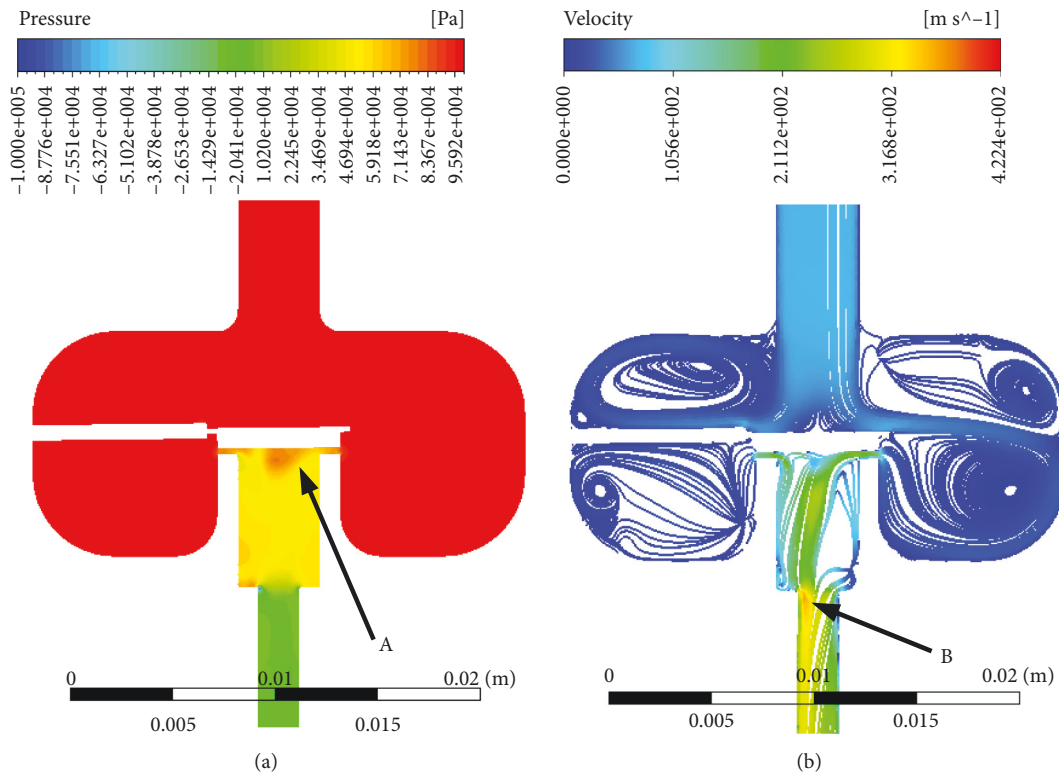


FIGURE 6: Example results at $d = 2$ mm, $h_{\text{eff}} = 0.3$ mm, and $\alpha = 0.68$ deg. (a) Pressure; (b) velocity. View in the longitudinal plane.

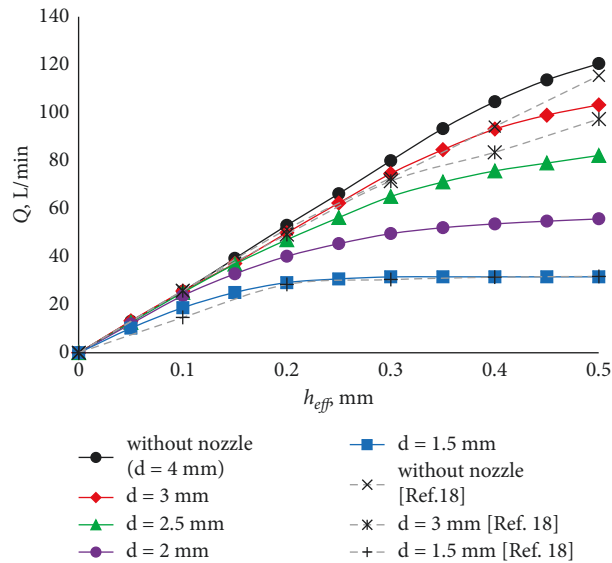


FIGURE 7: Flow characteristics of the injector.

Additionally, the flow characteristics are presented in the “Tanaka” coordinate axes, i.e., as a function of $(Q/Q_{\text{max}}) = f(h_{\text{eff}}/d)$ [27]. Flow characteristics of the injector according to “Tanaka” is given in Figure 8. In this way, the flow capacity

of the injector is inferred with respect to the maximum flow value obtained from the calculations at the maximum degree of opening and no outlet nozzle. The nozzle grading adopted in the calculations yielded a flow variation of 0.2 (Q/Q_{max}).

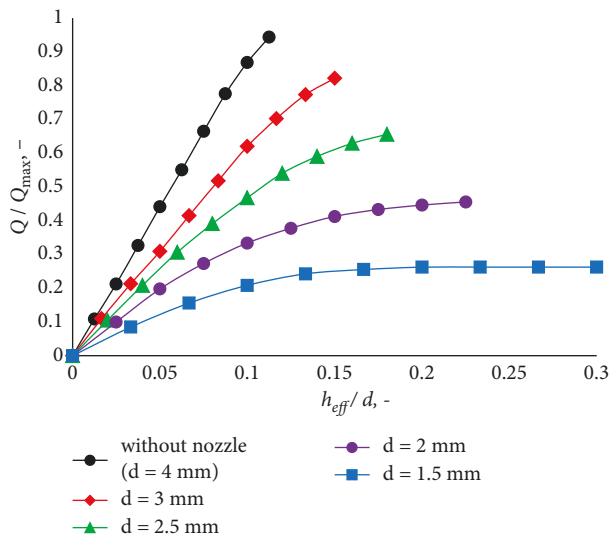


FIGURE 8: Flow characteristics of the injector according to "Tanaka."

4. Conclusions

The numerical calculations presented in the paper allowed the flow properties of the piezoelectric gas injector to be assessed. The methodology adopted for creating the fluid model, mesh, and the method of solving fluid mechanics problems using ANSYS software allowed, apart from a quantitative evaluation, also a qualitative assessment. The flow characteristics obtained as a result of the calculations indicated, apart from the maximum values of the volumetric flow rate, also the limits of the injector valve opening degree, at which the values determining the flow rate do not change or the gradient of changes is smaller. By taking the flow characteristic in the form of the "Tanaka" characteristic, the percentage difference of the volumetric flow rate corresponding to the jump in the opening degree of the injector valve was determined. On this basis, in addition to adjusting the nozzle diameter, a maximum valve opening degree can be suggested. Changing the diameter of the injector nozzle requires its replacement while varying the maximum opening degree is easier to implement. This can be done by a mechatronic system controlling the position of the maximum opening degree limiter. All measures aimed at increasing the precision of fuel dosage are conducive to reducing exhaust gas toxicity.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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