

Article

Numerical Simulation of the Performance of a Combustion-Driven SparkJet Actuator with Laval Outlet Configuration

Hai Chen ^{*}, Hongyan Zuo  and Guohai Jia 

College of Mechanical Engineering, Hunan Institute of Engineering, Xiangtan 411104, China; zuohongyan18@126.com (H.Z.); jiaguohai@hnie.edu.cn (G.J.)

* Correspondence: chfair@163.com; Tel.: +86-0731-58688686 (ext. 411104)

Abstract: To increase the jet momentum and improve the environmental adaptability, a combustion-driven SparkJet actuator with a Laval-configured outlet is proposed to improve the performance of the actuator. Numerical simulation results show that, compared to straight outlet combustion-driven actuators with outlet diameters of 2 mm and 2.8 mm, the maximum jet velocity of the Laval-configured actuator increases by approximately 100 m/s and 350 m/s, separately. while the peak times decrease by about 50% and 12%, respectively. The work frequency of the Laval-structured combustion-driven actuator is 1333 Hz, which is higher than the 1176 Hz of the straight-tube-structured combustion-driven actuator with an outlet diameter of 2 mm. The Laval configuration effectively improves the working performance of the actuator. As the equivalence ratio increases from 0.6 to 1, the actuator's jet velocity increases by approximately 65 m/s and 311 m/s, respectively, and its maximum combustion temperature is raised from 2700 K to 3000 K. The saturation work frequency is nearly the same. The pressure and jet mass flow rate in the actuator drop as the atmospheric pressure declines, while the combustion-driven actuator still exhibits high working performance when the atmospheric pressure is low. The maximum outlet velocity, Mach number, pressure, and temperature increase by about 20%, 13%, 25%, and 6%, while the peak time increases by about 40% as the ignition position moves from the middle position to a 2.8 mm displacement toward the outlet.

Keywords: actuator; combustion-driven actuator; Laval-shaped; Laval configuration; SparkJet; plasma actuator



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1. Introduction

Considerable effort has recently been devoted to the development of actuation technologies for flow control [1–4]. Effective manipulation of the flow field can improve the aerodynamic performance of vehicle systems, such as enhancing the range, payload, and maneuverability. Active flow control actuators can be categorized as plasma, mechanical, and fluidic [5]. Combustion-driven SparkJet and pulsed-jet actuators are fluidic, while spark discharge, DC, and dielectric-barrier discharge actuators are plasma actuators. The plasma synthetic jet actuator is a promising and novel active flow control technology due to its high operating frequency, fast response, and simple structure.

The Applied Physics Laboratory of Johns Hopkins University first proposed the plasma actuator in 2003 [6]. Narayanaswamy et al. [7] experimentally investigated the performance of a pulsed-plasma jet actuator and found that it induces high-speed jet ejection and has great promise in supersonic flow control. Huang et al. [8] studied the transient interaction between the plasma synthetic jet actuator with two-electrode and super-sonic

compression ramp flow fields. Li and Zhang et al. [9] designed an actuator that combines the SparkJet discharge and a piezoelectric oscillator to raise the pressure in the actuator cavity and improve the work frequency through the adjustment of the cavity volume through a piezoelectric oscillator. Liu and Lin et al. [10] designed an aerated plasma synthetic jet actuator with a one-way valve to reduce the cavity refill time. Researchers at the Air Force Engineering University [11–13] studied the influence of outlet configuration, capacitor energy, discharge frequency, electrode position, actuator structure, and other parameters using numerical calculation, PIV, shadowgraphs, and other scientific methods. Hardy et al. [14] raised the jet velocity of the actuator to 250 m/s and the operating frequency to 500 Hz by improving heat dissipation. Kim et al. [15] numerically investigated the correlation between the actuator performance and the pressure waves inside the actuator. Zheng et al. [16] designed a dual-cavity plasma synthetic jet actuator and numerically and experimentally investigated its static performance. The results indicate that the newly configured actuator has two saturation frequencies and that the new configuration enhances the jet intensity and increases the saturation frequency at high frequencies. Wu et al. [17] researched the effects of the pulse rising time, repetition frequency, and amplitude of the voltage on the jet. Zhang et al. [18] numerically investigated the inner performance of the plasma synthetic jet actuator and found that the base frequencies decreased with the increases in the inner height and width of the actuator. Moreover, the peak velocity of the jet increased with an increase in the inner height or width of the actuator. Nguyen et al. [19] tested the performance of a plasma jet actuator with dual-spark and single-spark pulses and found that the jet velocity increased with the increase in the time delay between pulses. To achieve a complete aerothermodynamic description of an actuator, Laurendeau et al. [20] combined an electric circuit model with the Euler solver and incorporated these source terms into large eddy simulations of the actuator. They found that their proposed methodology could predict the temporal evolution of the jet's front well. Wang et al. [21,22] designed a new configuration actuator by adding a high-voltage trigger electrode (Figure 1) to the two-electrode actuator. This three-electrode actuator has advantages, such as an increased cavity volume, increased discharge energy, and reduced breakdown voltage. They experimentally investigated the performance of the new actuator and found that the peak jet velocity of the actuator was more than 500 m/s [23]. Zhou et al. [24] numerically researched the property of a two-electrode plasma synthetic jet actuator and found that the numerical models can effectively predict experimental results. In addition, the effect of outlet shapes on the jet flow was discussed.

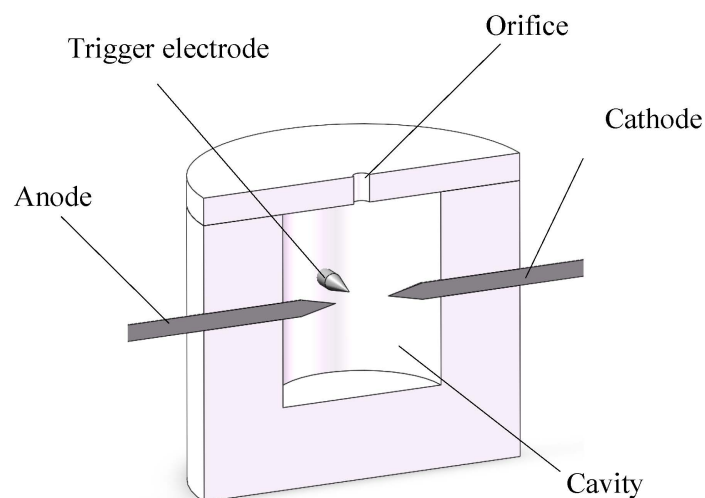


Figure 1. Three-electrode plasma synthetic jet actuator.

Using small-scale combustion technology [25–29], Crittenden [30] designed a new actuator that creates a high-velocity jet through combustion, as shown in Figure 2. The gaseous fuel/oxidizer blend with a low-volume flow rate fills the actuator and is ignited by a spark or other ignition source. The combustion-driven actuator yields a high-pressure and high momentum burst jet. The cycle resumes with a fresh fuel/air blend entering the actuator and displacing the remaining gas. Srinivasan [31], Rajendar [32], and Crittenden [33] investigated the influences of the exhaust orifice diameter, chamber surface area, fuel type, mixture ratio, chamber volume, and ignition source on small-scale combustion with numerical simulations and experiments. Crittenden [34] showed that the work performance of the actuator is not affected by ice, rain, vibration, or particulates in the environment. Jee et al. [35] numerically and experimentally researched this combustion-driven actuator and found that it can effectively improve the aerodynamic lift performance. However, the combustion-driven actuator jet velocity needs further improvement. Chen et al. [36] proposed a new type of actuator combining a combustion-driven actuator and a plasma synthetic jet actuator, as shown in Figure 3. Numerical simulation shows that the combustion-driven SparkJet actuator has an increased momentum jet and mass rate compared with the SparkJet actuator, while the saturation work frequency is almost the same as that of the SparkJet actuator. The proposed new type of actuator combines the advantages of SparkJet and combustion-driven actuators, thereby improving the jet velocity, mass flow rate, and environmental adaptability.

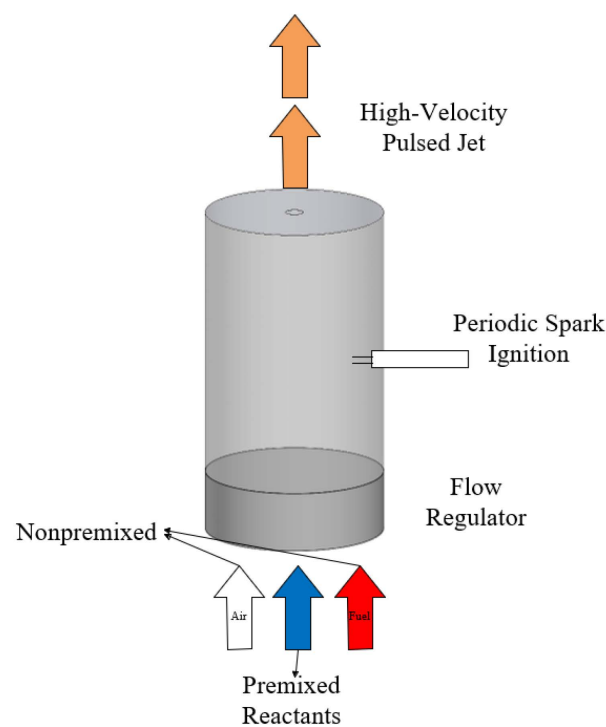


Figure 2. Schematic of a combustion-driven actuator.

To further improve the combustion-driven SparkJet actuator's working property, the Laval outlet configuration of the combustion-driven SparkJet actuator is designed, as illustrated in Figure 4. The working process of the combustion-driven SparkJet actuator is divided into the following three stages: (1) the mixture enters the cavity through the inlet upon opening of the valve; (2) the mixture is ignited by a spark, generated by two or three electrodes, and begins to burn, generating a high-speed jet from the exhaust orifices; and (3) the entire combustion process completes, and the cycle resumes upon opening the valve again. Fresh blends enter the cavity and displace the residual burned gas, and the valve

is closed again after the cavity is filled. The working performance of combustion-driven SparkJet actuators with Laval and straight-shaped exhaust orifice structures is numerically compared. Also, the effects of the equivalent ratio, air pressure, and ignition position on the performance of the new configuration actuator are investigated.

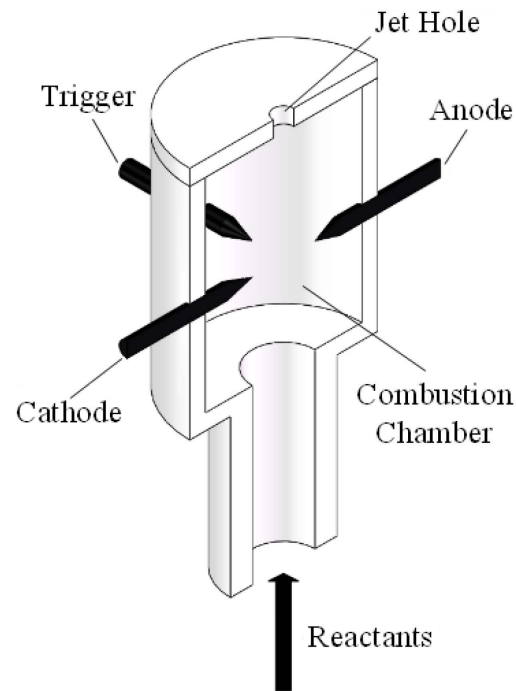


Figure 3. Schematic of the combustion-driven SparkJet actuator [36].

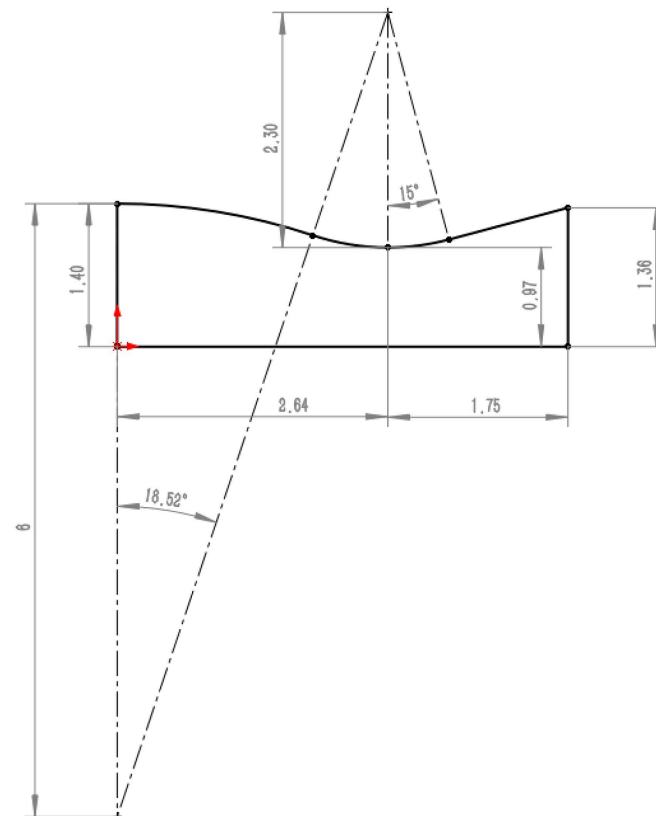


Figure 4. Laval outlet configuration parameters of the actuator.

2. Mathematical–Physical Model

2.1. Computational Model

The governing equations of the gas phase, including the continuity, momentum, chemical component transport, and the energy conservation equations, were solved using the commercial software ANSYS Fluent 15.

The solution methods and flux type were implicit formulation and RoeFDS, respectively. A second-order upwind method was adopted for the spatial discretization, and a second-order implicit method was applied for the unsteady formulation [18]. The time step was 2×10^{-8} s, each with 60 maximum iterations. The SST K- ω turbulent model was used for the viscous model during the simulation because of the high computational accuracy for separation and transonic shock wave. The specific heat and density of the blends were calculated using the mixing law and the compressible ideal gas law, respectively. The viscosity and thermal conductivity of the blend were calculated using kinetic theory and the mass-weighted mixing law. Kinetic theory was also employed to calculate the blend mass diffusivity. A piecewise polynomial fitting method was employed to compute the specific heat of each species. The pressure outlet conditions were specified as a fixed pressure of 1.013×10^5 Pa at the grid outlet, natural convection heat transfer coefficient of $10 \text{ W/m}^2/\text{K}$, and wall temperature of 300 K [5,37,38].

A detailed reaction mechanism involving nine species and 19 reversible reactions [39] was employed for modeling the combustion of the H_2/air blend. The eddy dissipation conception model [24] was adopted to solve the turbulence–chemistry interaction because it includes the turbulence’s influence on the reaction rate and incorporates the influence of finite rate kinetics on the computing costs [40]. The energy deposition of the discharge was simulated by adding a source term in the energy equation [38]. The discharge zone was defined as a separate region in the calculation, as shown in Figure 5. The energy source term was added into the discharge zone, and the energy was assumed to be uniformly distributed over the discharge duration and discharge region. The discharge duration and source term were $16 \mu\text{s}$ and $7 \times 10^{10} \text{ W/m}^3$, respectively. The geometry was modeled as a 2D axisymmetric model because of the axial symmetry of the actuator [18]. The Laval nozzle was designed based on a rocket engine tail nozzle with a design Mach number of 1.0 [41].

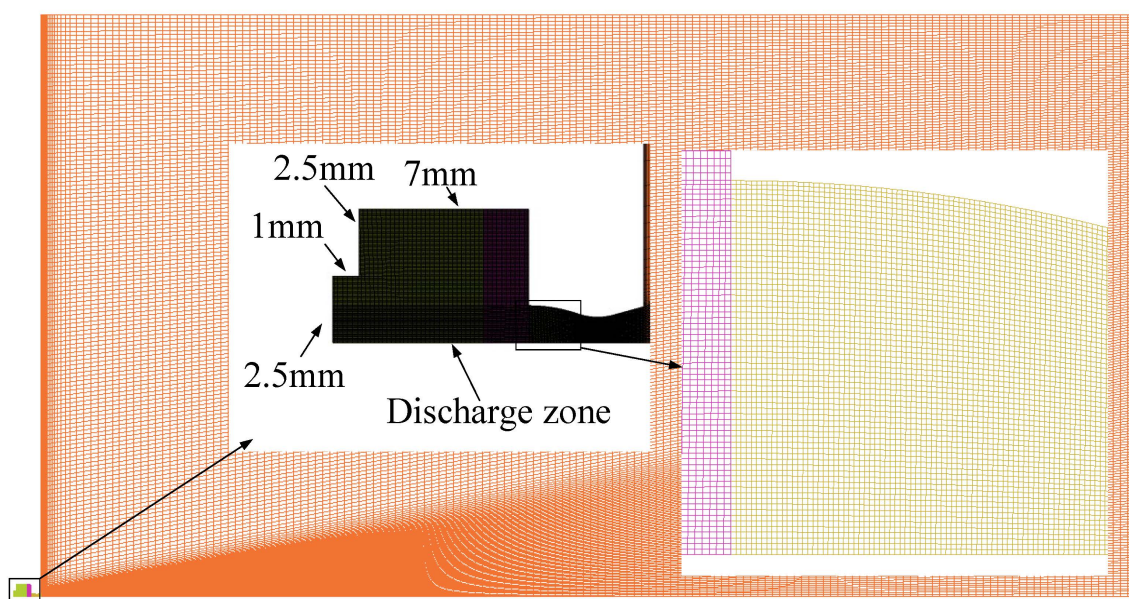


Figure 5. Computational domain and mesh of the actuator.

The dimensions of the Laval outlet configuration are shown in Figure 4. The minimum and maximum outlet diameters of the Laval configuration actuator are 2 and 2.8 mm, respectively. The computational domain includes the following three parts: actuator cavity, jet outlet, and external flow field. The grid model and actuator dimensions are shown in Figure 5. The structured grids of the computational domain were established using the commercial software ICEM 15, and the mesh near the wall was refined. In this study, the following are considered: the blends in the actuator have been premixed and filled, the valve has been closed, and the arc discharge is struck in the actuator.

2.2. Mesh Independency Test and Model Validation

The numerical results were compared with the experimental data [25] to ensure the accuracy of the numerical combustion simulations. The boundary conditions and combustion model parameters of the numerical simulations are consistent with those in the literature. Table 1 shows that the numerical results are consistent with the experimental data. Therefore, the numerical model is considered reliable.

Table 1. Comparison between the experimental data and numerical results under adiabatic condition [36].

	Experimental Results	Numerical Results
Temperature (K)	2382	2392
Mass fraction of H ₂ O	0.323	0.317
Mass fraction of O ₂	0.005	0.007
Mass fraction of H ₂	0.015	0.018
Mass fraction of OH	0.007	0.009
Mass fraction of H	0.002	0.003
Mass fraction of O	0.001	0.0012
Mass fraction of NO	0.003	-
Mass fraction of N ₂	0.644	0.63

The numerical results and experimental data [18] of the SparkJet actuator were compared under the same conditions. Figure 6 shows that the numerical and experimental results are consistent with the front jet and precursor shock wave. These data indicate the actuator computational model's ability to capture fluid characteristics accurately.

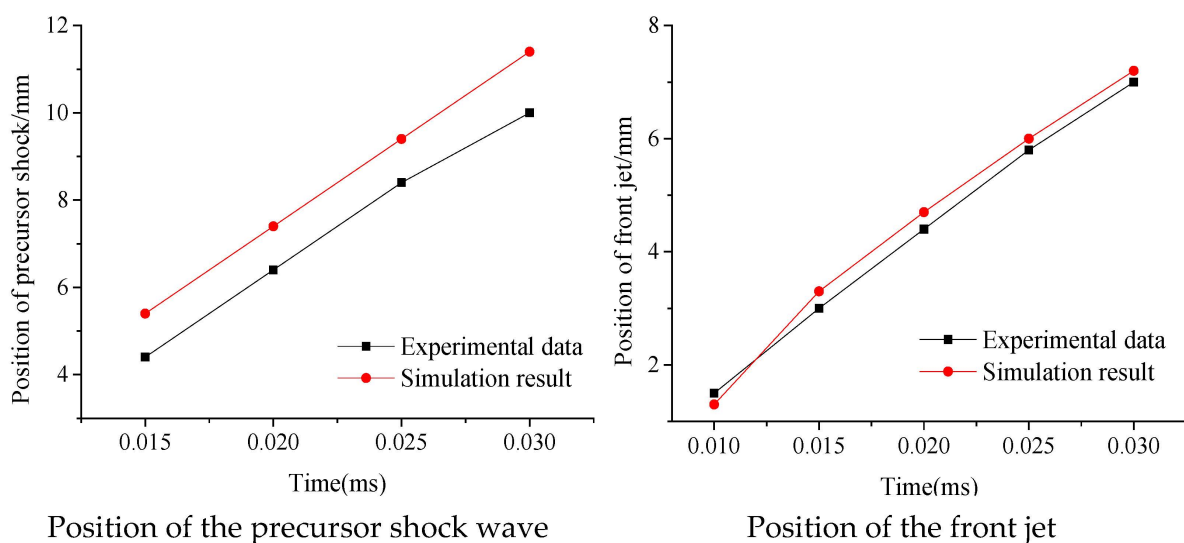


Figure 6. Position of the precursor shock wave and front jet [36].

Grid independence was verified for four mesh quantities using a combustion-driven SparkJet actuator 2D model. The equivalence ratio is 1. Figure 7 shows that the difference in the outlet velocities was small as the mesh quantities increased from 103,928 to 135,278. Hence, the mesh quantity was set to 103,928 for the calculation, mesh refinement was applied near the boundary layers, and the height of the first layer grid was 0.017 mm.

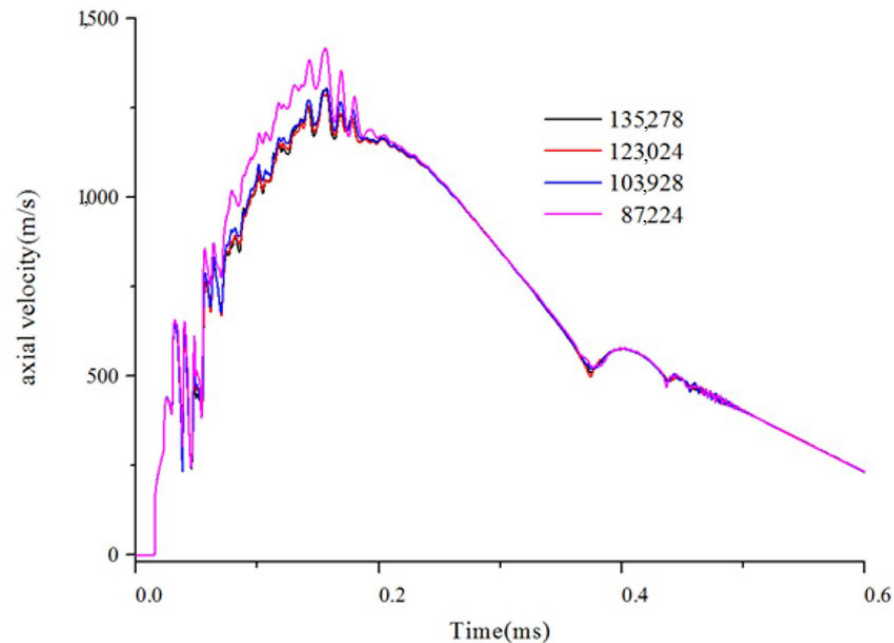


Figure 7. Comparison of the actuator outlet velocity with different mesh quantities.

3. Results and Discussion

3.1. Influence of Actuator Outlet Configuration

The effects of the Laval and straight-shaped outlet structures on the working property of the actuators can be investigated using the parameters in Table 2. The length and diameter of the actuator inlet are 1 and 2.5 mm, respectively. The exhaust orifice length is 4.4 mm. The default hydrogen-to-air equivalent ratio is 1, for which the hydrogen mass fraction is 2.795% and the oxygen mass fraction is 22.36%. The default external pressure is 101,325 Pa.

Table 2. Parameters of the actuator.

Cases	Actuator Type	Equivalent Ratio	Atmosphere Pressure
1	Laval-shaped outlet, combustion-driven SparkJet actuator	1	1 atm
2	Straight-shaped outlet, combustion-driven SparkJet actuator with an outlet diameter equal to 2 mm	1	1 atm
3	Straight-shaped outlet, combustion-driven SparkJet actuator with an outlet diameter equal to 2.8 mm	1	1 atm
4	Laval-shaped outlet, combustion-driven SparkJet actuator	0.8	1 atm
5	Laval-shaped outlet, combustion-driven SparkJet actuator	0.6	1 atm
6	Laval-shaped outlet, combustion-driven SparkJet actuator	1	0.8 atm
7	Laval-shaped outlet, combustion-driven SparkJet actuator	1	0.6 atm
8	Laval-shaped outlet, SparkJet actuator	-	1 atm
9	Laval-shaped outlet, SparkJet actuator	-	0.8 atm
10	Laval-shaped outlet, SparkJet actuator	-	0.6 atm

Wang L. et al. [40] defined the maximum working frequency that can completely refill the actuator cavity as the saturation work frequency in order to optimize the actuator's working performance and ensure that it contains sufficient gas. When the discharge frequency exceeds the saturation work frequency, it can cause a misfire due to the actuator cavity not being fully backfilled. Moreover, in order to evaluate the actuator's quick response ability, the time when the jet momentum of the actuator reaches its maximum value is defined as the peak time, t_{peak} , of the jet. A shorter peak time means a faster response of the actuator.

The jet momentum can be defined as follows:

$$P_{jet} = \int_0^{\tau} \dot{m} u_j dt \quad (1)$$

where u_j is the jet instantaneous velocity, $\dot{m}$ is the jet flow rate, and τ is the jet duration.

Figure 8 shows that the velocity magnitude at the orifice presents a remarkable oscillatory behavior. The maximum and minimum diameters of the Laval configuration are 2.8 and 2 mm, respectively. The maximum outlet velocity of the combustion-driven Laval configuration is approximately 1324 m/s, the maximum outlet Mach number is 1.53, and peak time is about 0.15 ms. The combustion drivers with diameters of 2 and 2.8 mm have maximum outlet velocities of 1248 and 1043 m/s and maximum outlet Mach numbers of 1.24 and 1.09, respectively. The respective peak times are approximately 0.3 ms and 0.17 ms. The maximum outlet velocity, saturation work frequency, and maximum outlet Mach number of the Laval-configured combustion-driven actuator are considerably larger than those of the straight-shaped outlet combustion-driven SparkJet actuator, and the peak time of the Laval configuration actuator is lower than that of the actuators with diameters of 2 mm and 2.8 mm. In addition, the outlet mass flow rate of the combustion-driven actuator with a diameter of 2.8 mm was the highest, with a peak value of 0.39, followed by the Laval-configured combustion-driven actuator at approximately 0.23. It was the smallest in the combustion-driven actuator with a diameter of 2 mm, with a peak value of 0.19. The Laval-configuration effectively improves the outlet jet velocity and mass flow rate of the combustion-driven actuator, as well as reduces the peak time, while also having a large saturation work frequency and a working performance better than that of the straight-shaped outlet combustion-driven actuator.

Figure 9 shows the temperature contours of the actuators at various delay times. At 16 μ s, the discharge of the actuator ends and the actuator's highest temperature for the three outlet types was about 2000 K, with little temperature difference. At 60 μ s, the maximum temperature of the actuator increased to approximately 2700 K, indicating that the blends inside the actuator begin to burn. At 100 μ s, the high-temperature area inside the actuator continued to expand. The temperature was the highest in the actuator with a diameter of 2 mm, followed by that of the Laval-configured actuator. It was the lowest in the actuator with a diameter of 2.8 mm. At 180 μ s, the temperature of the combustion chamber and the area of the high-temperature zone continued to increase. The temperature of the most area inside the actuator was above 2700 K. At 270 μ s, the high-temperature area moved toward the outlet, and the temperature of the actuator with an outlet diameter of 2 mm and a Laval configuration was much higher than that of the actuator with an outlet diameter of 2.8 mm. As time continues to go, the temperature inside the actuator chamber decreases over time.

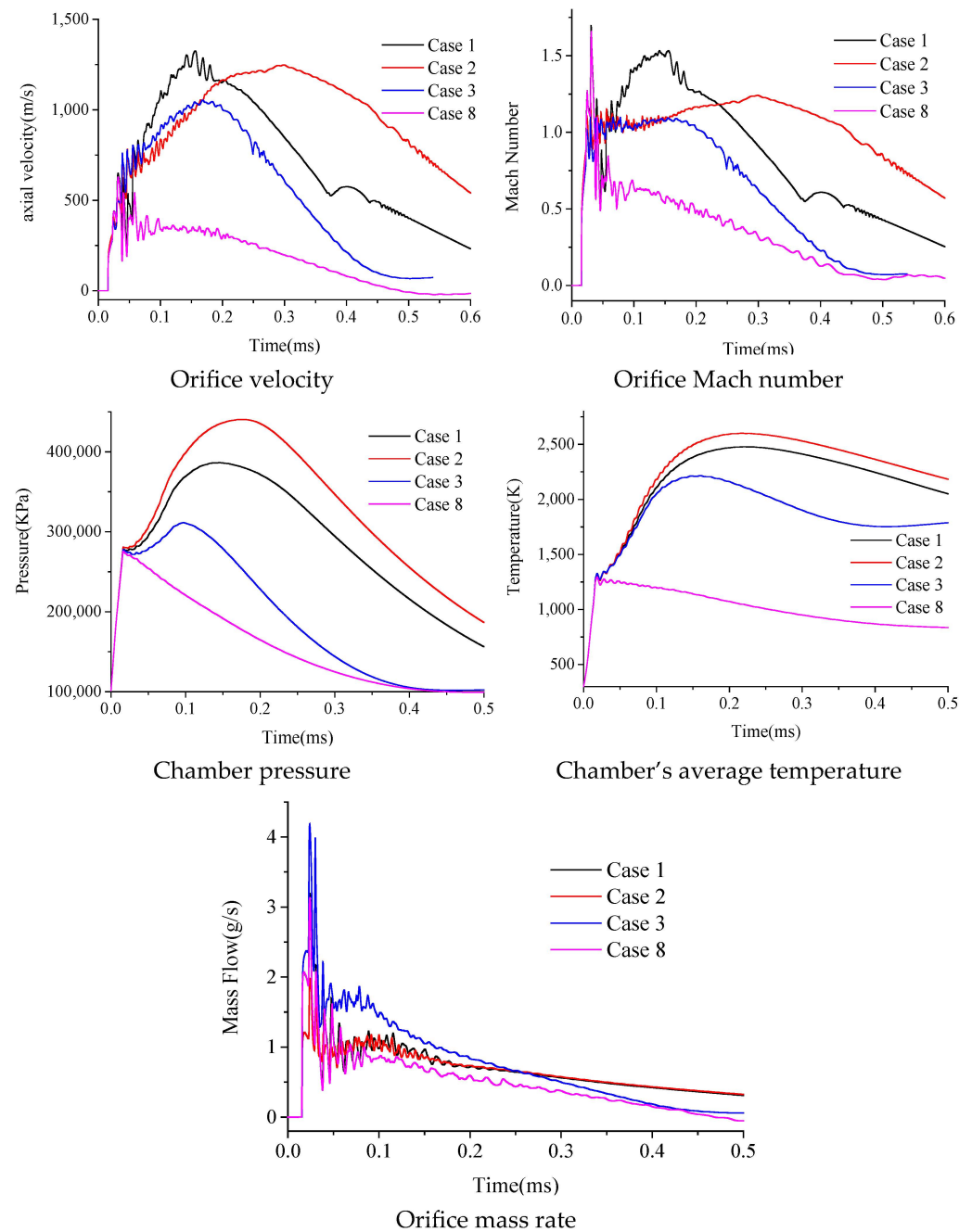


Figure 8. Comparison of the actuator performance with various outlet configurations.

As shown in Figure 10, at 16 μ s, no OH component was generated inside the actuator because the discharge had just ended, and the mixture inside the actuator had not yet reacted. At 60 μ s, OH components were generated near the wall and at the bottom of the actuator, indicating that the mixture had already begun to react. At 100 μ s, OH components were generated in most areas of the actuator, indicating that most of the mixture was reacting. The OH component concentration was the highest in the straight-shaped outlet combustion-driven actuator with an outlet diameter of 2 mm, and slightly lower in the Laval-configured actuator. It was the lowest in the straight-shaped outlet combustion-driven actuator with a diameter of 2.8 mm. High concentrations of OH components were generated at the throat of the 2.8 mm outlet diameter actuator because of the larger diameter, which reduces the blocking effect caused by the boundary layer thickness on the airflow at the throat. The larger the outlet diameter, the more the blend leaks during the

actuator's work, resulting in a more intense reaction at the throat compared with the other two actuators. At 180 μs , the concentration of the OH component increases, indicating that the reaction inside the actuator is intensifying. At 270 μs , the highest concentration of the OH components in the cavity with a diameter of 2 mm and the Laval-configured actuator continued to increase, while it began to decrease in the actuator with a diameter of 2.8 mm. This is because the larger diameter leads to more leakage of the mixture, resulting in less of the blend in the chamber and a lower reaction intensity. At 370 μs , the highest concentrations of OH components in the three actuators decreased.

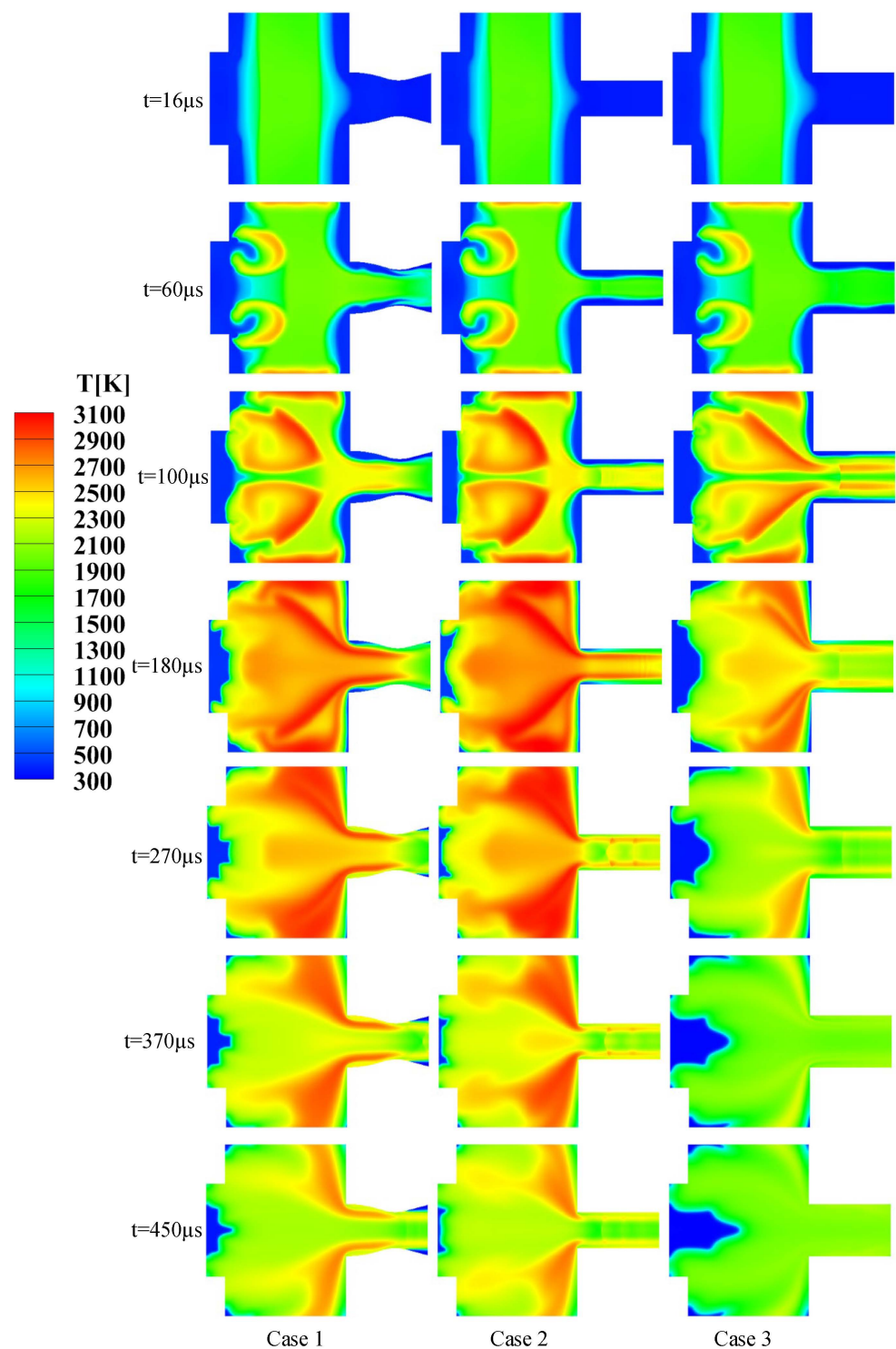


Figure 9. Temperature contours of the actuators with outlet straight and laval configuration.

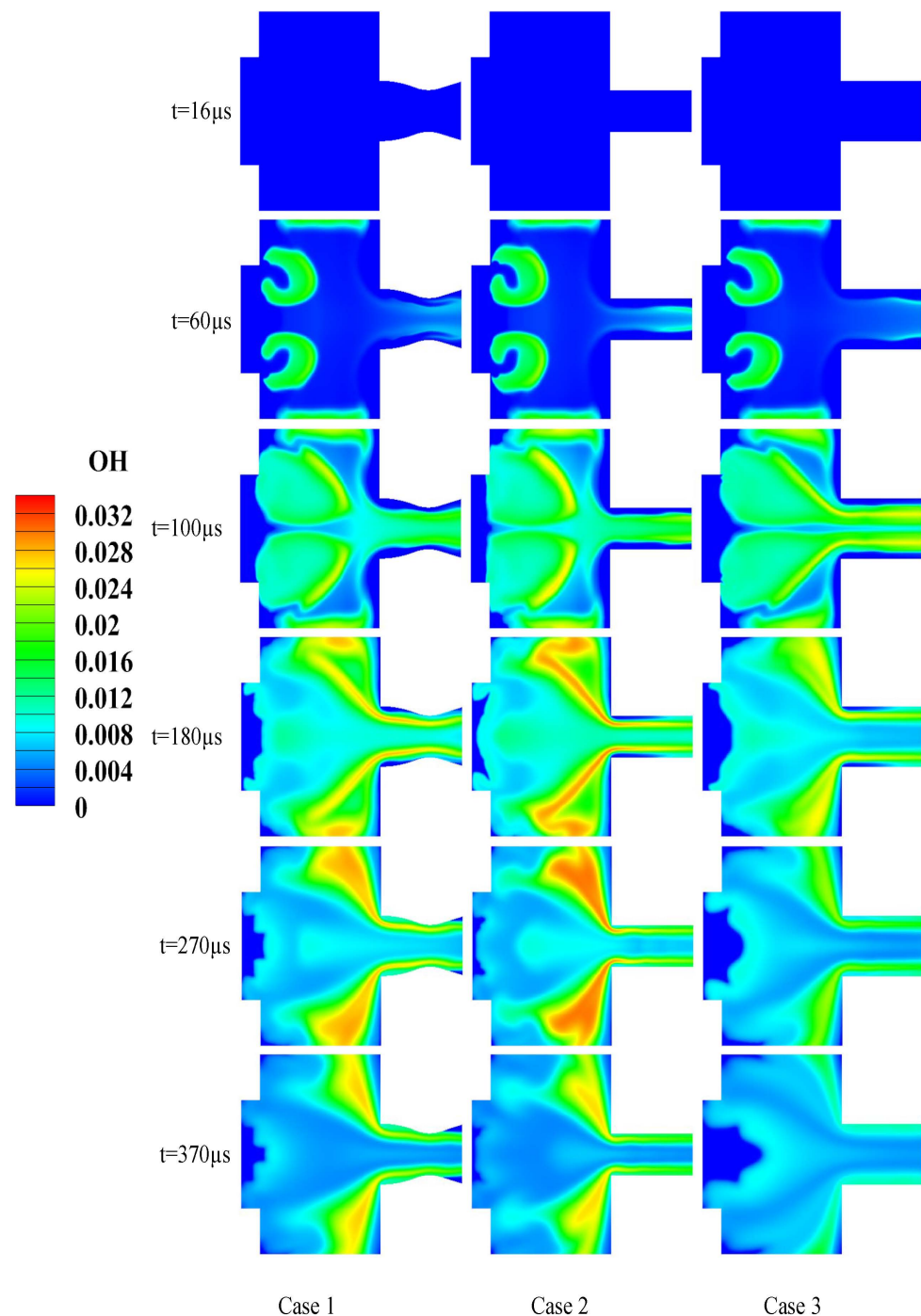


Figure 10. OH mass fraction of the actuators with various outlet configurations.

As shown in Figure 11, at 16 μs , the discharge ends and the pressure inside the three actuators rises to 300,000 Pa. The pressure continues to rise with time. At 100 μs , the pressures of the Laval-configured actuator and the 2 mm diameter actuator are 400,000 and 420,000 Pa, respectively, which are both higher than that of the 2.8 mm diameter actuator, where the pressure is 340,000 Pa. At 180 μs , the pressure inside the 2 mm diameter actuator and the Laval-configured actuator reached peak values of 450,000 Pa and 410,000 Pa, respectively, then the pressure inside the 2.8 mm diameter actuator began to decrease as time goes on.

Figures 12 and 13 show the velocity and Mach number contours of the combustion-driven actuators with different outlet configurations. At 16 μs , the Mach number of the

airflow in the outlet is still very low. At 60~270 μs , the Mach number of the airflow in the straight-shaped outlet was around 1 after the mixture entered the straight-outlet channel, and the flow velocity did not continue to increase in the outlet channel. The Mach number increased after the airflow exited the outlet due to volume expansion. After passing through the Laval outlet throat, the airflow velocity greatly increased because of the volume expansion, reaching its maximum velocity at the outlet, with a maximum average velocity of approximately 2000 m/s. The Mach number of the mixture exceeded 1 at the Laval throat as the mixture flowed through the outlet; hence, the mixture flow accelerates because of the expansion of the nozzle after passing through the throat. The outlet velocity and Mach number of the actuator with the Laval outlet configuration are much higher than those of the straight outlet configuration actuator, and the Laval outlet configuration of the actuator can improve the outlet jet velocity.

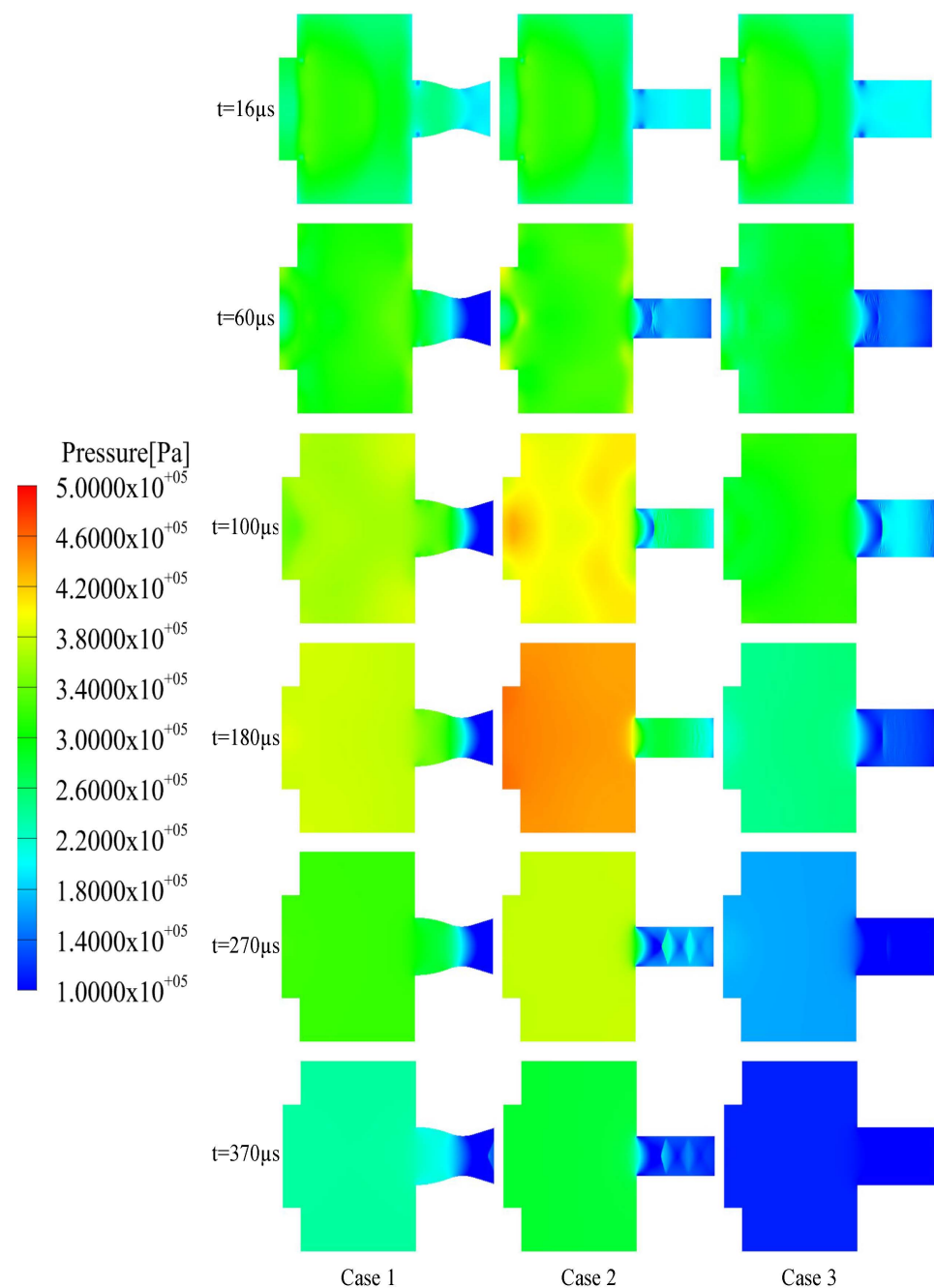


Figure 11. Pressure contours for the various actuators with various outlet configurations.

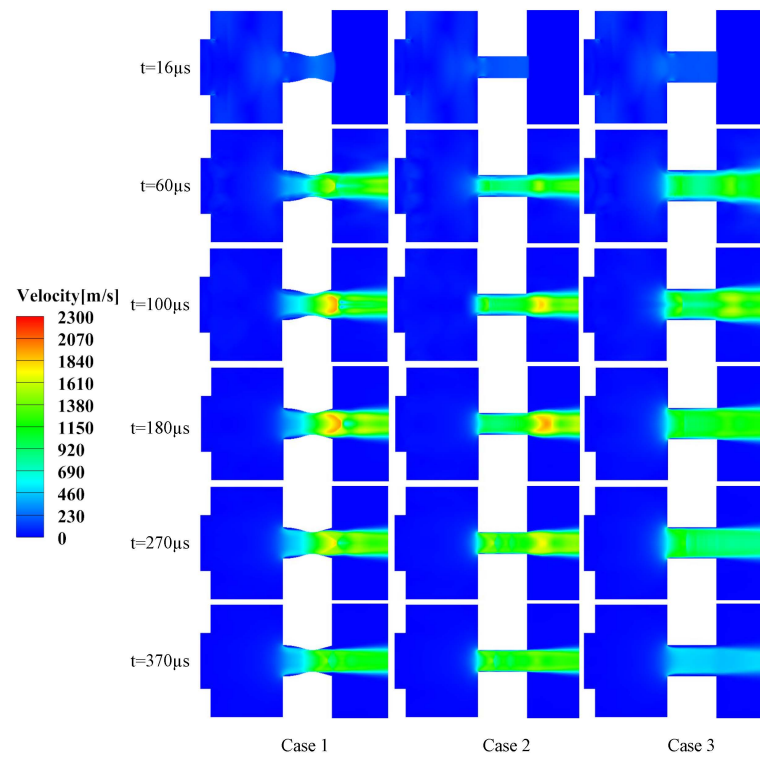


Figure 12. Velocity contours for the actuators with various outlet configurations.

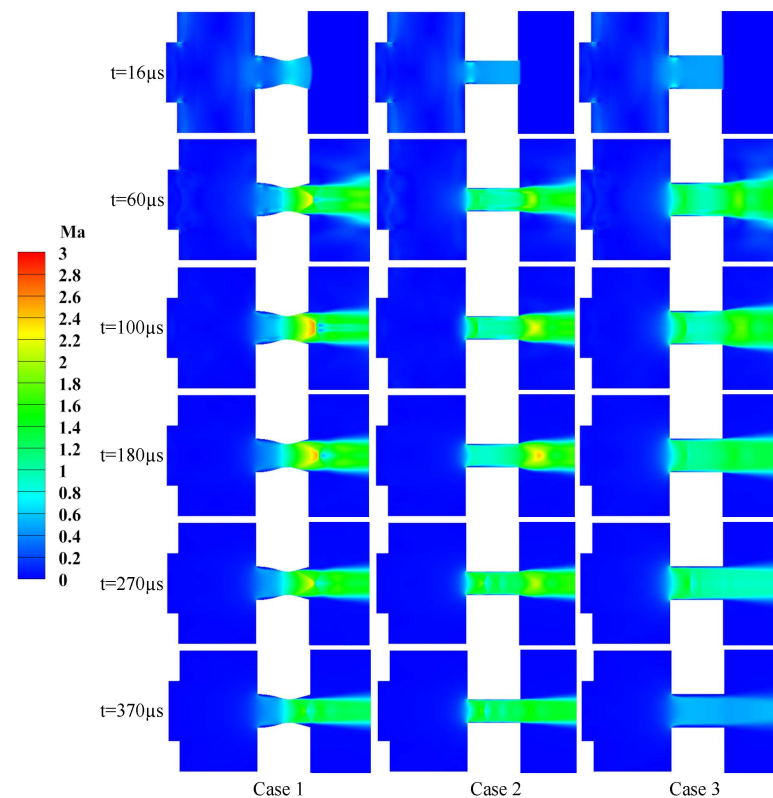


Figure 13. Mach number contours for the actuators with various outlet configurations.

3.2. Influence of the Equivalence Ratio on the Performance of the Laval-Configured Actuator

As shown in Figure 14, as the equivalence ratio increased from 0.6 to 1, the maximum outlet velocity, maximum Mach number, maximum temperature, and maximum pressure inside the cavity of the actuator increased by about 44%, 28%, 19%, and 18% respectively.

The refill time was almost the same. Given the same structure of the actuator, the outlet mass flow rate was nearly the same when the equivalence ratio was between 0.6 and 1. The larger the equivalence ratio, the more heat that is released from the combustion of the mixture, and the outlet velocity generated by the high-temperature expansion was higher as the equivalence ratio increased from 0.6 to 1. However, excessive temperature may exceed the material's bearing capacity; thus, choosing an appropriate equivalence ratio is crucial.

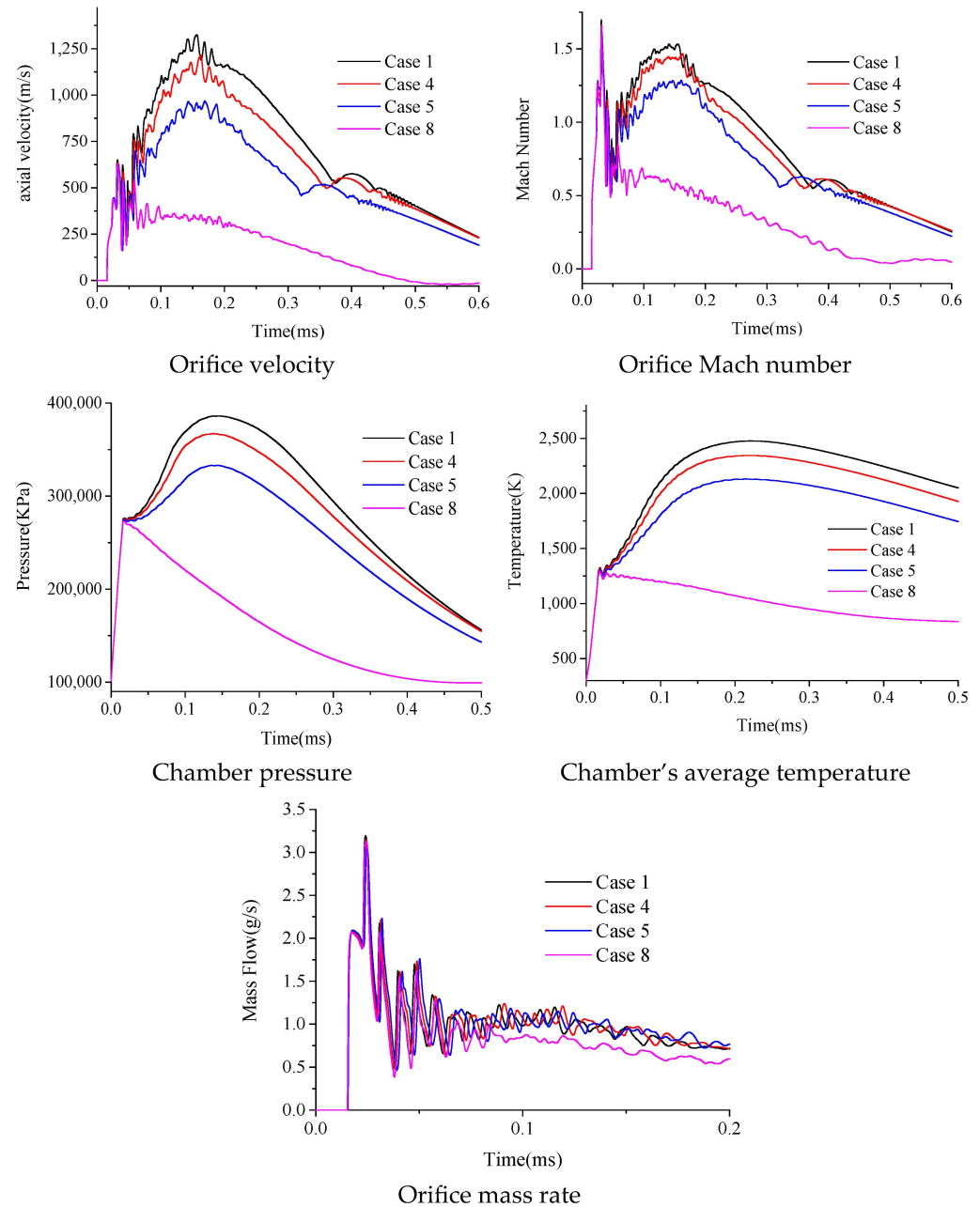


Figure 14. Comparison of the actuator performance with various equivalence ratios.

As shown in Figure 15, at 16 μ s, the actuator's discharge ends, and the actuator has a similar temperature field at different equivalence ratios. At 60–100 μ s, the temperature in the actuator increases, while the highest temperature in the actuator increases with the equivalence ratio. The temperature reaches its maximum at approximately 180 μ s. At this point, the highest temperatures are 3054, 2959, and 2861 K at equivalence ratios of 1,

0.8, and 0.6, respectively. At 270 μs , the area of the high-temperature region continues to increase. While the temperature inside the actuator decreases with time.

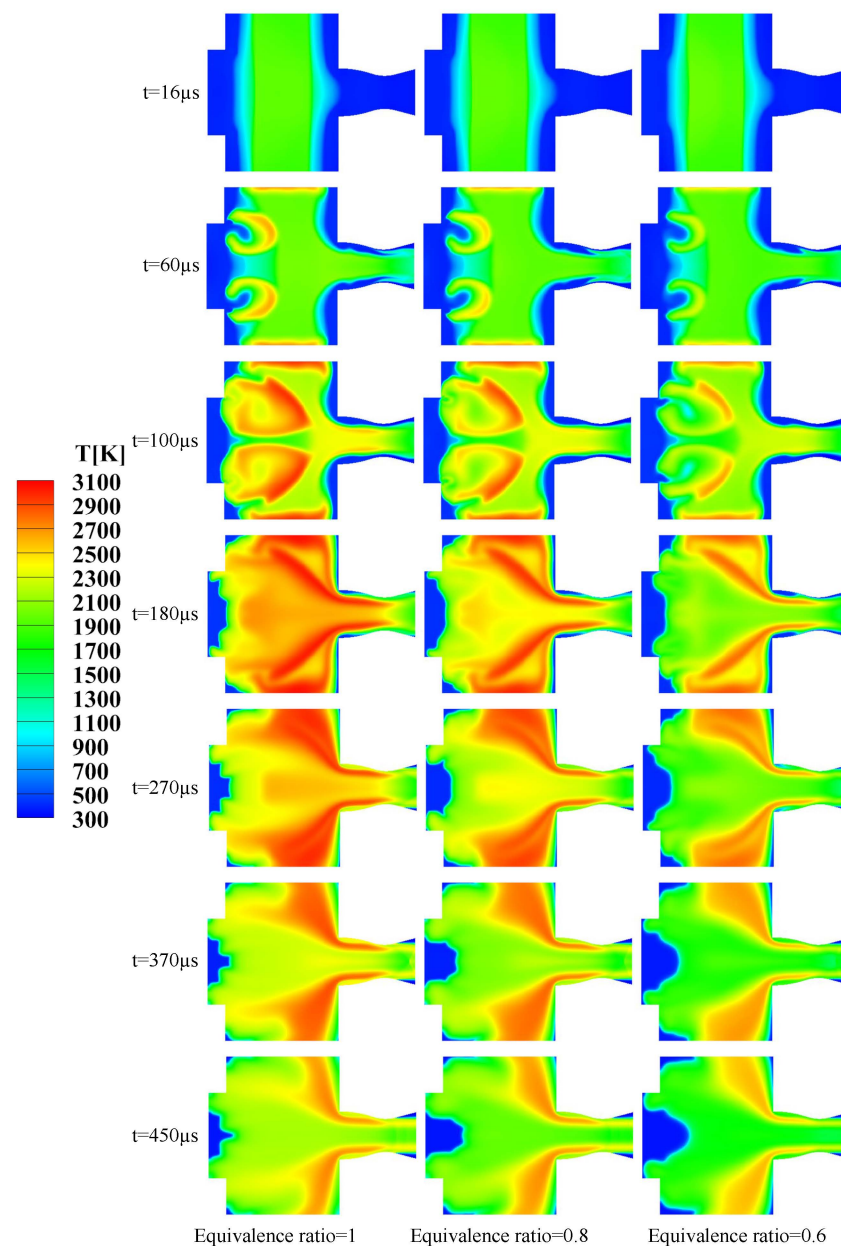


Figure 15. Temperature contours of the actuators with various equivalence ratios.

As shown in Figure 16, the OH components are generated near the wall and bottom of the actuators at 60 μs , indicating that a part of the mixture is starting to react. When the equivalence ratio is less than 1, the OH component concentration in the actuator raises with the increase in the equivalence ratio, which means that the degree of reaction in the actuator increases with a raise in the equivalence ratio. At 100 μs , the area of the region that generates OH components continues to increase, reaching the peak value at 180 μs . The OH components' concentration decreases over time, which means that most of the mixture has already been burned.

According to Figure 17, the pressure inside the three actuators is nearly the same at 16 μs because the blends in the actuator have yet to react, and the mixture is heated by discharge, leading to an increase in pressure. At 60 μs , the mixture in the actuator burns and releases heat, which causes an increase in pressure; as the equivalence ratio decreases,

the pressure inside the actuator chamber also decreases. This is because the amount of heat released by the combustion of the mixed gas is lower when the equivalence ratio is small, resulting in a slight increase in the actuator pressure. At 180 μs , the pressure inside the actuator reaches its maximum value and decreases over time.

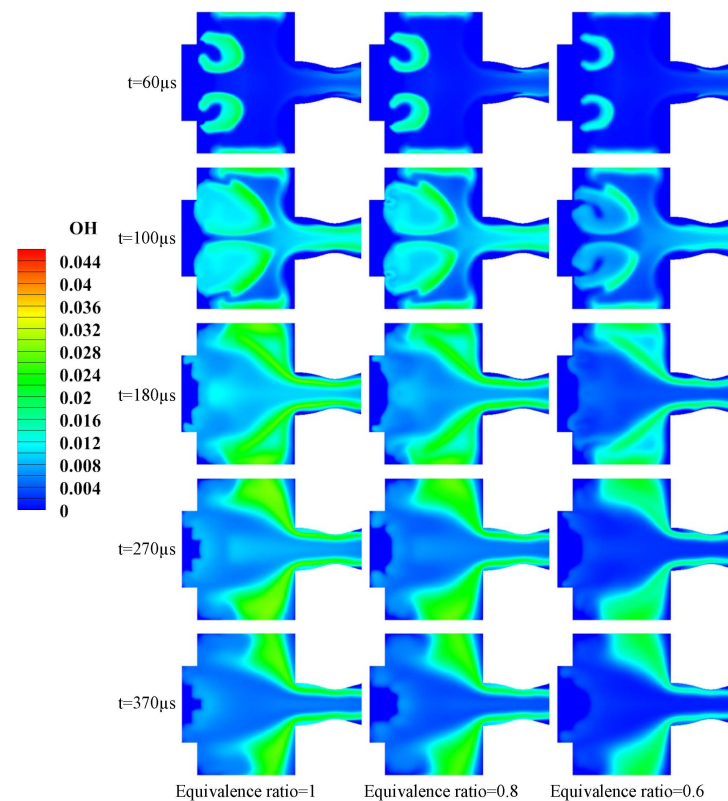


Figure 16. OH mass fraction of the actuators with various equivalence ratios.

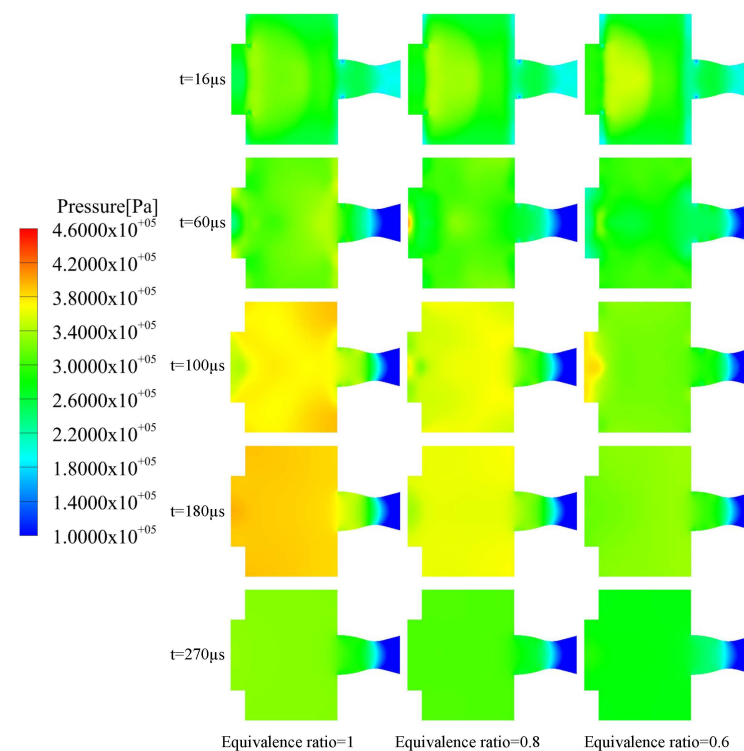


Figure 17. Pressure contours of the actuators with various equivalence ratios.

3.3. Influence of Atmospheric Pressure on the Performance of the Laval-Configured Actuator

As shown in Figure 18, the pressure and mass flow rate of the actuator drop as the atmospheric pressure declines, the lower the atmospheric pressure, the lower the mass of gas in the chamber. Moreover, the trends in the changes in outlet peak velocity, orifice Mach number, and pressure are opposite to that of the atmospheric pressure. This can be explained by the fact that the low pressure decreases the mass of gas in the actuator while the heating energy is the same; hence, the heated blend's temperature is also higher, resulting in a higher jet velocity. When the atmospheric pressure equals 0.6 atm, the outlet mass flow of the SparkJet actuator decreases considerably due to the decrease in gas, resulting in a significant decline in its performance; the outlet mass flow of the combustion-driven actuator is clearly higher than that of the SparkJet actuator.

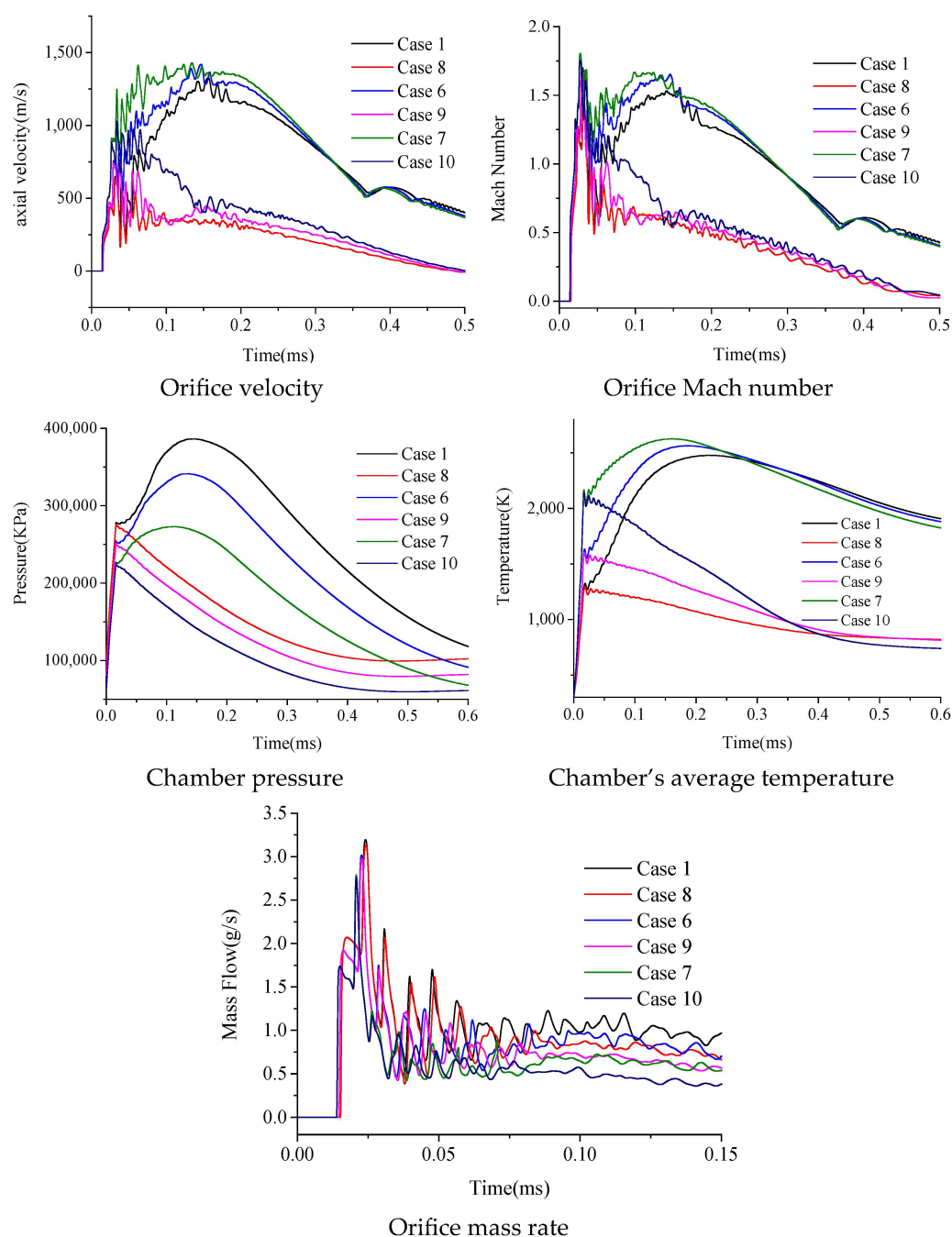


Figure 18. Comparison of the actuator performance with various atmospheric pressure values.

As shown in Figure 19, at 16 μs , the actuator's discharge ends, and the lower the atmospheric pressure, the higher the temperature in the actuator. This is because the heating energy of the actuator remains the same, and the lower the atmospheric pressure, the lower the gas mass in the actuator. The unit heating energy is also greater as the working medium is the same. At 60 μs , the mixture in the actuator begins to react, and the actuator's temperature increases as the atmospheric pressure decreases. At 100~180 μs , the actuator's temperature continues to rise, with 0.6 atm being the highest, followed by 0.8 atm, and 1 atm being the lowest. The temperature in the actuator decreases over time, and the temperature drops faster as the atmospheric pressure is lower.

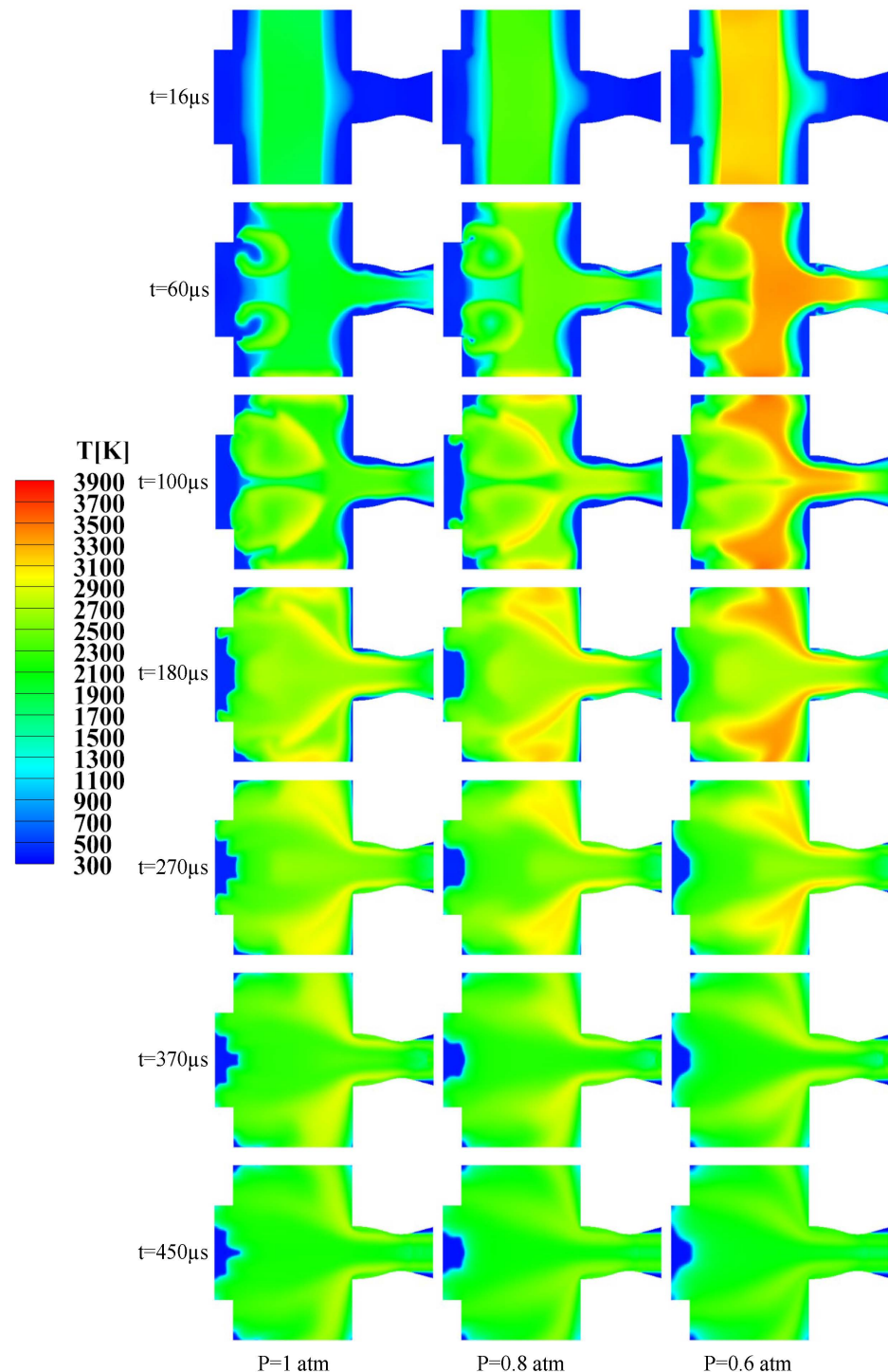


Figure 19. Temperature contours of the actuators with various atmospheric pressure values.

As shown in Figure 20, at 60 μs , the OH component is generated in the actuator. At 100 μs , as the flame inside the actuator spreads, the concentration and area of OH components inside the actuator further increase. The lower the atmospheric pressure, the higher the temperature in the actuator, which causes more intense reactions of the mixture and a higher concentration of OH components. At 180 μs , the components concentration reaches its maximum value. As time further increases, most of the unburned blend in the actuator completed the combustion reaction, and the OH components also decrease accordingly. At 370 μs , the components concentration is the highest in the actuator with a pressure of 1 atm, followed by 0.8 atm and, finally, 0.6 atm. This is because the mixture's mass content in the actuator decreases as the atmospheric pressure drops, and the time required for the mixture to completely react is short.

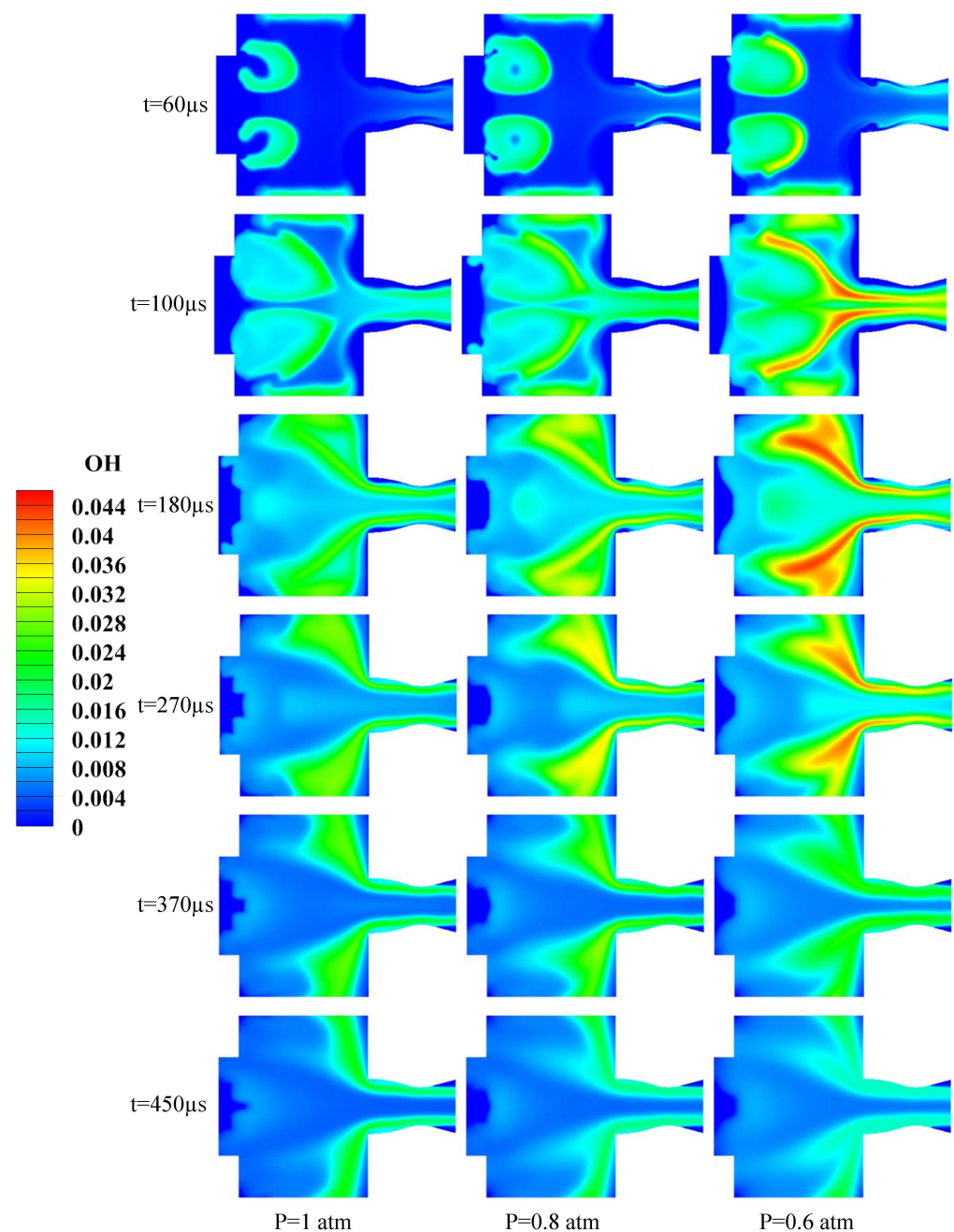


Figure 20. OH mass fraction of the actuators with various atmospheric pressure values.

At 16 μs , the discharge of the actuator ends, and the pressure in the actuator begins to rise, as shown in Figure 21. At 100 μs , the pressure of the actuator reaches its maximum value as the atmospheric pressure equals 0.6 atm, while it reaches its maximum at 180 μs when the atmospheric pressure equals 0.8 and 1 atm, respectively. As time goes on, the pressure in the actuator decreases. The peak pressure value and the peak time decreases with the decrease in the atmospheric pressure.

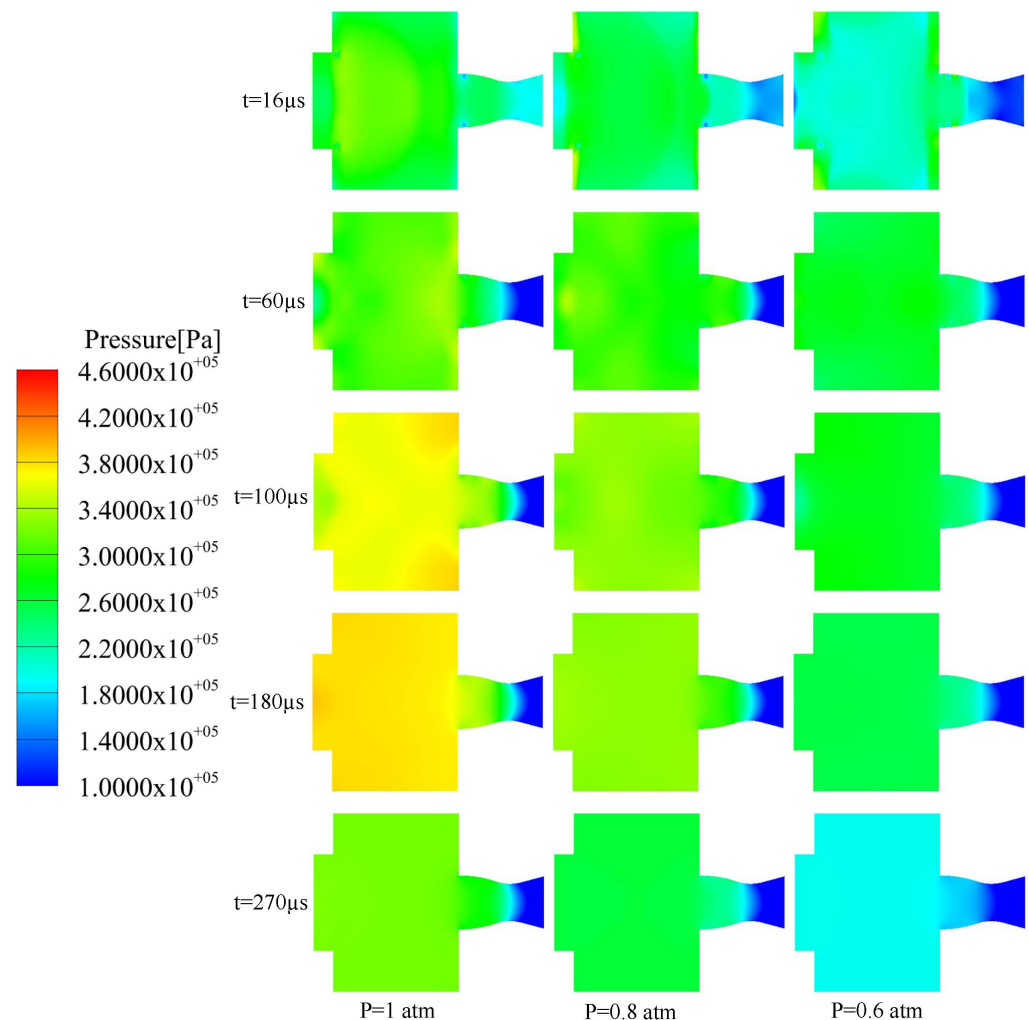


Figure 21. Pressure contours of the actuators with various atmospheric pressure values.

3.4. Influence of Ignition Position on the Performance of the Laval-Configured Actuator

The effect of the ignition position on the performance of the actuator was investigated by numerically studying the working characteristics of the actuator with the ignition area located at the middle position and 2 mm and 2.8 mm displacements toward the outlet, while the volume, shape, and work parameters of the ignition area remained the same. As shown in Figure 22, as the ignition position moves from the middle position to a 2.8 mm displacement toward the outlet, the maximum outlet velocity, Mach number, pressure, and temperature increase by about 20%, 13%, 25%, and 6%, while the peak time increased by about 40%.

As shown in Figure 23, at 16 μs , the actuator's discharge ends, and the difference in the peak temperature values of the actuator is negligible. In addition, the closer the ignition position is to the outlet, the higher the temperature in the outlet. At 60 μs , the further the ignition position is from the center, the larger the high-temperature area at the outlet. At 100 μs , most of the mixture in the actuator with the ignition position at the center begins

burning, while the further the ignition position is from the center, the larger the unburned area in the actuator. At 270 μs , most parts of the mixture in the actuator whose ignition position is not in the center begin to burn. The temperature in the actuator decreases over time. The farther the ignition position is from the center, the longer it takes for the flame to propagate to the bottom of the actuator, and the longer it takes for the mixture in the actuator to react completely, resulting in a low-saturation work frequency.

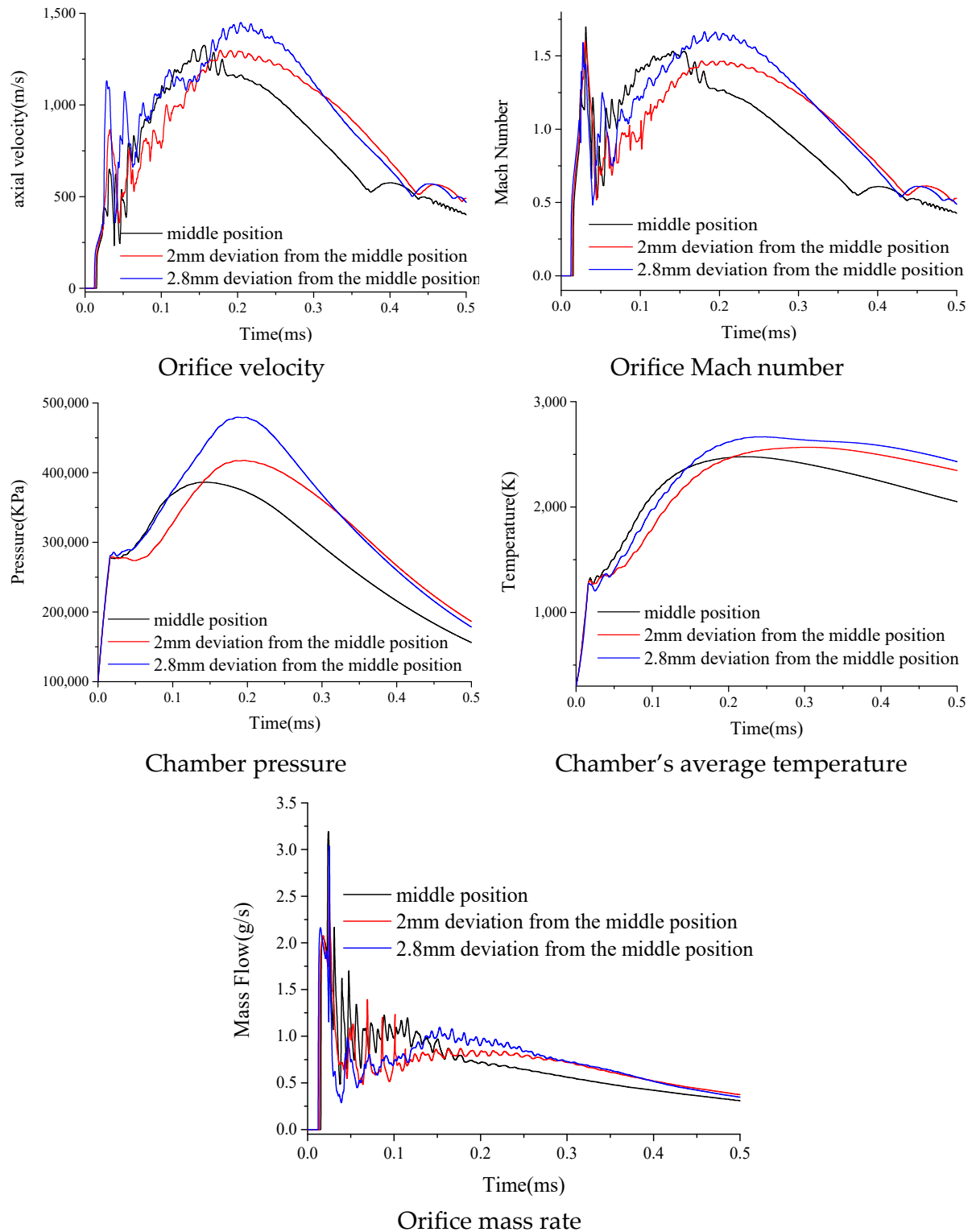


Figure 22. Comparison of the actuator performance with various ignition positions.

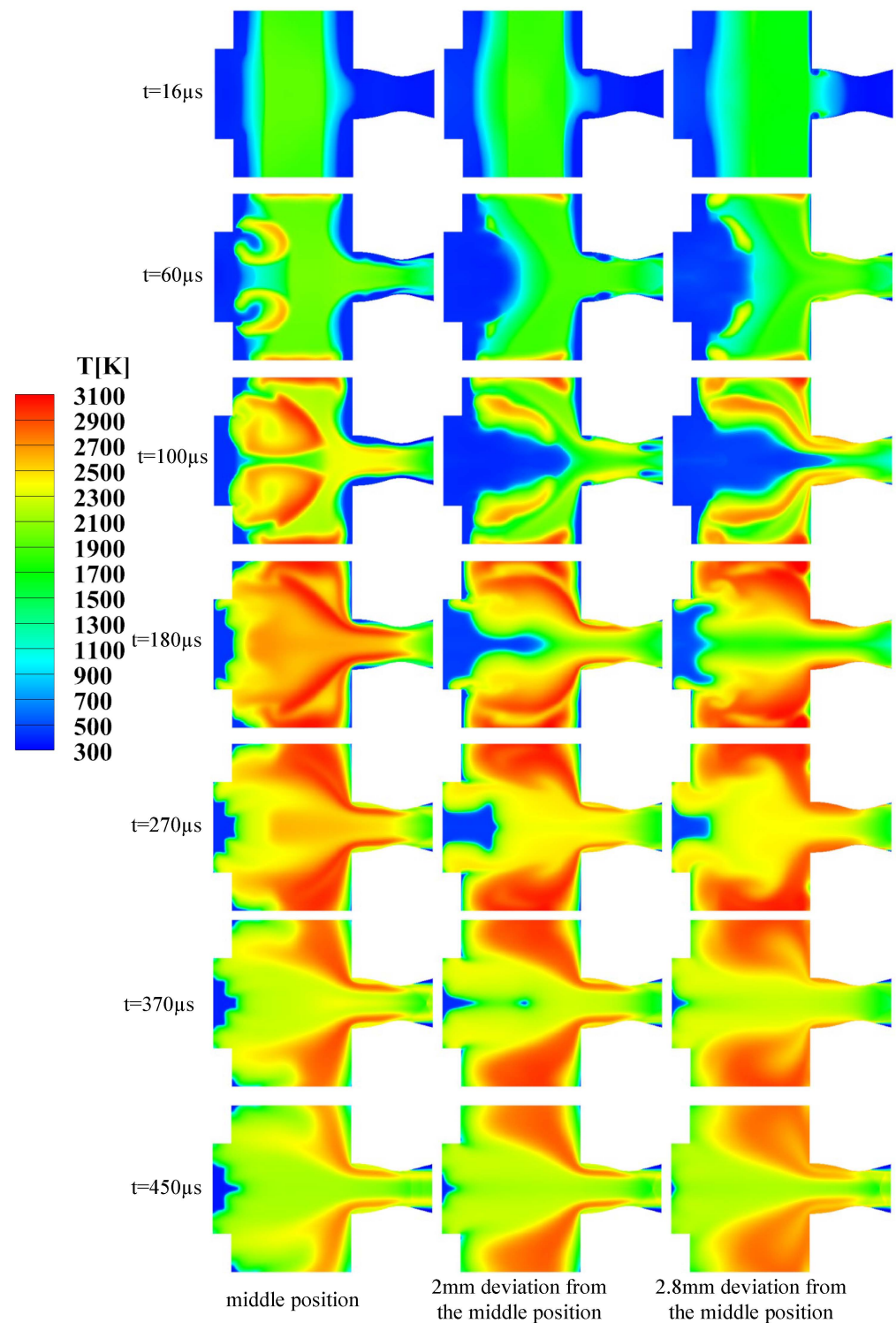


Figure 23. Temperature contours of the actuators.

As shown in Figure 24, at 16 μs , the OH components were generated at the outlet with an ignition position located 2.8 mm from the center of the actuator, while no OH was generated at the outlets of the other actuators. At 60 μs , the area of the OH components generated in the actuator with the ignition position located in the center is the largest; moreover, the closer the ignition position is to the outlet, the greater the concentration and area of OH components generated at the outlet. At 60~180 μs , the OH components' concentration in the actuator increases, indicating intensified combustion. Moreover, the area and concentration of OH components generated in the actuator with the ignition

position located in the center are notably higher than that of other actuators. At 270 μs , OH components were generated in most parts of the actuator, indicating that most of the mixtures in the actuator reacted. At 370 μs , the OH components' concentration began to decrease.

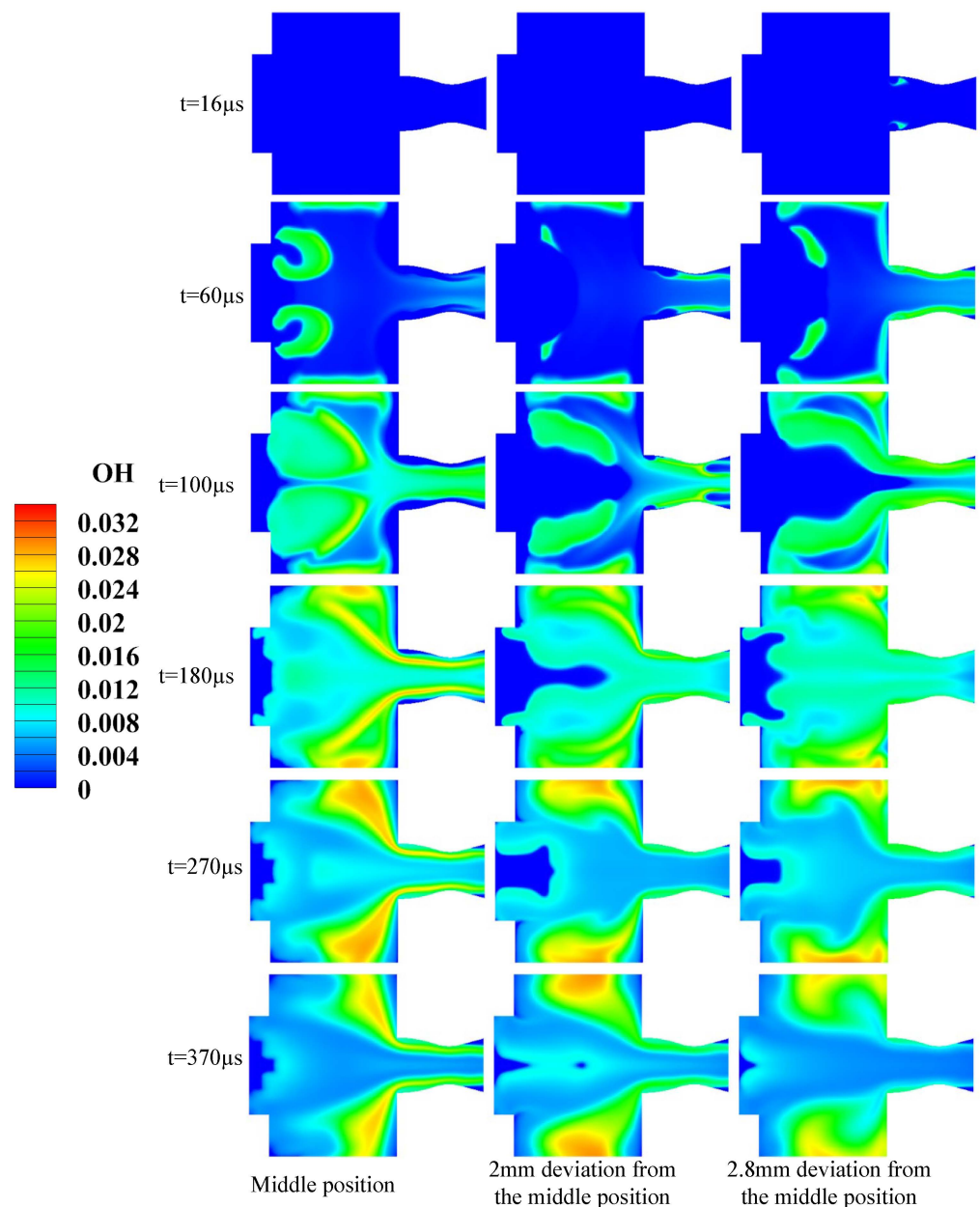


Figure 24. OH mass fraction of the actuators.

According to Figure 25, the pressure in the actuator increases at 16–180 μs , and the pressure reaches its maximum value at approximately 180 μs . The pressure in the actuator with an ignition position located 2.8 mm from the center is the highest, which equals 500,000 Pa, and the pressure decreases as the deviation from the center position decreases. The farther the ignition position is from the center, the more evident the pressure oscillation, which is due to the uneven ignition heating and combustion.

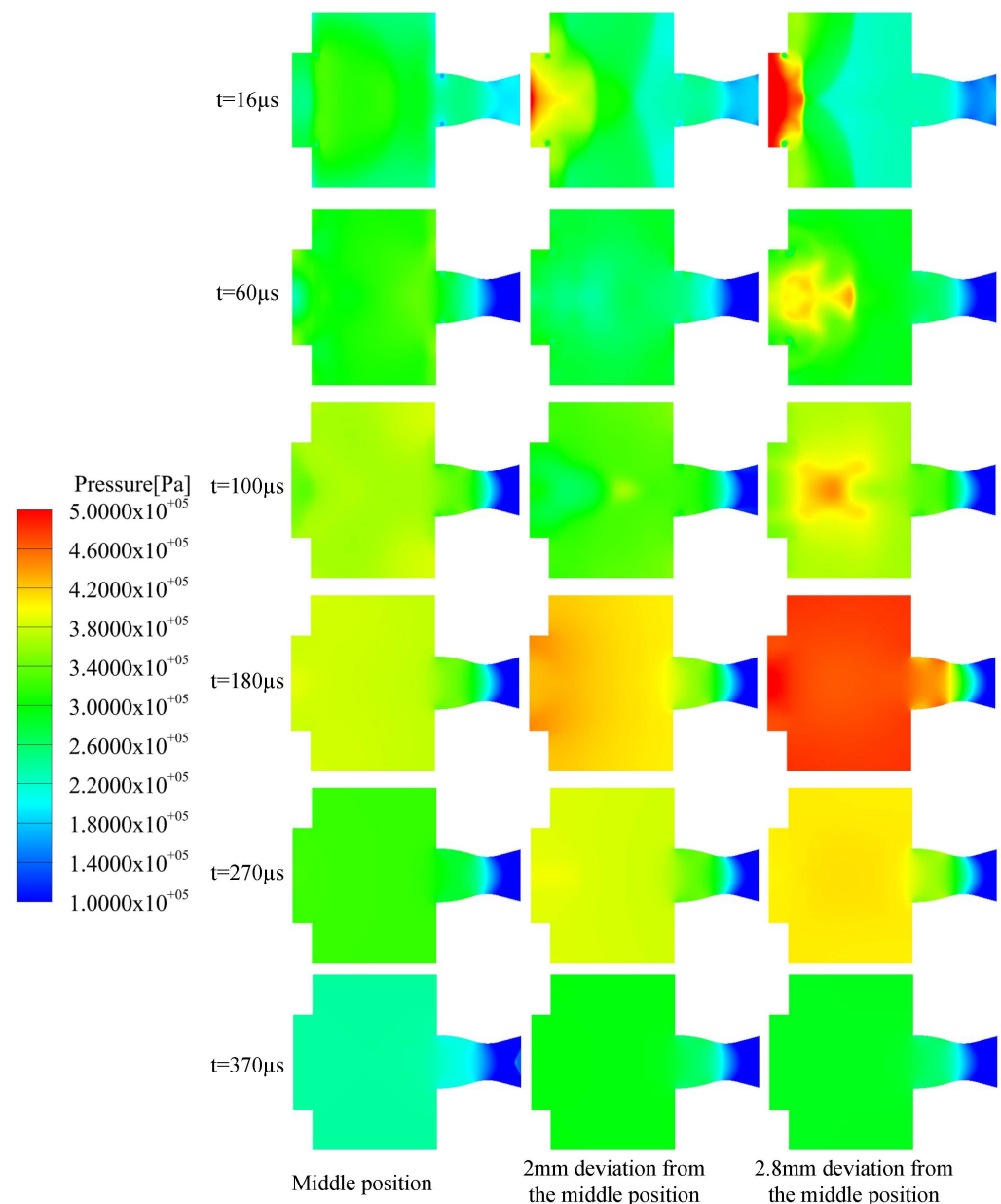


Figure 25. Pressure contours for the various actuators.

4. Conclusions

The combustion-driven SparkJet actuator with a Laval-configured outlet was numerically studied, and the working performance of the actuators with Laval and straight outlet configurations is discussed. The effects of the equivalence ratio, atmospheric pressure and the ignition position on the performance of the actuators were also analyzed. The results are as follows:

1. The maximum jet velocity of the Laval-configured actuator is 100 m/s and 350 m/s higher than that of the straight outlet combustion-driven actuator with outlet diameters of 2 mm and 2.8 mm, respectively. The maximum outlet Mach number of the Laval-structured combustion-driven actuator is 1.53, which is higher than that of straight outlet combustion-driven actuators with outlet diameters of 2 mm and 2.8 mm. The peak time decrease by about 50% and 12% compared with the straight outlet actuator with outlet diameters of 2 mm and 2.8 mm, respectively. The work frequency of the Laval-structured combustion-driven actuator is 1333 Hz, which is

higher than the 1176 Hz of the straight-tube-structured combustion-driven actuator with an outlet diameter of 2 mm. The Laval configuration effectively improves the working performance of the actuator, while simulation results need to be verified in future experiments.

2. As the equivalence ratio increased from 0.6 to 1, the actuator's maximum jet velocity increased by approximately 65 m/s and 311 m/s, respectively, and the outlet Mach number increased by about 0.16 and 0.09. The maximum combustion temperature rose from 2700 K to 3000 K, and the saturation work frequency remained nearly the same. The actuator has better performances as the equivalence ratio equals 1. While excessive temperature may exceed the material's bearing capacity. Hence the equivalent ratio of the actuator must be selected in accordance with the working conditions considering the performance and material's bearing capacity.
3. The pressure and jet mass flow rate of the actuator drop as the atmospheric pressure declines, while the combustion-driven actuator still exhibits high working performance as the atmospheric pressure is low.
4. The maximum outlet velocity, maximum Mach number, maximum pressure, and maximum temperature increased by about 20%, 13%, 25%, and 6%, while the peak time rise by about 40% as the ignition position moved from the middle position to a 2.8 mm displacement toward the outlet.

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