The Effects of Oil Temperature and Oil Return Pressure on Oil Film Damping Characteristics of a High-Speed Solenoid Valve

Peng Liu ✉ – Qing Zhao – Shijian Peng – Wenwen Quan – Zhida Gao ✉
Changsha University of Science and Technology, College of Automotive and Mechanical Engineering, China
✉ liupeng@csust.edu.cn; 202103130116@stu.csust.edu.cn

Abstract *A high-speed solenoid valve (SV) is a critical executive component in common rail fuel injection systems, where its dynamic response significantly influences the control accuracy of fuel injection. Moreover, this response is particularly affected by the damping force (DF) of the oil film between the armature and the iron core. To investigate the effects of oil temperature and oil return pressure on the oil film damping characteristics of high-speed SV, a numerical simulation approach was employed. Computational fluid dynamics (CFD) models were constructed to analyze the influence of oil temperature and oil return pressure on both the DF of the oil film and its cavitation properties across varying operational air gaps. The results indicate that as the oil temperature increases, the DF of the oil film generally exhibits a decreasing trend during the suction and release processes of the high-speed SV. Additionally, increasing the initial and residual air gaps can mitigate the influence of temperature on the DF of the oil film, thereby reducing the incidence of cavitation. Notably, the oil return pressure does not affect the DF of the oil film during the suction process. However, during the release process, the DF of the oil film increases with the oil return pressure when the residual air gap is small. At medium residual air gaps, the DF initially increases with the oil return pressure before subsequently decreasing, and is accompanied by oscillations during cavitation collapse. For large residual air gaps, the impact of oil return pressure on the DF of the oil film becomes negligible.*

Keywords *high-speed solenoid valve, oil temperature, oil return pressure, damping force of the oil film, cavitation*

Highlights
- *A CFD model is established to analyze the oil film damping characteristics of a high-speed SV.*
- *The impact of temperature and oil return pressure on the oil film damping characteristics is studied.*
- *The cavitation phenomenon during the release process of high-speed SV is analyzed.*
- *Enlarging the initial and residual air gaps helps mitigate temperature effects on the oil film's DF.*

1 INTRODUCTION

The development of a diesel fuel injection system to ultra-high-pressure injection and flexible control direction of the injection amount, and the injection timing and injection rate, full electronic control of the fuel injection system has become an inevitable trend for achieving flexible control of the fuel injection process. A high pressure common rail system, as the latest generation of electronic fuel injection system, is one of the core technologies used to achieve energy saving and emission reduction of diesel engines now [1,2].

High-speed solenoid valve (SV) is a key executive component in high pressure common rail system. Gu et al. [3] built a one-dimensional model of the common-rail fuel injector based on AMESim software, and then reduced the total response time, injection pressure fluctuation and injection pressure drop of the injector by optimizing the solenoid valve preload, solenoid valve lift and other relevant parameters, thus greatly improving the comprehensive performance of the common-rail fuel injection system. Xu et al. [4] found that the energizing time of the solenoid valve affects the increasing speed and injection efficiency of the needle valve in the injector. If the energizing time of the solenoid valve is long enough, the injection speed can even be adjusted to reduce the injection volume gap between different pressure waves, which helps to improve the injection stability under large injection volume working conditions. Hung and Lim [5,6] found that spring stiffness, plunger mass, SV coil turns, and coil position have significant effects on the electromagnetic force and displacement of the plunger in the injector, thus affecting the injection quality of the injector. Therefore, it is evident that the dynamic response characteristics of high-speed SV exert a significant influence on the control accuracy of the fuel injection system [7,8].

However, the armature of the high-speed SV operates in an oil environment. A thin damping oil film forms between the armature and the iron core. Whether it is the suction process of the high-speed SV (the armature gradually approaches the iron core) or the release process of the high-speed SV (the armature gradually moves away from the iron core), the armature will receive the damping force (DF) of oil film in the opposite direction of its movement, which hinders the movement speed of the armature itself, and then has an important impact on the dynamic response of the high-speed SV.

At present, scholars have conducted in-depth research on the oil film damping characteristics of high-speed SVs. Xia et al. [9,10] used the basic theory of parallel plate gap flow and laminar flow to simplify and analytically calculate the oil film damping flow problem of high-speed SVs, and explored the influence of the number and size of the damping holes on DF and pressure distribution for high-speed SVs with square and disk armatures. Resch and Scheidl [11] developed an advanced numerical computation model of the DF in the separation process of SVs, and analyzed the effects of fluid surface tension, cavitation, inlet pressure loss, and fluid viscosity on the accuracy of the DF calculation. Scheidl and Gradl [12] found that when two oil-filled plates are rapidly separated, if the pressure between the gaps is greater than the saturated vapor pressure of the oil, the oil film DF can be derived and solved by the Reynolds equation. However, for very fast movements, such as the armature movement of a SV, cavitation is likely to occur on the armature surface. In this case, the Reynolds equation of single-phase flow cannot solve the DF of oil film. Scheidl and Gradl [13] proposed an approximate method for calculating the DF during the separation process of SVs according to the characteristics of the solution of the non-cavitating viscous flow problem, which can be applied to deal with the cavitating viscous flow problem. Nevertheless, this approach does not consider the influence of inlet pressure loss and fluid inertia on the DF of the oil film. Through numerical simulation, Zhao et al. [14] found that the opening of damping holes and straight grooves structure on the armature of high-speed SV can effectively reduce the DF oil film, and inhibit the occurrence of the cavitation phenomenon within a certain range. But the impact of opening damping holes and straight grooves on the electromagnetic force of high-speed SV was not taken into account. Opening damping holes and straight grooves leads to a reduction in the upper surface area of the armature and a decrease in the amount of magnetic flux passing through it, making the electromagnetic force decline, which in turn affects the dynamic response speed of the high-speed SV. Scheidl and Hu [15] and Scheidl et al. [16] found that the opening of cushioning grooves on the edge of the armature of the SV, as well as avoiding contact between the armature and the core, is conducive to the reduction of the DF oil film. However, the high-speed SV exhibits a rapid motion speed and a minimal initial air gap, which significantly constrains the role of the opening cushioning grooves at the armature edge. Zhang et al. [17] proposed a novel damping sleeve structure with holes that can be easily installed. This structure is designed to alter the pressure distribution on the spool surface and the oil jet angle, thereby reducing the DF of oil film and enhancing the opening speed of the valve.

In summary, existing studies on the analysis of oil film damping characteristics of high-speed SV primarily focus on two key areas: the calculation of the oil film DF of high-speed SV and the investigation into how structural parameters of the armature influence this force. It is important to note that the aforementioned studies are predicated on the assumption that the fuel properties within the armature chamber of the high-speed SV remain unaltered. However, in the practical application of common rail electric fuel injectors, the oil temperature in the armature cavity of the high-speed SV may change. This will lead to changes in the oil physical properties [18,19], and further affect the damping characteristics of the oil film. In addition, the oil return pressure in the armature cavity may also change the flow state and cavitation characteristics of the oil film, which in turn affects the damping characteristics.

In this study, a numerical simulation method was employed to investigate the effects of oil temperature and oil return pressure on the film damping characteristics during the suction and release phases of the high-speed SV in common rail fuel injectors. The aim is to provide a theoretical foundation for optimizing the design of high-speed SVs and enhancing their operational consistency control. The main contributions of this study can be summarized as follows:

1. Computational fluid dynamics (CFD) models are developed to analyze the oil film damping characteristics of the high-speed SV.
2. The influence of oil temperature and oil return pressure on the DF of the oil film of high-speed SV is revealed, along with an explanation of the underlying reasons.
3. The cavitation phenomenon on the armature surface during the release process of the high-speed SV is analyzed, revealing the influence of oil temperature and oil return pressure on the gas volume fraction.

2 METHODS AND MATERIALS

Figure 1 is a structural diagram of the high-speed SV, which is built into the common rail injector. Upon energizing the coil, the iron core exerts an electromagnetic force on the armature. When the electromagnetic force is greater than the spring preload force, the armature drives the control valve stem to move upward, that is, the suction process of the high-speed SV. At this time, the high-pressure oil channel is opened and the injector begins to spray oil. Once the coil is de-energized, the electromagnetic force disappears, and the armature moves downward to fully set under the action of the spring preload, that is, the release process of the high-speed SV. At this time, the high-pressure oil channel is closed and the injector stops spraying. As well, the distance between the armature and the iron core is very small, and the maximum distance is not more than 0.3 mm. However, other areas of the armature cavity have relatively large voids and can be regarded as areas with equal pressure [20]. Therefore, when using ANSYS Fluent to develop the CFD model for oil film damping characteristics, the computational domain mainly considers the oil between the armature and the iron core. As far as the good symmetry of the armature structure, to improve computational efficiency, a quarter of the computational domain for the CFD model (shown in Fig. 1) was built, in which the computational domain of the suction process and the release process only have gap differences. The motion velocity of the armature was obtained by differentiating the measured displacement curve of the high-speed SV [21], as shown in Fig. 2. Because the high-speed SV is integrated into the injector, directly measuring the DF of the oil film applied to the armature is challenging. To address this issue, this study referred to the fluid viscosity test during the SV armature separation process in reference [11] to guide the establishment of the CFD model. Resch and Scheidl [11] describe the use of a specific experimental rig to obtain the DF of the oil film between two parallel circular plates. The diameter of the test plate was 33 mm. The test fluid utilized was a mineral oil-based hydraulic fluid, with a nominal viscosity of 3.2×10^{-5} m²/s and an actual viscosity of 43.2 mPa·s at 25 °C and atmospheric pressure.

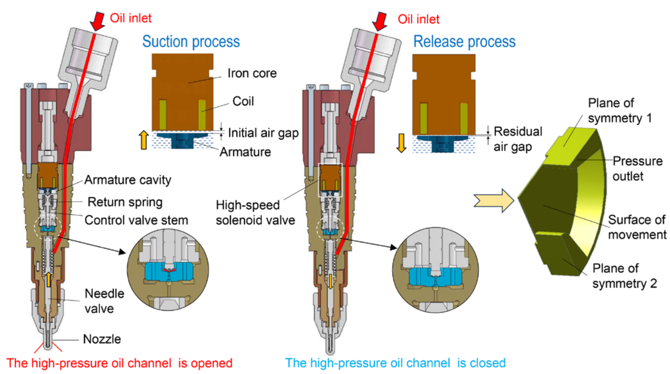

Fig. 1. High-speed solenoid valve (SV) for common rail injectors and its computational domain

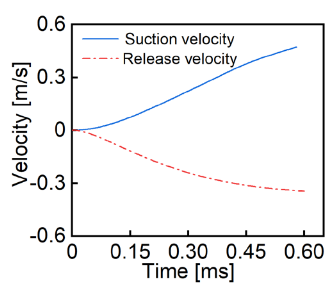

Fig. 2. Velocity profile of the armature during the suction and release processes

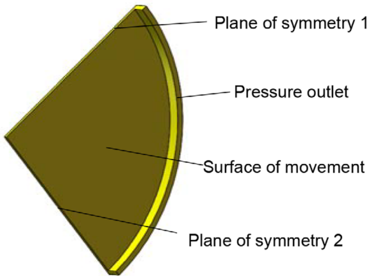

Fig. 3. Computational domain of oil film damping characteristics based on reference [11]

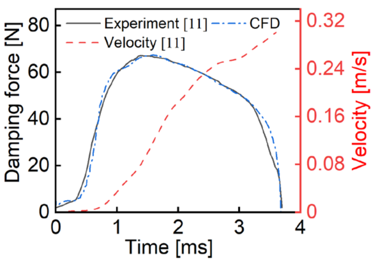

Fig. 4. Comparison of experimental result [11] and current CFD simulation result

Table 1. Setting of CFD models parameters

	Classification	Setting value
Main phase	As shown in Table 2	
Second phase	Viscosity [mPa·s]	1.8×10^{-3}
	Density [kg/m^3]	0.029
Multiphase model	Mixture	
Turbulence model	SST-k-omega	
Cavitation model	Schnerr–Sauer	
	Bubble number density [m^{-3}]	1×10^{11}
Wall boundary	No-slip surface conditions	
Dynamic mesh setup	Dynamic mesh method	Diffusion smoothing
	Diffusion function	Boundary distance
	Diffusion parameters	1.5
Speed of armature movement	As shown in Fig. 2	
Solving setup	Solution method	Pressure-velocity coupling scheme: simple
	Time step size [s]	2.5×10^{-6}
	Residual	1×10^{-5}

The computational domain was established for the analysis of oil film damping characteristics based on reference [11] as shown in Fig. 3. Also, Fig. 4 presents a comparison between the test results of the DF of the oil film from reference [11] and those obtained from CFD numerical analysis. As can be seen from Fig. 4, the results demonstrate a high degree of consistency, with a correlation coefficient of 0.99. The CFD model for oil film damping characteristics, as presented in this study, differs from the above referenced model only in terms of the geometry of the computational domain and the properties of the oil. Consequently, the model for reference [11] can be referred to construct the CFD model in this study. According to the different gaps between the suction and release processes, six groups of CFD models were established. The parameters of these models are identical except for their mesh configurations. Tables 1 and 2 detail the specific settings of the model parameters. Table 3 shows mesh setup in models.

Table 2. Physical properties of oil [22]

Property	Value		
Oil temperature [°C]	20	40	60
Saturated vapor pressure [Pa]	1280	4595	17125
Dynamic viscosity [mPa·s]	3.7	3.0	2.2
Surface tension [mN/m]	27.19	25.97	24.75
Density [kg/m^3]	833	812.31	803

3 RESULTS AND DISCUSSION

3.1 Effect of Oil Temperature on the Suction Process

Figure 5 illustrates the impact of oil temperature on the DF of the oil film during the suction process of the high-speed SV. It is observed that before 0.3 ms, the influence of different oil temperatures on the DF of the oil film is not obvious. However, as the armature gradually moves upward, that is, when it gradually moves closer to the iron core, the higher the oil temperature, the smaller the DF of the oil film. Moreover, by comparing Fig. 5a, b and c, it can be found that a smaller initial air gap in the high-speed SV results in a more pronounced effect of oil temperature on the DF of the oil film acting on the armature. At 0.58 ms, when the initial air gap is 0.2 mm, the DF of oil film at 20 °C is 199.25 N, which is 36.25 N greater than that at 60 °C. When the initial air gap is 0.25 mm, the DF of the oil film at 20 °C is 71.25 N, which is 10.69 N greater than that at 60 °C. When the initial air gap is 0.3 mm, the DF of the oil film at 20 °C is 39.17 N, which is 4.94 N greater than that at 60 °C.

This phenomenon can be attributed to the fact that with the increase of oil temperature, the surface pressure distribution is basically no different in the early movement of the armature. However, as the armature movement speeds up and the distance between the iron core and the armature decreases, the difference in surface pressure distribution gradually increases. Additionally, the surface pressure decreases with rising temperature (refer to Fig. 6). Moreover, with increasing temperature, the saturated vapor pressure of oil increases significantly, while its dynamic viscosity, surface tension, and density gradually decrease (as shown in Table 2). Through

Table 3. Mesh setup in CFD models

Classification	Suction process			Release process		
Initial/ Residual air gap [mm]	0.2	0.25	0.3	0.05	0.1	0.15
Mesh type	Tetrahedral mesh					
Body mesh [mm]	0.5			0.2		
Mesh of surface of movement [mm]	0.125			0.05		
Nodes numbers	26711	29622	32476	163029	167349	203010
Elements numbers	119435	136756	154348	730762	789185	1010515
Element quality (average)	0.82812	0.81745	0.82892	0.82037	0.82394	0.82992
Skewness (average)	0.24197	0.25725	0.24078	0.25242	0.24813	0.23855
Aspect ratio (average)	1.8775	1.9127	1.8726	1.9099	1.8913	1.8695

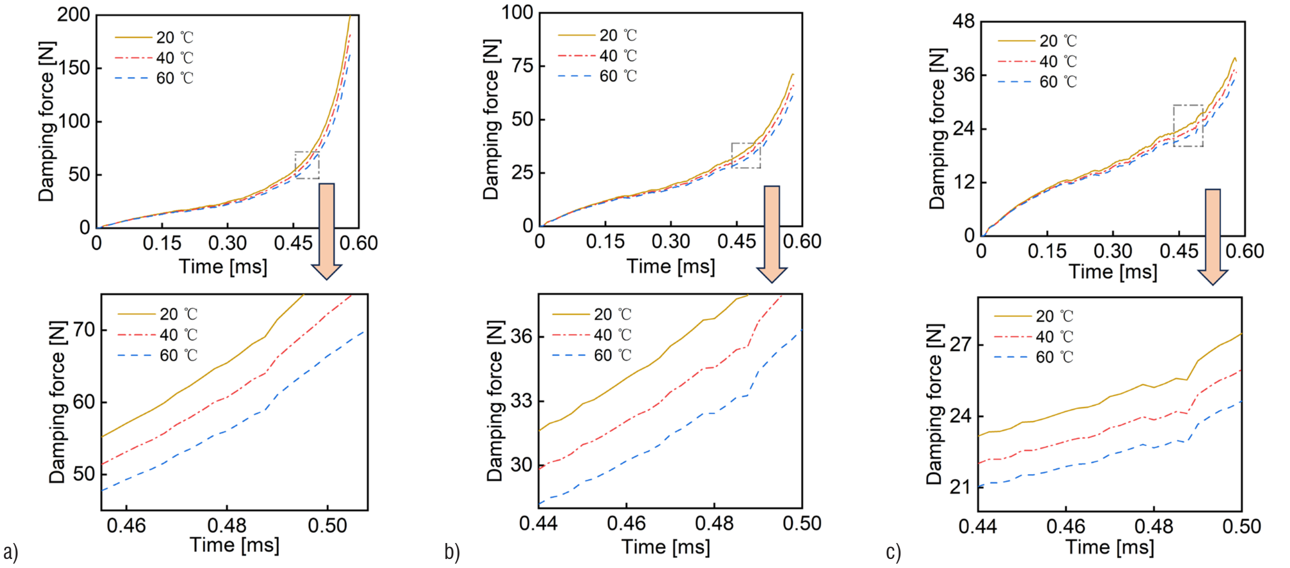

Fig. 5. Influence of temperature on the damping force (DF) of the oil film during the suction process at different initial gaps; a) 0.2 mm, b) 0.25 mm, and c) 0.3 mm

the single factor analysis of the relationship between oil physical properties and the DF of the oil film acting on the armature (as shown in Fig. 7), the authors found that the saturated vapor pressure and surface tension parameters have almost no effect on the DF of the oil film. However, as can be seen from Fig. 7b and d, the DF of the oil film acting on the armature decreases as the dynamic viscosity and density decrease. Moreover, this effect is more pronounced when the armature is close to the iron core. At 0.58 ms, the DF of the oil film at a dynamic viscosity of 2.2 mPa·s, which is 41.2 N smaller than that at 3.7 mPa·s; and the DF of oil film at a density of 803 kg/m^3, which is 4.7 N smaller than that at 833 kg/m^3. It is apparent that the dynamic viscosity has a more significant impact on the DF of the oil film. This is analogous to the conclusion that oil viscosity can exert a considerable influence on the DF of the oil film within the nozzle, as previously discussed in the literature [23]. Therefore, during the suction process, temperature mainly affects the damping characteristics of the oil film by influencing the dynamic viscosity and density of the oil.

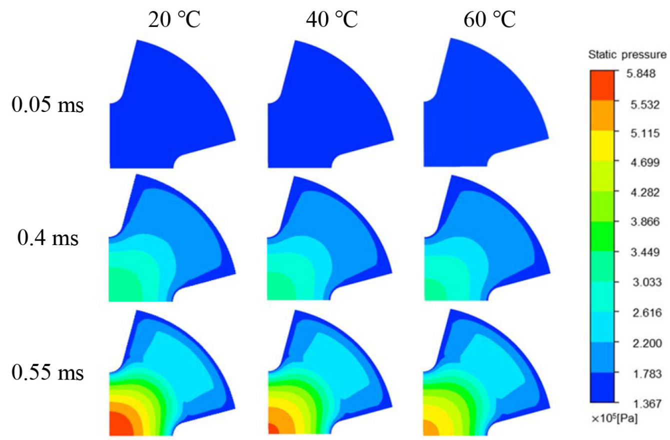

Fig. 6. Pressure distribution cloud at different temperatures for oil return pressure of 151,987.5 Pa and an initial air gap of 0.25 mm

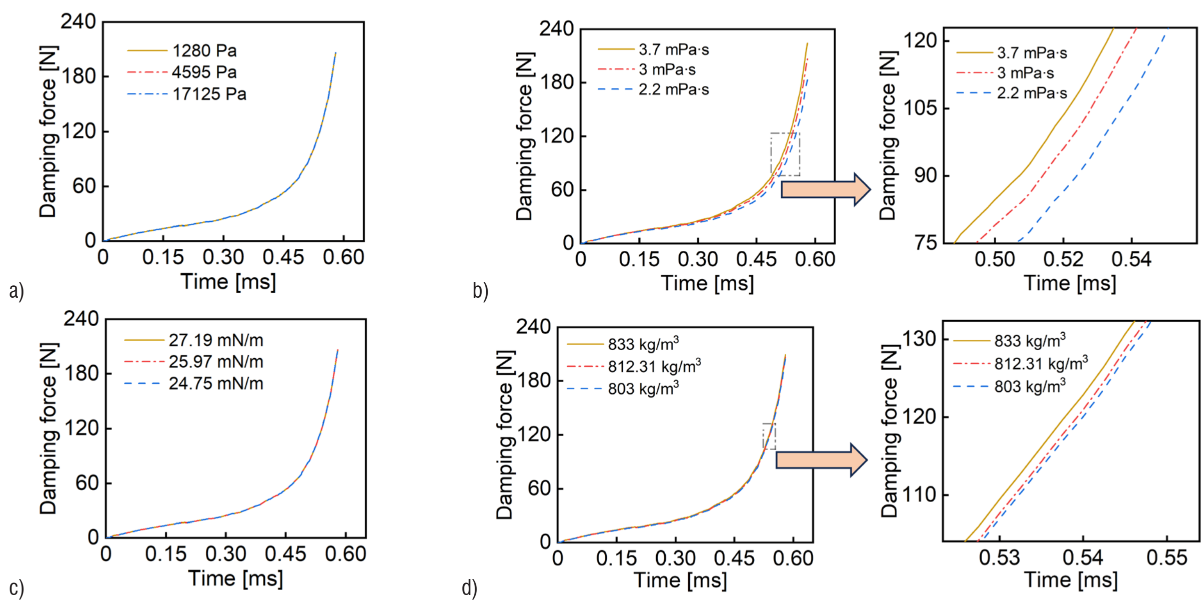

Fig. 7. Influence of oil physical parameters on the DF of the oil film during the suction process; a) saturated vapor pressure, b) dynamic viscosity, c) surface tension, and d) density

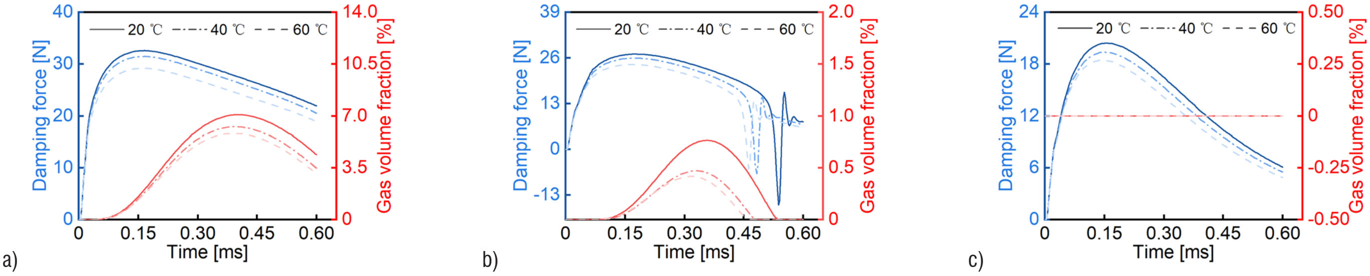

Fig. 8. Effect of temperature on the DF of the oil film and gas volume fraction during the release process at different residual gaps; a) 0.05 mm, b) 0.1 mm, and c) 0.15 mm

3.2 Effect of Oil Temperature on the Release Process

Figure 8 demonstrates the impact of oil temperature on the DF of the oil film and the gas volume fraction during the release process of the high-speed SV. As can be seen from Fig. 8, compared with the suction process (shown in Fig.5), the DF of the oil film on the armature during the release process is relatively small on the whole, and the maximum value of the DF of the oil film during the release process is 32.85 N. Also, as the oil temperature increases, the overall DF of the oil film during the release process gradually decreases, which is consistent with the influence law during the suction process. However, at the medium residual air gap (the small gap that still exists between the armature and the core after the SV is closed), the DF of the oil film appears to oscillate in the later stage of the armature movement. In addition, Fig. 8 also illustrates that at the small residual air gap, the gas volume fraction gradually decreases as the oil temperature increases. At 20 °C, 40 °C, and 60 °C, the maximum gas volume fraction was 7.08 %, 6.27 % and 5.81 %, respectively. After the armature stops moving, the gas volume fraction did not decrease to 0, that is, oil experienced cavitation, but no cavitation collapse phenomenon. At the medium residual air gap, with the increase of oil temperature, the change law of the gas volume fraction is similar to that of the small residual gap. At 20 °C, 40 °C and 60 °C, the gas volume fraction gradually increases from 0 % to 0.76 %, 0.46 % and 0.4 %, respectively, and gradually decreases to 0. Oil cavitation occurs and collapses. Notably, the moment when the DF of the oil film oscillates, it corresponds to the point when the gas volume fraction drops to zero, and the larger the peak value of the gas volume fraction, the greater the oscillation amplitude of the DF of the oil film. Therefore, it can be inferred that the bubble collapse leads to the oscillation of the above DF of the oil film. In contrast, at the larger residual air gap, the gas volume fraction within the oil is always zero, and no cavitation phenomenon occurs.

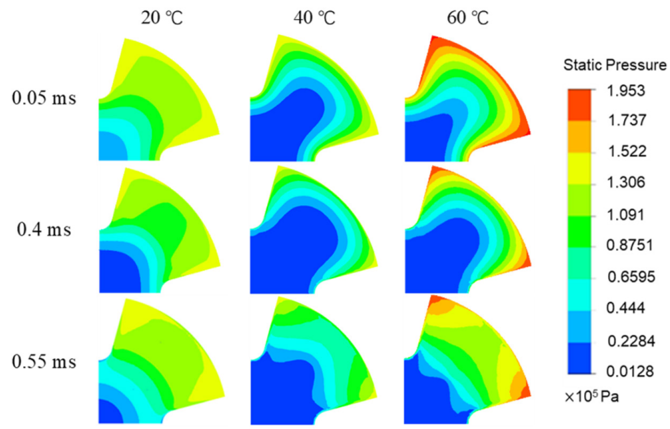

Fig. 9. Pressure cloud distribution at different temperatures for a pressure of 151987.5 Pa and a residual air gap of 0.1 mm

The above phenomena can be attributed to the fact that, as the oil temperature rises, the average pressure on the upper surface of

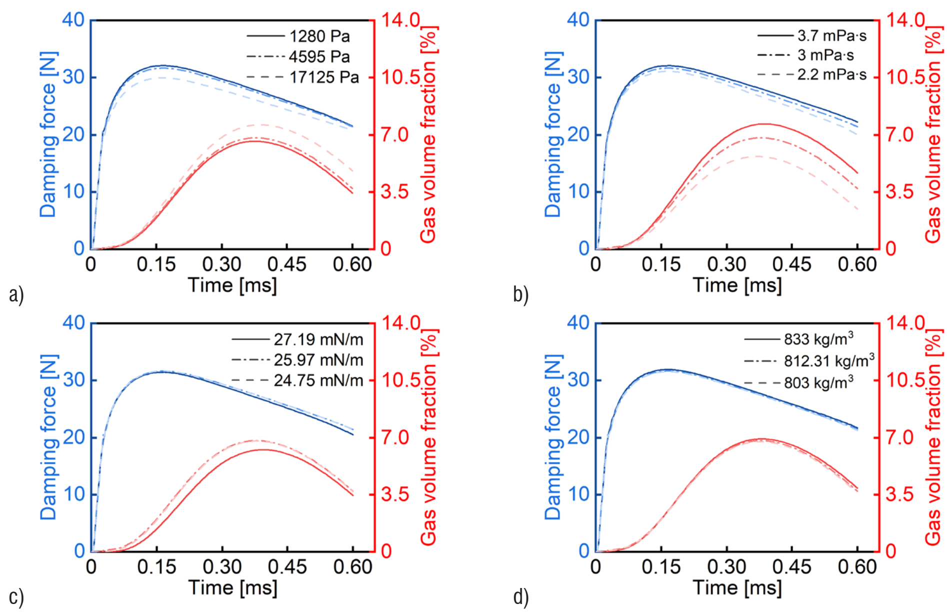

Fig. 10. Effect of oil physical parameters on the DF of the oil film and gas volume fraction during the release process at a residual air gap of 0.05 mm; a) saturated vapor pressure, b) dynamic viscosity, c) surface tension, d) density

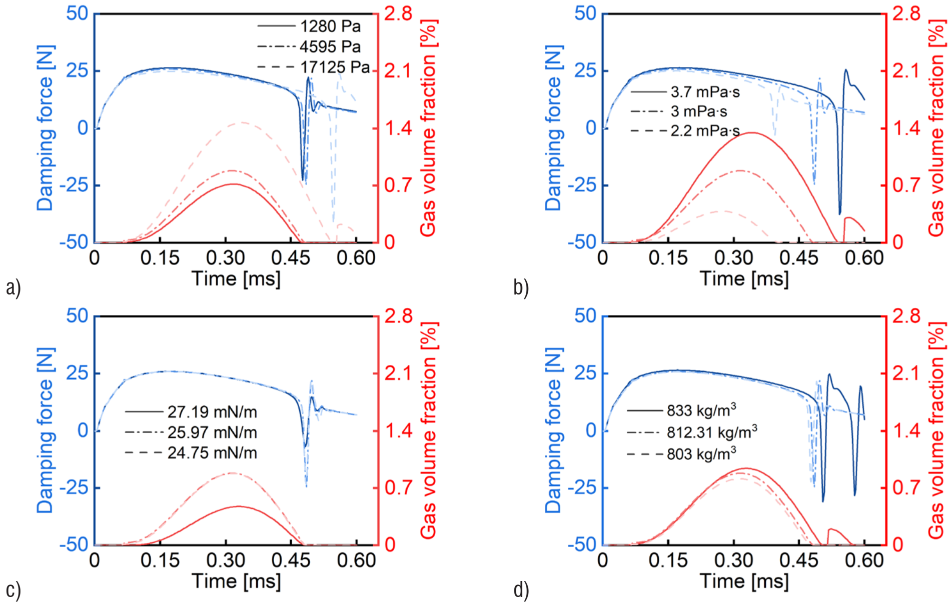

Fig. 11. Effect of oil physical parameters on the DF of the oil film and gas volume fraction during release process at a residual air gap of 0.1 mm; a) saturated vapor pressure, b) dynamic viscosity, c) surface tension, d) density

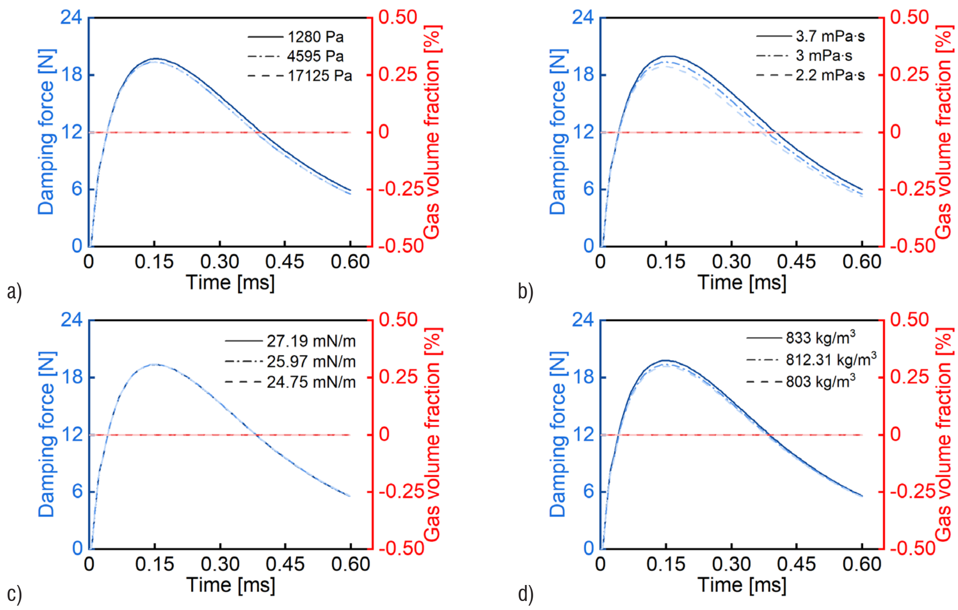

Fig.12. Effect of oil physical parameters on the DF of the oil film and gas volume fraction during release process at a residual air gap of 0.15 mm a) saturated vapor pressure, b) dynamic viscosity, c) surface tension, d) density

the armature gradually increases (shown in Fig. 9) when there is no cavitation collapse in the oil. So that the pressure difference between the upper and the lower surface of the armature gradually decreases. Therefore, the DF of the oil film during the release process tends to decrease as a whole.

In order to further explore the essence of the influence of oil temperature on oil film damping characteristics, a single-factor analysis was conducted to elucidate the relationship between the physical properties of oil and the DF of the oil film, as well as the gas volume fraction within the oil during the release process of a high-speed SV, as depicted in Figs. 10-12. The results reveal that the surface tension and the density of the oil have less influence on the DF of the oil film and the gas volume fraction during the release process of the high-speed SV. The DF curves of oil film almost overlap under different surface tension at the medium and large residual air gap. At the small residual air gap, the maximum difference between the DF of the oil film under the surface tension of 24.75 mN/m and 27.19 mN/m is only 0.88 N, and the maximum difference between the gas volume fraction is only 0.8 %. Similarly, at small and medium residual air gaps, the DF of the oil film curves at different densities almost overlap. At the large residual air gap, the difference between the DF of the oil film at a density of 833 kg/m^3 and 803 kg/m^3 is only 0.62 N at most, while the gas volume fraction curve also changes slightly, with a maximum difference of 0.31 %.

However, with the increase of saturated vapor pressure and the decrease of dynamic viscosity, the DF of the oil film acting on the armature decreases as a whole. Excluding oscillations due to cavitation collapse, the maximum difference between DF of oil film at saturated vapor pressure of 1280 Pa and 17125 Pa is 2.14 N, the maximum difference between the DF of oil film at the dynamic

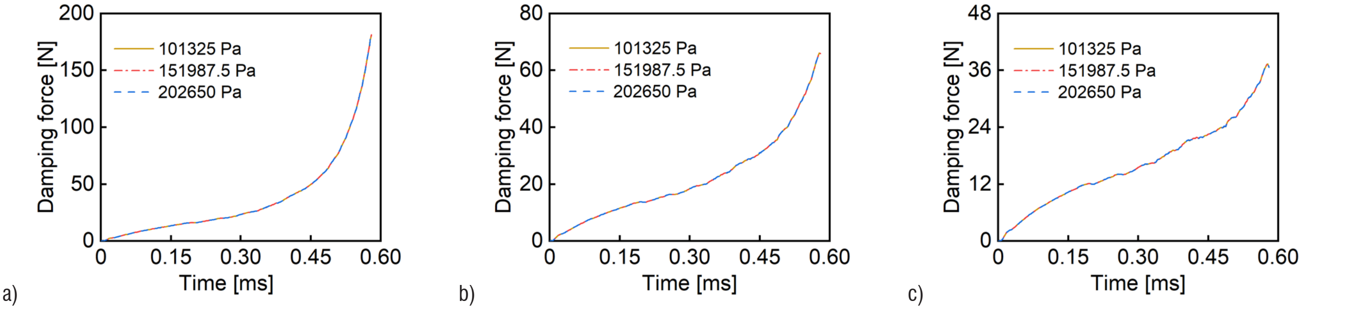

Fig. 13. Influence of oil return pressure on the DF of the oil film during the suction process at different initial air gaps; a) 0.2 mm, b) 0.25 mm, and c) 0.3 mm

viscosity of 3.7 mPa·s and the DF of the oil film at 2.2 mPa·s is 4.4 N. The saturated vapor pressure and dynamic viscosity of the oil also show the above pattern as the oil temperature increases. Therefore, as the oil temperature increases, the overall DF of the oil film acting on the armature also decreases gradually.

As can be seen from Figs. 10 and 11, the gas volume fraction gradually increases with an increase in the saturated vapor pressure and the dynamic viscosity, but the trend of the dynamic viscosity inversely correlates with temperature (shown in Table 2). However, it can be seen from Fig. 8 that the gas volume fraction decreases with increasing temperature at small and medium residual air gaps. This is because the effect of the dynamic viscosity on the oil cavitation is greater than that of the saturated vapor pressure at this time. At the small and medium residual air gaps, when the saturated vapor pressure of oil increases from 1280 Pa to 17125 Pa, the peak gas volume fraction increases by 1.37 % and 0.82 %, respectively. However, the viscosity decreases from 3.7 mPa·s to 2.2 mPa·s, the maximum gas volume fraction decreases by 2.23 % and 1.22 %, respectively.

In summary, during the release process, the temperature mainly changes the damping characteristics of the oil film by affecting the saturated vapor pressure and the dynamic viscosity of the oil.

3.3 Effect of Oil Return Pressure on the Suction Process

Figure 13 shows the influence of oil return pressure on the DF of the oil film during the suction process of the high-speed SV. As shown in Fig. 13, the oil return pressure has no influence on the DF during the suction process. As the armature progressively moves closer to the iron core during the suction process, the pressure on its upper surface incrementally rises, negating the possibility of cavitation. Therefore, it is not necessary to analyze the influence of oil return pressure on the gas volume fraction during the suction process. As can be seen from Fig. 14, during the suction process of the high-speed SV, the difference between the surface pressure of the armature and the oil return pressure does not change with the increase of the oil return pressure. Therefore, the oil return pressure has no influence on the DF of the oil film during the suction process.

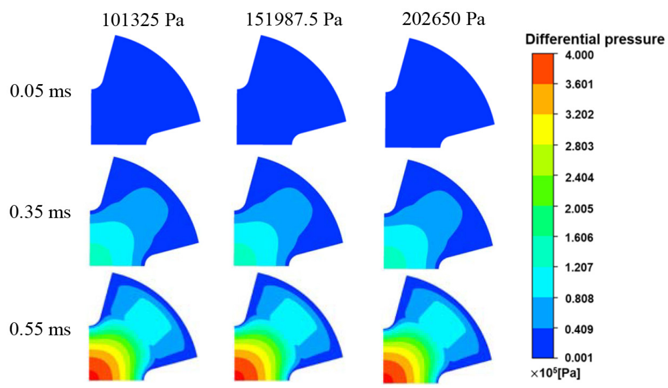

Fig. 14. Differential pressure cloud at different oil return pressures with a residual air gap of 0.1 mm during the suction process

3.4 Effect of Oil Return Pressure on the Release Process

Figure 15 demonstrates the impact of the oil return pressure on the DF of the oil film and the gas volume fraction within the oil during the release process of the high-speed SV. As shown in Fig. 15, when the residual air gap is small, the oil cavitation is observed, but the subsequent cavitation collapse does not occur. Also, the DF of the oil film gradually increases with the increase of oil return pressure. When the oil return pressure is 101,325 Pa, 151,987.5 Pa, and 202,650 Pa, the peak value of the DF of the oil film is 24.23 N, 31.48 N, and 37.75 N, respectively. Furthermore, the DF curve demonstrates a more rapid decline after reaching its peak with heightened oil return pressure. At the medium residual air gap, high oil return pressure effectively prevents the occurrence of oil cavitation, whereas medium and low pressures induce cavitation, with cavitation collapse occurring specifically medium oil return pressure. Under the circumstances, the DF of the oil film initially rises with increasing oil return pressure,

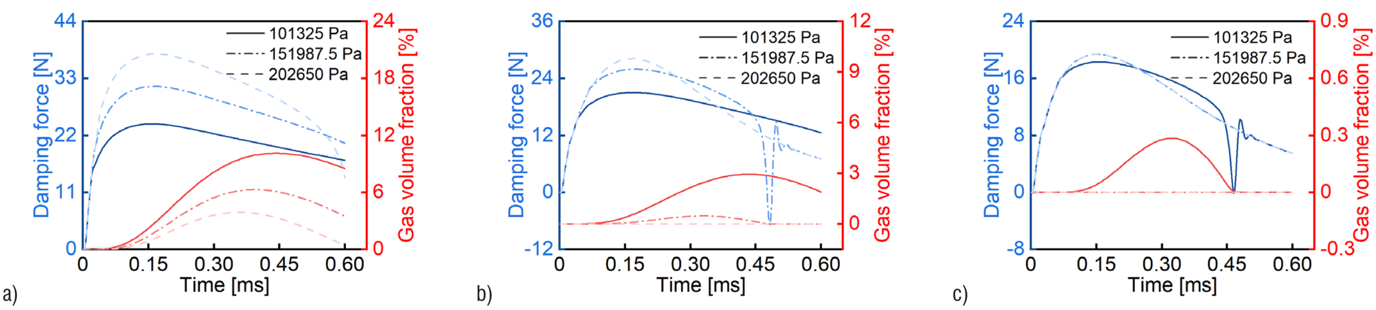

Fig. 15. Effect of oil return pressure on the DF of the oil film and gas volume fraction during the release process at different residual air gaps: a) 0.05 mm, b) 0.1 mm, and c) 0.15 mm

subsequently exhibiting a pattern of increase followed by decrease, with oscillations manifesting at the point of cavitation collapse. At the large residual air gap, oil cavitation and subsequent collapse occur only at low oil return pressure. The change law of the DF of the oil film is similar to that of the medium residual air gap, with the exception that the oil cavitation is absent at medium and high oil return pressures, rendering the oil return pressure inconsequential to the DF.

By comparing Fig. 15a, b, and c, it can be seen that under the same return oil pressure, when the residual air gap is larger, the DF of the oil film on the armature is smaller as a whole. When the oil return pressure is 101325 Pa, the peak values of DF of the oil film at small, middle, and large residual air gaps are 24.23 N, 21.02 N, and 18.29 N, respectively. When the return oil pressure is 151,987.5 Pa, the peak values of the DF of the oil film at low, middle, and high residual air gaps are 31.48 N, 25.94 N, and 19.36 N, respectively. When the return oil pressure is 202,650 Pa, the peak values of the DF of the oil film at small, middle, and large residual air gaps are 37.75 N, 28.17 N, and 19.37 N, respectively. Similarly, by comparing Fig. 15a, b, and c, it also can be noticed that for the same oil return pressure, the larger the residual air gap, the smaller the volume fraction of oil gas and the less likely the cavitation phenomenon is to occur.

The above behaviors can be explained by the fact that as the oil return pressure rises, when the fuel does not appear to collapse, the absolute difference between the upper surface pressure of the armature and the oil return pressure gradually increases (as shown in Fig. 16). Consequently, the pressure difference between the upper and lower surfaces of the armature gradually increases. Thus, the DF of the oil film overall rises with the ascent of the oil return pressure during the release process. Moreover, it is important to note that at a constant temperature, the saturated vapor pressure of the oil remains immutable; thus, a lower oil return pressure increases the likelihood of the cavitation occurring on the armature surface, consequently elevating the gas volume fraction. Therefore, appropriately increasing the oil return pressure can reduce the possibility of cavitation or cavitation collapse.

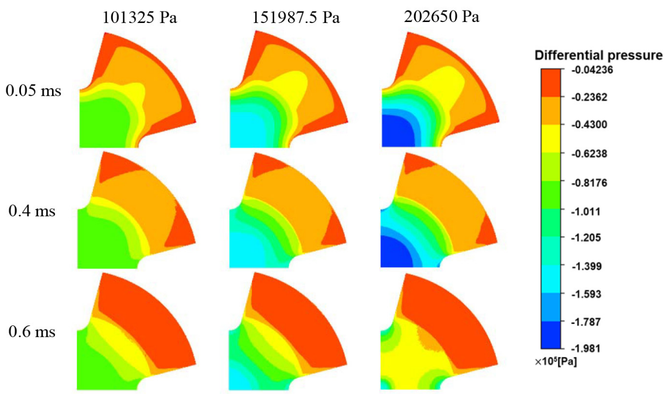

Fig. 16. Differential pressure cloud at different oil return pressures with a residual air gap of 0.05 mm during the release process

Furthermore, Fig. 17 illustrates that, under identical oil return pressure, a reduction in residual air gap results in a proportional increase in the absolute difference between the upper surface of the armature and the oil return pressure. Consequently, the DF of the oil film on the armature during the release process will also be amplified. This is similar to the law that the smaller the initial air gap, the greater the influence of the DF of the oil film during suction process. At the same time, a greater absolute pressure difference also means a lower pressure on the upper surface of the armature. Once the pressure on the upper surface of the armature falls below the saturated vapor pressure of the oil, cavitation or even cavitation collapse will occur on the surface of armature, which will greatly affect the service life of the high-speed SV. Therefore, when designing the high-speed SV, the residual air gap is not easy to be too small.

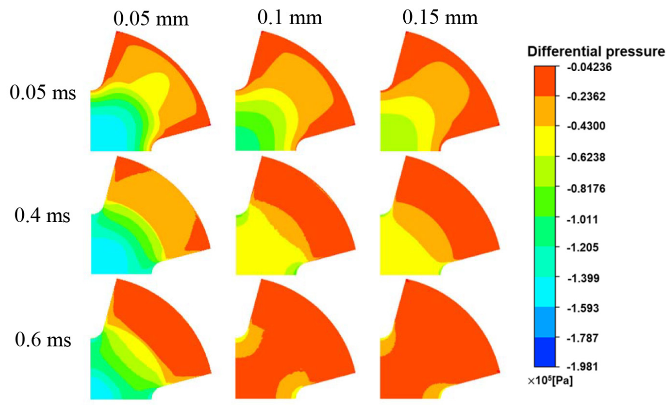

Fig. 17. Pressure difference cloud image under different residual air gaps when oil return pressure is 151987.5 Pa during the release process

4 CONCLUSIONS

The temperature greatly influences the DF of the oil film during both the suction process and the release process of the high-speed SV. Specifically, temperature changes the DF of the oil film during the suction process by affecting the dynamic viscosity and density of the oil, while temperature changes the DF of the oil film during the release process by affecting the saturated vapor pressure and dynamic viscosity of the oil. An increase in oil temperature results in a reduction the overall DF of the oil film in both processes of the high-speed SV. By enlarging the initial and residual air gaps, it is conducive to mitigate the impact of temperature on the DF of the oil film, thereby reducing the oil cavitation and improving the operational consistency and reliability of the high-speed SV.

The oil return pressure does not affect the DF of the oil film during the suction process of the high-speed SV. However, during the release process, at the small residual air gap, the DF of the oil film increases gradually with the oil return pressure, exhibiting a more rapidly descending curve beyond the peak value. At the medium residual air gap, the DF of the oil film shows a trend of increasing and then decreasing with the oil return pressure, and oscillations occur when the oil cavitation collapses. However, at the larger residual air gap, oil cavitation and collapse occur only under low oil return pressure, and the maximum gas volume fraction is only 0.3%. And at medium and high oil return pressures, cavitation does not occur, the DF of the oil film is consistent. Accordingly, when the residual air gap is large, the effect of the oil return pressure on the characteristics of the oil film is not significant.

In the context of the release process of high-speed SV, the increase of oil return pressure has the effect of reducing the possibility of cavitation on the armature surface. However, this increase also has the consequence of increasing the overall DF of the oil film, particularly when the residual air gap is small or medium. This represents a contradictory problem that is faced by high-speed SV in the working environment. To alleviate this contradiction, it is possible to expand the residual air gap in a way to reduce the impact of cavitation, while also reducing the DF of the oil film.

The design and optimization of novel damping characteristic structures on the armature for high-speed SVs should be prioritized in future research endeavors.

References

[1] Bai, Y., Lan, Q., Fan, L.Y., Yao, J., Kong, X.D., Yang, L., Wen, L.M. Pressure characteristics of the fuel system for two-stroke diesel engines under different operational modes. *Fuel*, 332, 126007 (2023) **DOI:10.1016/j.fuel.2022.126007**

[2] Bai, Y., Lan, Q., Fan, L.Y., Ma, X.Z., Liu, H. Investigation on the fuel injection stability of high-pressure common rail system for diesel engines. *Int J Engine Res* 22, 616-631 (2021) **DOI:10.1177/1468087419856981**

[3] Gu, Y., Fan, L., Lan, Q., Wei, Y., Zhou, J., Du, K. Multi-objective optimization of fuel injection performance of a common rail injector. *Int J Engine Res* 24, 3282-3296 (2023) **DOI:10.1016/j.applthermaleng.2024.123729**

[4] Xu, J., Fan, L., Chen, C., Lu, G., Tu, T. Study on fuel injection stability improvement in marine low-speed dual-fuel engines. *Appl Therm Eng* 253, 123729 (2024) **DOI:10.1016/j.applthermaleng.2024.123729**

[5] Hung, N.B., Lim, O. Development of a high-performance solenoid gas injector applied for compressed natural gas fueled engines. *Int J Automot Techn* 23, 567-576 (2022) **DOI:10.1007/s12239-022-0052-8**

[6] Hung, N.B., Lim, O. Improvement of electromagnetic force and dynamic response of a solenoid injector based on the effects of key parameters. *Int J Automot Techn* 20, 949-960 (2019) **DOI:10.1007/s12239-019-0089-5**

[7] Jeong, J., Kim, K., Jang, B., Park, G. Development of a fast-stabilized fuel injection system using a solenoid actuator. *J Mech Sci Technol* 37, 5207-5218 (2023) **DOI:10.1007/s12206-023-0923-6**

[8] Gowrishankar, S., Krishnasamy, A. Injection system modification and optimization for performance enhancement and emission reduction in a light-duty diesel engine fuelled by biodiesel-water emulsion *Fuel* 337, 127222 (2023) **DOI:10.1016/j.fuel.2022.127222**

[9] Xia, S.Z., Ouyang M.Y., Zhou, M. Squeeze flow analysis of damping oil film in solenoid valve of electronic unit pump. *J Tsinghua Univ* 43, 693-697 (2003) **DOI:10.16511/j.cnki.qhdxxb.2003.05.031** (in Chinese)

[10] Xia, S.Z., Ouyang, M.Y., Zhou, M. Study on squeeze film damping of high speed and powerful solenoid valve. *Chin J Mech Eng* 39, 84-88 (2003) **DOI:10.3321/j.issn:0577-6686.2003.07.018** (in Chinese)

[11] Resch, M., Scheidl, R. A model for fluid stiction of quickly separating circular plates. *Proc Inst Mech Eng Part C J Mech Eng Sci* 228, 1540-1556 (2013) **DOI:10.1177/0954406213509613**

[12] Scheidl, R., Gradl, C. An oil stiction model for flat armature solenoid switching valves. *ASME/BATH Symposium on Fluid Power and Motion Control* V001T01A041 (2013) **DOI:10.1115/fpmc2013-4467**

[13] Scheidl, R., Gradl, C. An approximate computational method for the fluid stiction problem of two separating parallel plates with cavitation. *J Fluids Eng-T ASME* 138, 061301 (2016) **DOI:10.1115/1.4032299**

[14] Zhao, J.H., Zhao, S.N., Grekhov, L. Study on transient fuel hydrodynamic force characteristics of high-speed solenoid valve for common rail injector. *Int J Automot Techn* 21, 1257-1269 (2020) **DOI:10.1007/s12239-020-0119-3**

[15] Scheidl, R., Hu, Z.D. Fluid stiction with mechanical contact-a theoretical model. *Proceedings of the BATH/ASME Symposium on Fluid Power and Motion Control* V001T01A033 (2016) **DOI:10.1115/fpmc2016-1769**

[16] Scheidl, R., Gradl, C., Plöckinger, A. The cushioning groove for solenoid switching valves. *Int J Fluid Power Syst* 8, 76-81 (2014) **DOI:10.5739/jfpsij.8.76**

[17] Zhang, J.H., Wang, D, Xu, B., Gan, M.Y., Pan, M., Yang, H.Y. Experimental and numerical investigation of flow forces in a seat valve using a damping sleeve with orifices. *J Zhejiang Univ-Scien* A 19, 417-430 (2018) **DOI:10.1631/jzus.a1700164**

[18] Dernotte, J., Hespel, C., Foucher, F., Houillé, S, Mounaïm-Rousselle, C. Influence of physical fuel properties on the injection rate in a diesel injector. Fuel 96, 153-160 (2012) **DOI:10.1016/j.fuel.2011.11.073.7**

[19] Payri, R., Salvador, F.J., Gimeno, J., Brancho, G. The effect of temperature and pressure on thermo dynamic properties of diesel and biodiesel fuels. *Fuel* 90, 1172-1180 (2011) **DOI:10.1016/j.fuel.2010.11.015**

[20] Park, S.H., Yoon, H.K., Suh, S.H., Lee, C.S. Effect of the temperature variation on properties of biodiesel and bio science diesel-ethanol blends fuels. *Oil Gas Sci Technol* 63, 737-745 (2008) **DOI:10.2516/ogst:2008038**

[21] Liu, P., Zhang, R., Zhao, Q., Peng, S. Eddy effect and dynamic response of high-speed solenoid valve with composite iron core. *Materials* 16, 5823 (2023) **DOI:10.3390/ma16175823**

[22] Cao, T., He, Z., Si, Z., El-Seesy, A.I., Guan, W., Zhou, H., Wang, Q. Optical experimental study on cavitation development with different patterns in diesel injector nozzles at different fuel temperatures. *Exp Fluids* 61, 185 (2020) **DOI:10.1007/s00348-020-03006-5**

[23] Payri, R., Salvador, F.J., Carreres, M., De la Morena, J. Fuel temperature influence on the performance of a last generation common-rail diesel ballistic injector. Part II: 1D model development, validation and analysis. *Energ Convers Manage* 114, 376-391 (2016) **DOI:10.1016/j.enconman.2016.02.043**

Acknowledgements *This work was supported by the National Natural Science Foundation of China (grant numbers 52001032), the Excellent Youth Project of the Education Department of Hunan Province of China (grant numbers 23B0305), the Natural Science Foundation of Hunan Province of China (grant numbers 2021JJ40588), and the Science and Technology Innovative Research Team in Higher Educational Institutions of Hunan Province (New energy intelligent vehicle technology).*

Received 2024-09-17, revised 2024-12-23, 2025-02-10, accepted 2025-02-27, *Original Scientific Paper.*

Data availability *The data supporting the findings of this study are included in the article.*

Author contribution *Peng Liu: resources, funding acquisition, project administration, methodology, writing – review & editing; Qing Zhao: data curation, formal analysis, visualization, validation, writing – original draft; Shijian Peng: visualization, writing – review & editing; Wenwen Quan: data curation, writing – review & editing; Zhida Gao: conceptualization, methodology, writing – review & editing, resources.*

Vpliv temperature olja in povratnega tlaka olja na značilnosti dušenja oljnega filma elektromagnetnega ventila za visoke hitrosti

Povzetek *Elektromagnetni ventil visoke hitrosti je kritična komponenta v sistemih vbrizga goriva skupnim vodom kjer njegov dinamični odziv pomembno vpliva na natančnost krmiljenja vbrizga goriva. Poleg tega na ta odziv še posebej vpliva dušilna sila oljnega filma med armaturo in železnim jedrom. Za preučitev učinkov temperature olja in povratnega tlaka olja na značilnosti dušenja oljnega filma v elektormagnetnega ventila visoke hitrosti je bil uporabljen pristop numerične simulacije. Modeli računalniške dinamike tekočin so bili izdelani za analizo vpliva temperature olja in povratnega tlaka olja na dušilno silo oljnega filma in njegove kavitacijske lastnosti v različnih zračnih razmikih. Rezultati kažejo, da se s povečevanjem temperature olja dušilna sila oljnega filma na splošno zmanjšuje med procesi sesanja in izpuščanja pri elektromagnetnem ventilu visoke hitrosti. Poleg tega lahko s povečanjem začetne in preostale zračne reže ublažimo vpliv temperature na dušilno silo oljnega filma in s tem zmanjšamo pojavnost kavitacije. Pomembno je, da povratni tlak olja ne vpliva na dušilno silo oljnega filma med postopkom sesanja. Vendar pa se med postopkom sproščanja dušilna sila oljnega filma povečuje s tlakom vračanja olja, kadar je zaostala zračna reža majhna. Pri srednjih zaostalih zračnih režah se dušilna sila sprva povečuje s povratnim tlakom olja, nato pa se zmanjšuje in jo spremljajo nihanja med kavitacijskim kolapsom. Pri velikih preostalih zračnih režah je vpliv povratnega tlaka olja na DF oljnega filma zanemarljiv.*

Ključne besede *elektromagnetni ventil visoke hitrosti, temperatura olja, povratni tlak olja, dušilna sila oljnega filma, kavitacija*