Experiment on the Influence of Residual Exhaust Gas on the Combustion Characteristics of a Miniature Engine with Platinum Wire Ignition

Huichao Shang, Li Zhang,* Zhigang Tang, and Xi Chen

ABSTRACT: Affected by the scale effect, it is difficult for the gas exchange of a micro-internal combustion (IC) engine to reach the level of a conventional-size engine, resulting in excessively high residual exhaust gas content in the cylinder and serious deterioration of combustion. In order to verify the above point, experiments were carried out based on the variation characteristics of the residual exhaust gas content of the micro-engine during the starting process. The residual exhaust gas content of the micro-engine exhibits a gradually increasing change characteristic during the starting process. Through continuous monitoring of the in-cylinder pressure, the combustion characteristics of the first ignition cycle without residual exhaust gas were captured. Then, it was compared with that in the transitional combustion stage and the stable combustion stage. The latter two combustion stages have different residual exhaust gas contents. The results show that for micro-engines, the combustion cycle with different residual exhaust gas contents presents significantly different combustion characteristics. As the residual exhaust gas content increases, the combustion pressure and the heat release rate decrease, and the combustion duration extends. Excessive residual exhaust gas content is the main reason for the abnormal combustion characteristics of the micro-IC engine with platinum wire ignition. In addition, when there is no residual exhaust gas, the indicated work is the largest and the thermal efficiency is higher. As the in-cylinder residual exhaust gas content increases, the indicated work decreases significantly.

1. INTRODUCTION

A micro-power generation system can achieve ultra-high energy density energy power output at a microscale/intermediate scale, so as to meet the needs of micro-aircrafts, portable equipment, and other fields. Therefore, in recent years, a large amount of research has been done on the development of various micro-power generation systems. Among them, micro-heat engines using liquid hydrocarbon fuels have attracted more and more attention because the heat released by the combustion of liquid fuels in these micro-heat engines may generate high-energy density power sources. Though several micro-heat engine programs have been developed for a long time, such as micro-internal combustion (IC) engines, micro-gas turbine engines, micro-free piston engines, and micro-rotary engines; however, the scaled-down reciprocating IC engines are the most commendable and expected, which are showing the prospect as a promising component of a high-energy density power source for various applications.

However, as the size decreases, the irreversible loss becomes larger and the efficiency is low, which makes the development of ultra-high energy density micro-engines more challenging. Rowton et al. analyzed and created scaling relationships for the performance and efficiency among the scaling study IC engines, deduced that when the ratio of a cylinder surface area to swept volume is less than 1.5 cm⁻¹, the wall heat loss is the main mechanism of thermal efficiency loss, and the performance of the scaled-down IC engine will be significantly affected. Sher et al. developed a phenomenological model to consider the relevant processes inside the cylinder of a homogeneous charge-compression-ignition engine, proposed an approximated analytical solution to yield the lower possible limits of scaling down HCCI cycle engines, and indicated the minimum allowed engine size is between 0.3 and 0.4 cm². Menon and Cadou studied the scaling rules, which were derived from comprehensive dynamometer investigations of nine of the smallest commercially available miniature IC engines, indicated that the minimum length scale of a thermodynamically viable IC engine is approximately 5 mm.

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For further scaling down miniature IC engine to a mesoscale, a 0.99 cm³ miniature IC engine has been used for an in-cylinder combustion test. The results show that glow-ignition combustion under the micro-space conditions tends to produce abnormal combustion phenomena such as high cyclic variation, partial burning, and slow heat-release rate. Micro-space combustion efficiency and combustion stability are still the key constraints for further reducing its structure to the mesoscale.

Miniature IC engines mainly use methanol as a fuel. Because the lower heating value of the methanol mixture (2.81 MJ/kg) is close to that of gasoline (2.83 MJ/kg), and the laminar combustion speed of methanol is faster than gasoline, it can be determined that the difference in fuel is not the main reason for the poor combustion characteristics of the miniature IC engine. Considering the gas exchange process of the miniature IC engine, which adopts the scavenging mode, as shown in Figure 1. The reciprocating motion of the piston controls the opening and closing of the ports, which realizes the exhaust, scavenging, and intake of the engine. Therefore, it is inevitable that a certain amount of residual exhaust gas will stay in the cylinder. Under the condition of small size, the low average speed of the piston leads to the low momentum of the scavenging gas, and the increase in the surface-to-volume ratio of the cylinder caused by the scale effect also increases the flow friction resistance. Meanwhile, the relative gap between the piston and the cylinder wall increases, resulting in poor gas compression in the crankcase. Affected by these factors, it is difficult for the in-cylinder charge of a micro-IC engine to reach the perfection level of a conventional-size IC engine, resulting in excessively high residual exhaust gas content in the cylinder. The excessively high amount of residual exhaust gas not only reduces the fresh charge but also makes flame propagation difficult; slows down the burning rate, and may cause misfires or partial fires. However, whether the combustion characteristics of the micro-engine with a low heat release rate, long combustion duration, and high cycle fluctuation rate are essentially causal with the characteristics of insufficient gas exchange in the cylinder and high residual exhaust gas content. This point has yet to be verified objectively.

In response to the above problems, in this paper, it uses a micro-combustion test platform, taking a micro-IC engine with a cylinder diameter of 11.25 mm and a stroke of 10 mm as the research object, and testing the basic characteristics of the combustion process in the cylinder of the micro-IC engine. In order to study the influence of the residual exhaust gas content in the cylinder on the combustion characteristics of the micro-IC engine with platinum wire ignition, the ignition start experiment under different cylinder temperature conditions was designed, and the combustion cycle of the ignition start process was continuously monitored in real time. According to the variation characteristics of the residual exhaust gas content of the combustion cycle during the ignition and starting processes, the combustion cycle is divided into three stages, namely: the first ignition cycle, the transitional combustion stage, and the stable combustion stage. By capturing the first ignition cycle of the starting process, the combustion characteristics of the micro-IC engine without residual exhaust gas were obtained. Then, it was compared with the characteristics of the combustion cycle in the transitional combustion stage and the stable combustion stage, and the difference in combustion characteristics under different residual exhaust gas content condition was analyzed. The results show that the excessive residual exhaust gas content in the cylinder caused by the difficulty of charge exchange is the main factor that produces the abnormal combustion characteristics of a micro-IC engine with platinum wire ignition. Compared with the stable combustion stage, the indicated work of the combustion cycle without residual exhaust gas is the largest and the thermal efficiency is higher. As the residual exhaust gas content increases, the indicated work decreases significantly.

2. COMBUSTION CHARACTERISTIC TEST UNDER STABLE CONDITIONS

A specialized miniature engine combustion test bench is constructed, as shown in Figure 2, which is made up of a motor
driving system, load absorption system, data acquisition system, as well as a test engine. The working principle of the test bench is described in detail in ref 22. In Figure 2, a pressure sensor and a crank angle sensor are installed on the test bench to carry out combustion diagnosis. The pressure sensor is Kistler Type 6052B and the crank angle sensor is Kistler Type 2613B. The data of combustion parameters were analyzed by a data acquisition system of DEWE-2010. During the test, signal sampling resolution is set up to 0.2°CA.

The test engine in this project is a “three leaf model engine AP06”, which has a displacement volume of 0.99 cm³. It is a two-stroke, single-cylinder, glow-ignition, no piston ring, and air-cooled reciprocating engine with following dimensions: bore 11.25 mm, stroke 10 mm, and a geometric compression ratio of 8. The AP06 engine uses a glow ignition system. Neither a spark plug nor fuel injectors are used. It has been fueled with a mixture of 65% methanol, 15% nitromethane, and 20% castor oil. The cylinder head of the engine was structurally redesigned and fabricated (the position of the glow plug deviates from the cylinder centerline by 3.5 mm) for the installation of the pressure sensor. Combustion diagnosis was carried out at 6000 r/min with a fuel/air equivalence ratio about 1.5.

Figure 3 shows the combustion parameters calculated in real time by a DEWESOFT at an engine speed of 6000 r/min. Figure 3a,b shows the indicated mean effective pressure ($p_{mi}$) and the peak combustion pressure ($p_{max}$) of the continuously sampled 150 test cycles. It shows that the miniature engine with a displacement of 0.99 cm³ has serious cyclic variation. For example, the coefficients of variation for the miniature engine are around 16.3% for $p_{mi}$ and around 23.4% for $p_{max}$. In Figure 3a, for some measured cycles, $p_{mi}$ is even less than 50% of the overall average $p_{mi}$, which indicates poor combustion occurring inside the cylinder. In Figure 3b, it should be noted that $p_{max}$ of several cycles are even equal to those in motoring conditions, which is proved to be relevant to misfire or partial burning by heat release analysis.

Figure 3c shows the crank angle of $p_{max}$ ($A_{pmax}$) for the individual cycles of the continuously sampled 150 test cycles at 6000 r/min. The average value of $A_{pmax}$ is about 20.5°CA ATDC (after top dead center), which is much higher than that of conventional-sized IC engines. For some test cycles, $A_{pmax}$ is
close to TDC (top dead center) because of serious partial burning and misfiring. Figure 3d shows the severe variation of the crank angle at which a fuel mass fraction of 5 percent (CA05) is burned, which usually represents the start of combustion. It is deduced that the glow ignition of the miniature IC engine cannot give stable ignition timing, and thus the start of combustion varies considerably from cycle to cycle, bringing about the serious cycle-by-cycle variation of the miniature IC engine. Figure 3e shows the severe variation of the crank angle at which a fuel mass fraction of 50 percent (CA50) is burned. The average value of CA50 is close to 30°CA ATDC, which is much higher than that of conventional-sized IC engines (referring to the value of about 6–8°CA for the conventional-sized spark-ignition engine), and it leads to a lower thermal efficiency. Figure 3f shows the variation of combustion duration (interval between CA05 and CA90, CA90 indicates the crank angle corresponding with the burned mass fraction of 90%), which also indicates a serious cycle-by-cycle variation. The combustion duration of the miniature IC engine was longer than that of conventional size gasoline engines, which indicate a much slower heat release rate.

3. COMBUSTION CHARACTERISTIC TEST UNDER DYNAMIC CONDITIONS OF IGNITION START

The abnormal combustion characteristics of the micro-IC engine may have a causal relationship with the characteristics of insufficient gas exchange in the cylinder and high residual exhaust gas content. In order to verify this point of view, the continuous real-time monitoring of the combustion cycle during the ignition start process was carried out. The design of such an experiment is based on the fact that the residual exhaust gas content of the combustion cycle of the micro-IC engine exhibits a gradually increasing change characteristic over time during the ignition and starting processes (the residual exhaust gas content of the first ignition cycle is zero and gradually changes to the level of the residual exhaust gas content of the combustion cycle in the stable combustion stage). By capturing the first ignition cycle and compared with the combustion cycle with residual exhaust gas content, the influence of the residual exhaust gas content in the cylinder on the combustion characteristics of a micro-engine is analyzed.

During the ignition start process, the micro-engine was motored at 6000 r/min by the motor at cylinder temperatures of 90, 140, and 150 °C, and then the ignition current was switched on to ignite the micro-IC engine. Figure 4a–c shows...
the data band of $p_{mi}$ for the individual cycles of the continuously sampled 300 test cycles under hot start conditions. It shows that at the beginning of the test because the mixture in the cylinder has not been ignited, the values of $p_{mi}$ are all 0 MPa. Subsequently, the first ignition combustion cycle is clearly observed, which has the largest $p_{mi}$ value in the test conditions. Immediately afterward, several transitional combustion cycles occurred. The $p_{mi}$ keeps a high value, but the cyclic variation in $p_{mi}$ becomes more severe and more misfiring cycles were found. In the evaluation criteria for combustion diagnosis, it is generally considered that if $p_{mi}$ of an individual cycle is less than one-third of the mean value of the continuously sampled test cycles, the individual cycle is regarded as a partial burning or misfiring cycle, where an individual cycle with $p_{mi}$ less than or close to zero must be a misfiring cycle.\(^{1)}\) Subsequently, the phenomenon of misfiring cycles whose values of $p_{mi}$ are almost close to zero disappears, and the combustion cycle gradually tends to stabilize. However, the values of $p_{mi}$ at this stage become lower than that of the early stages of ignition (from the beginning of the first ignition cycle to the end of the transitional cycles).

For the first ignition cycle, because no combustion occurred in the previous cycle, the residual gas in the cylinder was all fresh charge, so the amount of residual burned gas of the first ignition cycle is 0, and the fresh charge in the cylinder reaches the maximum, thereby obtaining the maximum $p_{mi}$. After the first ignition cycle is the transitional combustion cycle. These combustion cycles have a certain amount of residual burned gas. Due to the low temperature of the platinum wire at this time and the influence of residual exhaust gas in the cylinder, more misfire cycles occurred at this stage. However, due to the large number of misfire cycles, the mixture cannot be completely burned during the misfire such that the residual gas in the cylinder contains a part of the unburned fresh charge. Therefore, the residual exhaust gas content in the cylinder in the next cycle is relatively small, so the $p_{mi}$ of the non-misfire combustion cycle in the transition phase is relatively high. In the later stable combustion stage, the misfire cycle is less, the combustion is more complete, the residual gas in the cylinder is all burned gas, and the residual exhaust gas content in the cylinder is relatively high, which causes its $p_{mi}$ to decrease compared with the early stages of ignition.

For further analysis and comparison, the same method is used for the combustion test during the cold start process. Figure 4d shows $p_{mi}$ for the individual cycles of the continuously sampled 300 test cycles under the conditions of a cold start with a cylinder temperature of 40 °C. It can be seen that $p_{mi}$ under the cold start conditions is generally higher than that in the hot start conditions, and its maximum value can reach 0.65 MPa. Meanwhile, the average value of $p_{mi}$ in the stable combustion stage is relatively high. This is because the temperature of the cylinder block is higher during hot start conditions, and the high cylinder block temperature reduces the intake charge, thereby reducing $p_{mi}$. However, it is worth noting that although the increase in the cylinder temperature will cause the $p_{mi}$ to decrease, by observing the test cycle between 150 and 300 in Figure 4a–c (the duration is about 1.5 s), the $p_{mi}$ in this stage does not show an obvious downward trend. Therefore, in the short time of the ignition start process, the cylinder block will not cause a large temperature rise and cause the charging efficiency to drop. This shows that the decrease in $p_{mi}$ in the early stages of ignition in Figure 4 is not due to the cylinder temperature rise.

In addition, further analyzing the test data of the dynamic process of hot start and cold start, it can be found that there are basically no consecutive two or more misfire cycles or partial misfire cycles. For a misfire or partial misfire cycle, the next combustion cycle adjacent to it can usually burn completely and have a higher $p_{mi}$. This phenomenon is quite obvious in the transitional combustion phase of the hot start process. During this period, the normal combustion cycle and the misfire cycle alternately occur. In this alternating process, the $p_{mi}$ of the non-misfire combustion cycle tends to decrease as a whole, while the residual exhaust gas content gradually increases. After a certain number of alternating combustion cycles, $p_{mi}$ and residual exhaust gas content gradually tend to a stable value. As a result, the transitional combustion phase of the ignition and starting process ends, and the stable combustion phase begins. The above phenomenon shows that, for a micro-IC engine, the non-misfire combustion cycle during the ignition and starting processes has experienced a process in which the residual exhaust gas content is zero and gradually increases, and finally approaches a certain stable value. Using this process characteristic, it is possible to test and analyze the combustion characteristics of the micro-IC engine under different residual exhaust gas content conditions, so as to evaluate the influence of the residual exhaust gas content on the micro-space combustion characteristics of the micro-engine with platinum wire ignition.

Here, in order to analyze the influence of the residual exhaust gas content in the cylinder on the combustion characteristics of the micro-engine, according to the amount of residual exhaust gas content, the test hot start conditions in Figure 4 are divided into three stages, namely: the first ignition cycle (the residual exhaust gas content in the cylinder is 0, marked at S1 in Figure 4), the transitional combustion stage (marked at S2 in Figure 4, at this stage, the residual exhaust gas content of the non-misfire cycle is relatively small), and the stable combustion stage (combustion cycles between 150 and 300 in Figure 4, the residual exhaust gas content at this stage is higher, and its value can reflect the residual exhaust gas content of the micro-IC engine under stable operating conditions). By capturing the first ignition cycle of the starting process, the combustion characteristics of the micro-IC engine without residual exhaust gas can be obtained. Comparing it with the characteristics of the transitional combustion cycle and the stable combustion cycle, the difference in the combustion characteristics of the micro-IC engine under different residual exhaust gas states can be analyzed. Here, for the convenience of data comparison and analysis, the first ignition cycle is marked as S1, the combustion characteristics of the transitional combustion phase and the stable combustion phase are, respectively, averaged for the non-misfire cycles of their respective phases, and the averaged cycles are, respectively, marked as S2 and S3. In addition, the misfire cycles in the transitional combustion phase are averaged and marked as S2', as shown in Figure 4.

Figure 5 shows the comparison of the in-cylinder pressure of the scavenging process of motoring conditions, transitional combustion cycle S2, stable combustion cycle S3, and misfire cycle S2'. It can be seen that the in-cylinder pressure curves basically coincide at the end of scavenging (≈120°CA BTDC) and during the compression stroke under various temperature conditions. It shows that there is no significant change in the total amount of gas in the cylinder at the end of the scavenging process at each stage of the ignition start process. However, at
the beginning of scavenging (120°CA ATDC), the in-cylinder pressure of S2 and S3 is much higher than that of motoring and misfire cycle S2’. Higher cylinder pressure is not conducive to scavenging, making scavenging worse. This leads to an increase in the residual exhaust gas content of the next combustion cycle. Therefore, it can be determined that the residual exhaust gas content of cycle S3 is the highest, followed by cycle S2 (the previous cycle of S2 is the misfire cycle S2’, which has a lower pressure at the beginning of scavenging, which is beneficial to scavenging. Meanwhile, S2’ is a misfire cycle, the residual gas contains more fresh charge, so it reduces the residual exhaust gas content of the next cycle S2), and there is no residual exhaust gas in cycle S1.

4. RESULTS AND DISCUSSION

4.1. Influence of the Residual Exhaust Gas Content on the Characteristics of Combustion Pressure. Figure 6 shows the comparison of the combustion pressure of first ignition cycle S1, transitional combustion cycle S2, and stable combustion cycle S3. It can be seen that the residual exhaust gas has a significant effect on the combustion pressure of the micro-IC engine. Under the three temperature conditions, the peak pressure of first ignition cycle S1 is close to 1.8 MPa. With the increase of the residual exhaust gas content, peak pressures of transitional combustion cycle S2 and stable combustion cycle S3 are significantly reduced. For example, for stable combustion cycle S3, its peak pressure drops to between 0.8 and 1.1 MPa, which is more than 50% lower than first ignition cycle S1. For stable combustion cycle S3, in Figure 5, it can be seen that the pressure in the cylinder at the beginning of scavenging (120°CA ATDC) is relatively high, which is very unfavorable for scavenging. It reduces the fresh charge in the cylinder and thus makes the in-cylinder pressure significantly decline.

When the cylinder temperature is lower, the higher the residual exhaust gas content, the earlier the crankshaft angle of $p_{\text{max}}$ ($A_{p_{\text{max}}}$) is. As shown in Figure 6a, when the cylinder temperature is 90 °C, the $A_{p_{\text{max}}}$ of S2 and S3 are higher than first ignition cycle S1. However, as the cylinder temperature increases, the $A_{p_{\text{max}}}$ of first ignition cycle S1 is greatly advanced. It can be seen that when the cylinder temperature...
rises from 90 to 150 °C, the $\Delta P_{\text{max}}$ of S1 advances from 30.4°CA ATDC to 21.6°CA ATDC, which is an advance of 8.8°CA. However, as the cylinder temperature increases, the $\Delta P_{\text{max}}$ of S2 and S3 does not advance significantly.

4.2. Influence of the Residual Exhaust Gas Content on the Characteristics of Heat Release Rate. Figure 7 shows the comparison of the heat release rate of first ignition cycle S1, transitional combustion cycle S2, and stable combustion cycle S3. It can be seen that the lower the residual exhaust gas content, the higher the heat release rate, and the shorter the combustion duration. For example, the first ignition cycle S1, the heat release rate is the highest and the combustion duration is the shortest. For transitional combustion cycle S2, the heat release rate is significantly reduced, and the maximum heat release rate drops to 2/3 of S1 under the three temperature states. For stable combustion cycle S3, its heat release rate is the lowest, which is only 1/2 of S1, and its combustion duration is also the longest, and its afterburning is more serious. Thus, it can be seen that one of the main reasons for the poor combustion performance of the micro-IC engine is that the residual exhaust gas content in the cylinder is too high.

Comparing the heat release rate curves under different cylinder temperature states, it can be seen that the cylinder temperature has a certain degree of influence on the initial heat release rate. When the cylinder temperature is 90 °C, the larger the residual exhaust gas content, the higher the initial heat release rate ($S3 > S2 > S1$). As the cylinder temperature rises, the increase in residual exhaust gas content does not accelerate the initial heat release rate. Conversely, in the case of no residual exhaust gas, the initial heat release rate is faster, and the crank angle of the maximum heat release rate is more advanced. For example, when the cylinder temperature is 150 °C, the initial heat release rate of S1 is significantly higher than S2 and S3. Meanwhile, the crank angle of the maximum heat release rate of S1 advances to 14.8°CA ATDC, which is 3.8°CA and 6.4°CA in advance than S2 and S3, respectively. It is believed that this is due to the combined effect of residual exhaust gas and cylinder block temperature. When the cylinder temperature is low, as the residual exhaust gas content increases, the temperature of the mixture in the cylinder increases, which increases the initial heat release rate. It can be seen that when the cylinder temperature is low, the residual exhaust gas can promote the initial heat release. When the cylinder temperature is high, the effect of the cylinder temperature becomes prominent, and the residual exhaust gas plays a restraining effect to a certain extent, so that the influence of the residual exhaust gas content on the initial heat release rate shows an opposite trend. Although the higher residual exhaust gas content has a more obvious promotion effect on the initial heat release rate when the cylinder temperature is lower, but overall, its influence on the combustion heat release characteristics is more negative.

Figure 8 shows the effect of residual exhaust gas content on combustion parameters such as CA05, CA50, CA90, and combustion duration under three temperature conditions. In Figure 8a, under different cylinder temperature states, the influence of residual exhaust gas on CA05 is not consistent. When the cylinder temperature is 140 and 150 °C, CA05 shows an overall increasing trend with the increase of residual exhaust gas content. That is, the greater the residual exhaust gas content, the more delayed CA05. However, when the cylinder temperature is 90 °C, CA05 shows a linear decrease trend with the increase of the residual exhaust gas content, which advances from 9.6°CA ATDC of cycle S1 to 5°CA ATDC of cycle S3. Therefore, it can be seen that when the temperature of the cylinder is low, the residual exhaust gas promotes ignition, and when the temperature of the cylinder is high, the residual exhaust gas has an inhibitory effect on ignition.

In Figure 8b,c, as the residual exhaust gas content increases, both CA50 and CA90 show an increasing trend. In Figure 8d, there is an obvious positive correlation between the combustion duration and the residual exhaust gas content in the cylinder. That is, the more residual exhaust gas content is in the cylinder, the longer is the corresponding combustion duration. It can be seen that the combustion duration of S1 is about 25°CA, which is close to that of a conventional-size IC engine, while the combustion duration of S3 is greatly extended to about 49°CA, which is about twice the former. In addition, it can be seen from Figure 8d that the influence of cylinder temperature on the combustion duration is relatively

Figure 7. Heat release rate at different amounts of residual exhaust gas with cylinder temperatures of 90, 140, and 150 °C.
weak, and there is no significant change in the combustion duration at different cylinder temperatures. Therefore, for the miniature IC engine, the cause of poor combustion characteristics, low heat release rate, and longer combustion duration is mainly due to the high residual exhaust gas content in the cylinder.

4.3. Influence of the Residual Exhaust Gas Content on $p_{mi}$. In order to evaluate the influence of the residual exhaust gas content on $p_{mi}$, the $p_{mi}$ of the first ignition cycle S1, the transitional combustion cycle S2, the stable combustion cycle S3, and the corresponding $p-V$ indicator diagrams were compared, as shown in Figures 9 and 10. It can be seen that as the residual exhaust gas content increases, the $p_{mi}$ shows a significant downward trend. For example, when the cylinder temperature is 90 °C, the $p_{mi}$ of the first ignition cycle S1 is as high as 0.48 MPa. When the cylinder temperature is 150 °C, the $p_{mi}$ of stable combustion cycle S3 is only 0.17 MPa. The latter is 0.31 MPa lower than the former, a decrease of 64.3%.

Therefore, the development direction of the micro-engine should focus on how to further improve its gas exchange process under the conditions of the micro-structure size, including strengthening the control of the cylinder temperature to avoid heating the charge. It can be seen from Figure 4d that the maximum $p_{mi}$ of the first ignition cycle and some transitional combustion cycles of the cold start condition is close to 0.7 MPa (the residual exhaust gas content in this state is small and the cylinder temperature is low), which is quite close to the technical level of conventional-size gasoline engines. It demonstrates the potential of performance development for the micro-engine and the possibility of further reduction in structural dimensions.
the first ignition cycle without the residual exhaust gas content and comparing it with the characteristics of the combustion cycle with different residual exhaust gas contents in the transitional combustion stage and the stable combustion stage, it is fully proved that excessive residual exhaust gas content is the root cause of abnormal combustion characteristics of the micro-engine with platinum wire ignition.

(3) The combustion cycle of the micro-engine with different residual exhaust gas contents presents significantly different combustion characteristics. With the increase of the residual exhaust gas content, the combustion pressure and the heat release rate gradually decrease, and the combustion duration is also gradually extended. At the same cylinder temperature, compared with the first ignition cycle, the peak combustion pressure, maximum heat release rate, $p_{\text{mi}}$ of the transitional combustion cycle decrease by more than 30%, and the combustion duration increases by about 150%. For the stable combustion cycle, the peak combustion pressure, maximum heat release rate, $p_{\text{mi}}$ decrease by more than 50%, and the combustion duration increases by about 200%. As the residual exhaust gas content increases, the indicated work decreases significantly.

(4) Under the condition of small size, the increase of the surface-to-volume ratio enhances the heat transfer in the cylinder, and the thermal state of the micro-engine has a significant impact on its combustion process. The results show that both the cylinder temperature and residual exhaust gas content affect the starting point of combustion. When the cylinder temperature is low, as the content of residual exhaust gas increases, the flame development angle advances, and the residual exhaust gas promotes the heat release at the initial stage of combustion. When the temperature of the cylinder is high, the flame development angle tends to increase with the increase of the residual exhaust gas content, and the residual exhaust gas inhibits the heat release in the early stages of combustion. In general, the heat release rate is mainly affected by the residual exhaust gas content.

(5) The higher the temperature of the cylinder, the lower the density of the fresh charge entering the cylinder and the lower the $p_{\text{mi}}$ value of the combustion cycle. When the cylinder temperature is 150 °C, the $p_{\text{mi}}$ of the stable combustion cycle is about 0.31 MPa lower than the $p_{\text{mi}}$ of the first ignition cycle with a cylinder temperature of 90 °C, a decrease of 64.3%. Under cold-start conditions, the maximum value of $p_{\text{mi}}$ for the first ignition cycle is close to 0.7 MPa, which is quite close to the technical level of conventional gasoline engines, which shows potential for the performance development of micro-engines. Therefore, for the micro-engine, in order to further reduce the size of the structure, it should focus on how to further improve the gas exchange process.

(6) Compared with the stable combustion stage, the indicated work of the combustion cycle without residual exhaust gas is the largest and the thermal efficiency is higher. On the one hand, due to the acceleration of the combustion rate, the iso-volume degree is improved. On the other hand, under the conditions of constant friction loss, the increase of $p_{\text{mi}}$ means the increase of the effective thermal efficiency. Therefore, by greatly increasing the $p_{\text{mi}}$ of the micro-engine, the impact of various loss multiplications caused by the scale effect, such as heat transfer, friction, and leakage, can be reduced. Then, the thermal efficiency will further increase and may even reach the level of traditional IC engines.

5. CONCLUSIONS

(1) Under the conditions of small size, the gas exchange process of the micro-IC engine is affected by the scale effect, the scavenging flow rate is low, the flow friction resistance is large, and the effectiveness of the compression of the gas in the crankcase is reduced. Affected by these factors, it is difficult for the gas exchange in the cylinder of a micro-IC engine to achieve the perfection level of a conventional-size IC engine, resulting in excessively high residual exhaust gas content in the cylinder, thereby severely affecting the combustion characteristics in the cylinder.

(2) The residual exhaust gas content of the combustion cycle in the ignition and startup processes of the micro-engine shows a gradually increasing change characteristic over time. By capturing the combustion characteristics of

![Figure 10. $p$--$V$ indicator diagram at different amounts of residual gas with cylinder temperatures of 90, 140, and 150 °C.](https://doi.org/10.1021/acsomega.2c00082)
increasing the $P_{\text{mi}}$ of the micro-engine to reduce the impact of various loss multiplications, such as heat transfer, friction, and leakage, the thermal efficiency will further increase and may even reach the level of traditional IC engines.

**AUTHOR INFORMATION**

**Corresponding Author**
Li Zhang  – College of Mechanical and Vehicle Engineering, Chongqing University, Chongqing 400044, P. R. China; Email: zhangli20@cqu.edu.cn

**Authors**
Huichao Shang  – College of Mechanical and Vehicle Engineering, North China University of Water Resources and Electric Power, Zhengzhou 450045, P. R. China; orcid.org/0000-0002-4676-5944
Zhigang Tang  – College of Mechanical and Vehicle Engineering, Chongqing University, Chongqing 400044, P. R. China
Xi Chen  – College of Mechanical and Vehicle Engineering, Chongqing University, Chongqing 400044, P. R. China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c00082

**Author Contributions**
H.S.: methodology, investigation, validation, and writing original draft; L.Z.: conceptualization, funding acquisition, supervision, and writing—reviewing and editing; Z.T.: investigation, software, and formal analysis; X.C.: investigation and data curation.

**Notes**
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