**SHOR T COMMUNICATION**

An effective approach of dropping the backfire possibilities of a hydrogen-fuelled opposed rotary piston engine

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**Abstract**  
Backfire of hydrogen-fuelled internal combustion engines limits the hydrogen fuel applications and drops the power output. Opposed rotary piston (ORP) engines are characterized by high power density, smooth operations, and few moving parts. However, the intake structures of ORP engines tend to deliver high possibility of backfire under hydrogen utilization conditions due to more residual exhaust. This paper proposed an effective approach of eliminating backfire for a hydrogen fuelled ORP engine, and it did not generate any penalty of power output theoretically. The effectiveness of this method was demonstrated using a 3D numerical simulation method. The results indicated that the average in-cylinder temperature started to increase at the start of the intake process if without any backfire control strategies; however, it decreased continuously if backfire control was applied. The mass flow rates of the intake fluid were at a low level without backfire control, but it increased sharply if backfire control was adopted. Backfire in this investigation was caused by the pre-ignition of mixture in cylinders. The temperature in intake pipes reached up to 1000 K over backfire scenarios, and heat of reaction was higher than 3 W. Hydrogen mass fractions at the bottom of intake pipes were low at the start of intake process due to the backfire; meantime, slight backflow also happened in the intake process due to the pre-ignition of cylinders mixture. The fluid velocity was higher than 100 m/s at the beginning of intake process if backfire was controlled.

**KEYWORDS**  
backfire, cooling effect, hydrogen fuel, intake strategy, opposed rotary piston engines

\section{INTRODUCTION}

Hydrogen fuel applications in internal combustion engines attracted increasing attentions due to its inherent merits, such as higher energy density, faster flame propagation speed, lower lean-burn limits, lower ignition energy, and smaller quenching distances than other fuels,\(^1\)\(^-\)\(^5\) especially for the cold start emissions.\(^6\),\(^7\) Effectiveness of hydrogen utilizations improving the performance of reciprocating engines,\(^8\),\(^9\) Wankel engines,\(^10\) and opposed rotary piston (ORP) engines\(^11\),\(^12\) was investigated using both experimental and simulation methods. Power density of ORP engines was demonstrated to be much higher than reciprocating engines and Wankel engines due to their short cyclic period in time.\(^13\) Nowadays, hydrogen fuel has not been put into practice in large scales for internal combustion engine...
applications. Except for hydrogen fuel production and storage, backfire,\textsuperscript{14} pre-ignition,\textsuperscript{15} knock,\textsuperscript{16} and nitrogen oxides (NO\textsubscript{x})\textsuperscript{17} also impeded the popularizations of hydrogen fuel utilizations in internal combustion engines. Backfire was much easier to happen when engines were fuelled with hydrogen than other fuels, due to its low ignition energy, wide flammability, and high flame propagation speed.\textsuperscript{18} Backfire could result in the drop of engine power output; moreover, it was harmful to the intake manifold systems and fuel injection systems due to the pressure and temperature rise in the intake manifold.

Backfire was usually detected by the pressure rise in intake pipes where the pressure reached higher than 1.5 bar for high engine load cases (normally, it was 1.02 bar under the same condition);\textsuperscript{19} additionally, higher engine speed led to higher pressure rise in intake pipes, as demonstrated by Sun et al\textsuperscript{19} based on experiments. Possibilities of backfire were mainly dependent on the hydrogen concentration and mixture temperature around intake ports at the start of the intake process that low concentration and temperature conduced to dropping backfire possibilities.\textsuperscript{18,20} It was also indicated by Sun et al\textsuperscript{19} based on a port fuel injection (PFI) engine that backfire could also be caused by the flame in crevices where rich air/fuel mixture was ignited at the end of exhaust stroke over low engine load conditions; however, it was caused by the backflow of hot spots under high engine load conditions. Both types of backfire could be effectively avoided by adjusting hydrogen injection timing, as demonstrated using experiments.\textsuperscript{19} Further, Duan et al\textsuperscript{21} explored the theory of backfire control by adjusting hydrogen injection timing using a 3D numerical simulation method. If hydrogen injection was much earlier than intake valve opening, it led to a rich air/hydrogen zone behind the seats of intake valves; it also caused same phenomenon for late hydrogen injection, but the rich zone was resulted from the residual hydrogen from the last injection.\textsuperscript{21} He et al\textsuperscript{22} concluded that high compression ratios, late fuel injection, and failure of ignition also increased the possibilities of backfire. These factors resulted in back flow and high temperature around intake ports. Additionally, abnormal electric discharge could induce backfire due to high residual electric energy in ignition systems of hydrogen engines.\textsuperscript{23}

Effective backfire control methods were widely investigated, including adjusting valve timing, using lean air/fuel mixture, adopting exhaust gas recirculation (EGR), employing intake air cooling, and so on.\textsuperscript{15,20,24} Dhyani et al\textsuperscript{25} indicated that both cooled EGR and water injection were effective to control backfire; however, water injection performed better due to higher reduction of flame propagation speed. Decreasing valve overlap periods effectively dropped the possibilities of backfire, but the power output was decreased due to less intake air.\textsuperscript{26} Combinations of postponing fuel ignition timing and water injection in intake manifold were also proved to be effective using experiments.\textsuperscript{27} However, significant postponement of hydrogen ignition and water injection was demonstrated to be harmful to engine power output; meantime, water injection would cause corrosions of intake manifold systems and cylinders, as well as diluting lubricating oil.

Most of the approaches mentioned above effectively dropped the backfire possibilities for reciprocating engines; however, engine power output was also seriously worsened. To the authors’ knowledge, backfire control was not reported for hydrogen fuelled ORP engines. In this paper, an effective method of controlling backfire by adjusting intake strategies was proposed for a hydrogen fuelled ORP engines. In this paper, an effective method of controlling backfire by adjusting intake strategies was proposed for a hydrogen fuelled ORP engines, and it would not generate any negative effects on engine power output and durability. The overall equivalence ratios of air/fuel mixture could be the same as the cases without backfire control, achieved by adjusting the equivalence ratios of individual intake pipes. It was benefited from the intake pipe layout that the intake ports were opened sequentially during piston rotations. The effectiveness of this method was demonstrated using a 3D numerical simulation method. Temperature and pressure distributions in combustion chambers and heat of reactions at the start of intake stroke were investigated to analysis the drop of backfire possibilities.
2 MATERIAL AND METHODS

In this section, the structures of the ORP engine were introduced briefly; then, the 3D numerical simulation model was described; finally, the method of dropping backfire possibilities was proposed.

2.1 Configurations and operations of the opposed rotary piston engine

This ORP engine has four pistons, four cylinders, three intake ports, one exhaust port, two spark plugs, and two shafts, as shown in Figure 1. Each two opposed pistons is connected with one shaft. Specifications of this ORP engine and the operation theory are shown in the authors’ previous work.13,28 The operations of this ORP engine including combustion process is shown in Video S1,29 which also indicated the combustion chamber evolutions. Limited by the image processing capability of the authors’ workstation, only one combustion chamber is presented in Video S1. During the engine operations, cylinders pass the bottom of exhaust pipe and intake pipes sequentially; the bowls in cylinders pass the bottom of spark plug zones. The crank angle of this ORP engine is defined based on the center positions of the individual combustion chambers. There are two top dead centers (TDCs) and two bottom dead centers (BDCs) in this ORP engine; TDCs and BDCs are corresponding to the minimum and maximum cylinder volume, respectively. The cyclic period of this ORP engine is $360^\circ$ crank angle (CA), contributing to high power density of this ORP engine. In order to ensure complete combustion of fuel, it is without early opening for the exhaust port. Each stroke of this engine lasts $90^\circ$ CA; the exhaust and intake port area is much larger than reciprocating engines (if the same engine displacement).

2.2 Approaches of controlling backfire

At the start of the intake process, the in-cylinder temperature was high due to the exhaust residuals, which may induce backfire under specific conditions discussed in introduction; additionally, backflow of this ORP engine was more severe than reciprocating engines due to the lack of late closing of the exhaust port. An effective method of eliminating the backfire was to cool the exhaust residuals using incombustible gas (fresh air) at the beginning of intake process. This method effectively prevented the combustible mixture from exposing in high temperature atmosphere. The practice of this method in the ORP engine is shown in Figure 2. Intake pipe 1 provided fresh air, and air/fuel mixture were delivered by intake pipes 2 and 3, which was benefited from the sequential opening of intake pipes 1, 2, and 3 during engine operations. Residual exhaust in cylinders was cooled down at the beginning of intake process by the fresh air from intake pipe 1; then, air/fuel mixture were provided when intake ports 2 and 3 opened. So the possibilities of backfire could be avoided in theory. In order to compensate for the hydrogen missing in intake pipe 1, air/fuel mixture from intake pipes 2 and 3 could be rich. For this method, backfire would not happen even under backflow scenarios in intake port 1, due to the shortage of hydrogen.

The effectiveness of this method would be demonstrated using a 3D numerical simulation method. The simulation scenarios are presented in Table 1. In these scenarios, equivalence ratios of zero referred to fresh air. This method would be verified over different equivalence ratios. The overall equivalence ratios of intake mixture over scenarios 1 and 2 were the similar (limited difference); and it was similar for scenarios 3 and 4. In this investigation, slightly higher wall temperature (650 K) was set than the authors’ previous researches in order to stimulate the happen of backfire. It was port fuel injected, and the air-fuel was fully mixed at the inlet of intake ports.

2.3 Numerical simulation model

Demonstrations of this approach dropping the possibilities of backfire were conducted using a 3D numerical simulation method. Since the volume and positions of cylinders changed continuously, dynamic meshes were applied to the simulation model. The quality of the meshes was shown in the authors’ previous work, and sensitivity analysis of the calculation residuals and mesh numbers (size) was also analyzed.11 It indicated the effect of calculation residuals and mesh numbers on the simulation results were limited.11 At the beginning of simulation, calculation residuals and total grid numbers were $10^{-6}$ and 2 710 453, respectively. Species transport and k-epsilon Re-Normalisation Group (RNG) viscous models were chosen in FLUENT software.30 Demonstrated by the authors’ previous work, the ignition timing corresponding to the maximum engine torque was around $14.2^\circ$ CA before...
Ignition timing, ignition duration, and ignition energy were 14.2° CA before TDC, 50 μs, and 0.005 J, respectively. Based on the simulation, heat of reactions and temperature distributions in combustion chambers and intake pipe 1 at the start of intake process would be analyzed for the given scenarios.

3 | RESULTS AND DISCUSSION

In order to demonstrate the effectiveness of this approach on dropping the backfire possibilities of the hydrogen fuelled ORP engine, temperature evolutions, heat of reactions, hydrogen mass distributions, and streamlines in combustion chambers and intake pipes were discussed both with and without backfire control strategies.

3.1 | Temperature, mass flow, and heat of reactions in cylinders and intake pipes

One of the main sources of the backfire was high local temperature, which could ignite the air/hydrogen mixture in cylinders, as shown in Figure 3A. Average in-cylinder temperature was higher than 740 K at the start of the intake process. The average in-cylinder temperature started to increase from 5 °CA after TDC for the two scenarios without any backfire control strategies; meantime, higher equivalence ratios tended to have higher average in-cylinder temperature. It meant that mixture in cylinders were ignited, which could stimulate the backfire in the intake systems. Pre-ignition was one of the main reasons causing backfire, as indicated by the work.15 After the applications of the backfire control strategy, the average in-cylinder temperature decreased continuously in the intake process. Pre-ignition in cylinders also caused low power output of the engine, resulting from less air/hydrogen mixture, as indicated by the mass flow of the intake system (Figure 3B). 4 °CA after TDC corresponded to the start of intake pipe opening. Mass flow rates in the intake process increased significantly with backfire control strategies; however, they were at a low level for the scenarios without backfire control strategies. This effective backfire control approach was benefited from the cooling effect of fresh air from intake pipe 1.

In order to explore the backfire in the intake pipes, temperature distributions in combustion chambers and intake pipes were discussed both with and without backfire control strategies.
pipes are presented in Figure 4A. The position was corresponding to 7 °CA after TDC. At the bottom of intake pipe 1, high temperature zones were observed, which indicated the backfire. As shown in Figure 3B, no backflow happened at the start of the intake process which demonstrated that the backfire in this paper was resulted from the pre-ignition of air/hydrogen mixture in cylinders. Due to the high flame propagation speed, flame in cylinders was developed into the intake pipes. The pre-ignition of the mixture started from the top of cylinders (interfaces between cylinders and intake pipes) where the mixture became rich at the earliest time. The maximum local temperature was higher than 1000 K, which had significant harms to the intake system. The temperature in cylinders was much lower over the two cases without backfire. The cooling effect started from the top of the cylinders, being benefited from the cooled fresh air. Cooling effects and extremely lean mixture (no hydrogen) were perfect methods to prevent the pre-ignition, further eliminating the backfire. Heat of reaction distributions in cylinders and intake pipes are shown in Figure 4B. For the cases with backfire, the maximum heat of reactions was approximately 5 W in cylinders, and it was slightly lower for intake pipes. When backfire control approach was adopted, there was no chemical reactions being observed in both cylinders and intake pipes.

3.2 | Hydrogen mass distributions and streamlines in cylinders

Hydrogen mass percentage distributions in cylinders and intake pipes are shown in Figure 5A. For the cases without backfire control strategies, hydrogen/air mixture flowed into the cylinders and was ignited in the high temperature atmosphere. High temperature zones in cylinders were formed firstly around the fluid streamlines from intake pipes due to high equivalence ratios. Hydrogen mass concentration at the bottom of the intake pipes dropped significantly. From Figure 5B, slight backflow was observed after the backfire happened, which was consistent with Figure 3. Compared with backfire cases, fluid speed over cases without backfire was much higher, with the local speed reaching up to 100 m/s. This method effectively controlled the backfire of hydrogen fuelled ORP engines; moreover, there wasn't any performance penalty if the overall equivalence ratios in cylinders were controlled properly. Backfire control for reciprocating engines was usually achieved by adjusting engine operation parameters, and performance loss was inevitable. However, the control strategy in this investigation couldn't be applied to conventional reciprocating engines due to different structures of intake pipes.
This paper investigated the effectiveness of a backfire control strategy for hydrogen fuelled ORP engines using a 3D numerical simulation method. The main findings of the research are as follows:

1. Average in-cylinder temperature was high at the start of the intake process, which caused the pre-ignition of mixture in cylinders, further leading to the backfire in intake pipes due to high flame propagation speed. Average temperature in cylinders was increased greatly in the intake process due to the pre-ignition; however, the temperature was dropped continuously when backfire control was adopted.

2. Mass flow rates of the cylinders were low in the intake process if backfire happened, and slight backflow was observed in this process; however, the mass flow rates reached up to 10 g/s in a short duration for backfire control scenarios. Local temperature in cylinders and intake pipes was higher than 1000 K for backfire scenarios, which would generate significant harms to the intake systems. Backfire control of this approach was benefited from the cooling effects by intake air from intake pipe 1 and extreme low hydrogen concentration in cylinders at the start of intake process.

3. Hydrogen mass fractions at the bottom of intake pipes were much lower than normal values when backfire happened, which could worsen the engine performance. When the overall equivalence ratios were controlled properly for backfire control scenarios, the control strategy wouldn't generate any penalties to the engine performance.

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CONFLICT OF INTEREST
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

1. Gong C, Li Z, Yi L, Sun J, Liu F. Comparative analysis of various combustion phase control methods in a lean-burn H2/methanol fuel dual-injection engine. Fuel. 2020;262:116592.

2. Gong C, Li Z, Huang K, Huang K, Liu F. Research on the performance of a hydrogen/methanol dual-injection assisted spark-ignition engine using late-injection strategy for methanol. Fuel. 2020;260:116403.

3. Akal D, Öztuna S, Büyükakın MK. A review of hydrogen usage in internal combustion engines (gasoline-Lpg-diesel) from combustion performance aspect. IJHE. 2020;45:35257-35268.

4. Shi C, Ji C, Wang S, Yang J, Ma Z, Xu P. Assessment of spark-energy allocation and ignition environment on lean combustion in a twin-plug Wankel engine. Energy Convers Manage. 2020;209:112597.

5. Shi C, Ji C, Wang S, Yang J, Ma Z, Ge Y. Combined influence of hydrogen direct-injection pressure and nozzle diameter on lean combustion in a spark-ignited rotary engine. Energy Convers Manage. 2019;195:1124-1137.

6. Gao J, Tian G, Sorniotti A, Karci AE, Di Palo R. Review of thermal management of catalytic converters to decrease engine emissions during cold start and warm up. Appl Therm Eng. 2019;147:177-187.

7. Gao J, Tian G, Sorniotti A. On the emission reduction through the application of an electrically heated catalyst to a diesel vehicle. Energy Sci Eng. 2019;7:2383-2397.

8. Zhu H, Zhang Y, Liu F, Wei W. Effect of excess hydrogen on hydrogen fueled internal combustion engine under full load. IJHE. 2020;45:20419-20425.

9. Gu X, Huang Z, Cai J, Gong J, Wu X, Lee C. Emission characteristics of a spark-ignition engine fuelled with gasoline-n-butanol blends in combination with EGR. Fuel. 2012;93:611-617.

10. Ji C, Meng H, Wang S, et al. Realizing stratified mixtures distribution in a hydrogen-enriched gasoline Wankel engine by different compound intake methods. Energy Convers Manage. 2020;203:112230.

11. Gao J, Tian G, Ma C, Balasubramanian D, Xing S, Jenner P. Numerical investigations of combustion and emissions characteristics of a novel small scale opposed rotary piston engine fuelled with hydrogen at wide open throttle and stoichiometric conditions. Energy Convers Manage. 2020;221:113178.

12. Gao J, Tian G, Ma C, Xing S, Huang L. Three-dimensional numerical simulations on the effect of ignition timing on combustion characteristics, nitrogen oxides emissions, and energy loss of a hydrogen fuelled opposed rotary piston engine over wide open throttle conditions. Fuel. 2021;281:119722.

13. Gao J, Tian G, Jenner P, Burgess M, Emhardt S. Preliminary explorations of the performance of a novel small scale opposed rotary piston engine. Energy. 2020;190:116402.

14. Dhyani V, Subramanian K. Experimental investigation on effects of knocking on backfire and its control in a hydrogen fueled spark ignition engine. IJHE. 2018;43:7169-7178.

15. Menaa A, Louici M, Amrouche F, Loubac K, Kessal M. CFD analysis of hydrogen injection pressure and valve profile law effects on backfire and pre-ignition phenomena in hydrogen-diesel dual fuel engine. IJHE. 2019;44:9408-9422.

16. Kawahara N, Tomita E. Visualization of auto-ignition and pressure wave during knocking in a hydrogen spark-ignition engine. IJHE. 2009;34:3156-3163.

17. Xu P, Ji C, Wang S, et al. Effects of direct water injection on engine performance in engine fueled with hydrogen at varied excess air ratios and spark timing. Fuel. 2020;269:117209.

18. Liu X-H, Liu F-S, Zhou L, et al. Backfire prediction in a manifold injection hydrogen internal combustion engine. IJHE. 2008;33:3847-3855.

19. Sun B, Duan J, Liu F. Backfire mechanism and control of PFI hydrogen internal combustion engine. Trans Chin Soc Agric Mach. 2013;44(3):1–5.

20. Lee K-J, Huynh TC, Lee J-T. A study on realization of high performance without backfire in a hydrogen-fueled engine with external mixture. IJHE. 2010;35:13078-13087.

21. Duan J, Liu F, Sun B. Backfire control and power enhancement of a hydrogen internal combustion engine. IJHE. 2014;39:4581-4589.

22. He Y, Zhou L, Yuan J, et al. 3-D simulation analysis on backfire conditions of HCNG engine with high compression ratio. J Chongqing Jiaotong Univ. 2015;34:140.

23. Kim Y, Ryu T, Lee JT. Backfire occurrence by abnormal electric discharge in hydrogen fueled engine. Trans Korean Hydrogen New Energy Soc. 2002;13:65-73.

24. Lee J, Lee K, Lee J, Anh B. High power performance with zero NOx emission in a hydrogen-fueled spark ignition engine by valve timing and lean boosting. Fuel. 2014;128:381-389.

25. Dhyani V, Subramanian K. Control of backfire and NOx emission reduction in a hydrogen fueled multi-cylinder spark ignition engine using cooled EGR and water injection strategies. IJHE. 2019;44:6287-6298.

26. Huynh T, Kang J, Noh K, et al. Controlling backfire using changes of the valve overlap period for a hydrogen-fueled engine using an external mixture. In: Internal Combustion Engine Division Fall Technical Conference; 2007:243-251.

27. Yang Z, Wang L, Zhang Q, Meng Y, Pei P. Research on optimum method to eliminate backfire of hydrogen internal combustion engines based on combining postponing ignition timing with water injection of intake manifold. IJHE. 2012;37:12868-12878.

28. Gao J, Tian G, Jenner P, et al. Intake characteristics and pump loss in the intake stroke of a novel small scale opposed rotary piston engine. J Clean Prod. 2020;261:121180.

29. Gao J, Tian G, Ma C, et al. Lean-burn characteristics of a turbo-charged opposed rotary piston engine fuelled with hydrogen at low engine speed conditions. IJHE. 2021;46:1219-1233.

30. ANSYS. ANSYS Fluent Theory Guide; 2013.

31. Gao J, Tian G, Ma C, Huang L, Xing S. Explorations of the impacts on a hydrogen fuelled opposed rotary piston engine performance by ignition timing under part load conditions. IJHE. 2021;46:11994-12008.

SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section.

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