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A Novel Onboard Syngas-Assisted Cold-Start Strategy for Methanol-Fueled Spark Ignition Engines

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Abstract Alternative fuels are emerging as promising energy sources for the power and transportation sectors due to their potential for high performance and lower emissions. The growing demand for clean energy and the need to reduce dependence on fossil fuels in the automotive sector have increased the utilization of alternative fuels. However, cold-start challenges associated with alternative fuels, especially methanol, remain a serious limitation. The onboard production of syngas, consisting mainly of hydrogen and carbon monoxide, can help overcome these cold-start issues. Methanol-derived syngas can be utilized in onboard automotive applications to address cold-start problems at ambient temperatures below 15 °C. Due to its high energy content, low ignition energy requirement, and cleaner combustion characteristics, hydrogen plays an important role in overcoming cold-start challenges, even at extremely low ambient temperatures down to −50 °C. Carbon monoxide also possesses favorable combustion properties, which assist in achieving stable and efficient combustion of the fuel-air mixture. The introduction of syngas (H_2/CO ratio of 67/33 by mole fraction) during the initial few minutes of engine operation, particularly for the first 3–4 minutes, can help achieve the required in-cylinder pressure of more than 6 MPa and an in-cylinder temperature of approximately 2400 K. These conditions promote proper combustion and enable the engine to reach stable operating temperatures within a short time. Subsequently, methanol fuel can be introduced together with syngas for a few additional minutes, after which the engine can transition to fully methanol-fueled operation.

Keywords: Alternative fuels, Syngas, Spark Ignition Engines, Methanol, Hydrogen, Cold Start

1. Introduction

Methanol is a promising alternative fuel for spark-ignition (SI) engines due to its high knock resistance, favorable combustion characteristics, and ease of storage and transportation. However, its high latent heat of vaporization causes significant charge cooling, leading to poor fuel vaporization, delayed ignition, and unstable combustion under cold-start conditions. To overcome these challenges, hydrogen-rich syngas (H_2/CO), produced through catalytic methanol decomposition, offers a promising enhancement strategy. The high reactivity, low ignition energy, and rapid flame

propagation of hydrogen facilitate ignition, improve flame development, and enhance combustion stability at low temperatures. Thus, syngas-assisted methanol combustion presents a potential solution for improving cold-start performance in SI engines [1]. However, methanol's poor vaporization at low temperatures, primarily due to its high latent heat of vaporization and relatively low volatility, hinders the formation of a homogeneous air–fuel mixture and reliable ignition during cold starts [2, 3]. Consequently, incomplete combustion may occur, resulting in increased emissions of unburned methanol and formaldehyde [4].

Several strategies have been investigated to improve air–methanol mixture formation and cold-start performance, including fuel heating [5], intake-air heating [6], LPG assistance [7], mixture preheating [8], oxygen-enriched intake air [9], hydrogen direct injection with methanol port injection [10], hydrogen port injection with methanol direct injection [11], hydrogen–methanol blends [12], hydrogen as an auxiliary fuel [13], spray-line nozzle methanol distribution [14], natural gas–methanol blends [15], and spray-line nozzle methanol direct injection [16].

Hydrogen enrichment of methanol enhances laminar flame speed [17], improves flame resistance [18] to strain-induced extinction [19] , and extends the stable combustion limits [20]. Similarly, LPG assistance improves mixture flammability during cold starts [21], while oxygen-enriched intake air promotes the formation of reactive O, H, and OH radicals, facilitating ignition and combustion [22]. However, methanol's flammability [23], fire hazards at temperatures above its flash point [24], and explosive vapor–air mixtures [25] pose significant safety risks [26]. Furthermore, poor vaporization and prolonged ignition delays under cold-start conditions can increase unregulated emissions, particularly unburned methanol and formaldehyde [27]. Therefore, appropriate safety precautions are essential when handling and introducing methanol or other liquid fuels into combustion systems [28].

Gong et al. [29] improved methanol cold-start performance using twin-spark ignition and optimized injection and ignition timings, reducing unburned methanol (UBM) and soot emissions. Li et al. [30] demonstrated that LPG-assisted methanol combustion enabled reliable cold starts at −13 °C. Gong et al. [31] further reported that LPG addition with late methanol injection (300 °CA) reduced misfires, UBM, and HC emissions. Gong et al. [32] identified optimal injection and ignition timings of 45 °CA and 14 °CA BTDC, respectively, improving cold-start combustion and reducing UBM and formaldehyde (FA) emissions. Liu et al. [27] reported over 90% lower UBM and FA emissions under optimized steady-state conditions compared with cold-start operation.

Gong et al. [33] demonstrated that oxygen enrichment improved in-cylinder pressure, temperature, and cold-start combustion while reducing UBM emissions. Hu et al. [34] reported that gasoline addition enhanced methanol cold-start combustion and reduced CO and HC emissions. Yuan et al. [35] identified intake-air heating and water droplet size as important factors influencing cold-start performance, particularly at 283–293 K. Gong et al. [36] improved first-cycle combustion through LPG port injection combined with glow-plug heating. Li et al. [37] demonstrated that motor dragging combined with exhaust control and exhaust gas recirculation (EGR) improved cold-start performance. Gong et al. [38] found that LPG provided more reliable cold-start ignition than methanol at temperatures below 16 °C. Li et al. [39] reported that gasoline improved first-cycle ignition, while methanol–gasoline blends enhanced subsequent combustion cycles. Li et al. [40] identified glow-plug preheating as the most effective method among several fuel and air heating techniques. Gong et al. [41] demonstrated that ozone addition improved ignition and combustion stability during cold starts. Kozole et al. [42] reported that methanol blends containing up to 70% dimethyl

ether (DME) improved cold-start reliability and reduced emissions. Similarly, Li et al. [4] showed that optimizing methanol–LPG ratios and injection and ignition timings reduced UBM and FA emissions during cold starts.

Overall, previous studies demonstrate that auxiliary fuels, combustion enhancers, preheating, and optimized injection and ignition strategies can mitigate methanol cold-start challenges. These findings also highlight the potential of hydrogen-rich syngas (H_2/CO) as an auxiliary fuel to enhance ignition, flame propagation, and combustion stability during cold starts. Hydrogen-rich syngas (H_2/CO) is a promising auxiliary fuel for overcoming cold-start challenges in methanol-fueled spark-ignition (SI) engines. Its high hydrogen content provides a wide flammability range, high laminar flame speed, and low ignition energy, promoting reliable ignition, rapid flame propagation, and stable combustion at low temperatures [43],[44]. Compared with natural gas, hydrogen-rich syngas offers potential advantages during cold starts due to its enhanced combustion reactivity [45]. Furthermore, syngas can be produced onboard through catalytic methanol decomposition, providing a practical approach to cold-start assistance without requiring a separate primary fuel. Therefore, syngas-assisted methanol combustion represents a promising strategy for improving cold-start reliability, combustion stability, and overall engine performance.

The novelty of this study lies in integrating a compact onboard methanol cracking unit with a methanol-fueled SI engine to overcome cold-start challenges using hydrogen-rich syngas (67% H_2/33% CO by mole fraction). The proposed approach enables rapid syngas production and its utilization during initial engine cycles, targeting in-cylinder pressures above 6 MPa and temperatures around 2400 K. A gradual transition from syngas to syngas–methanol co-combustion and ultimately pure methanol operation is proposed to enhance ignition reliability, combustion stability, and cold-start performance at low ambient temperatures.

2. Methodology

2.1 Engine Setup

In this study, the assessment focuses on combustion characteristics, including in-cylinder pressure (P), heat release rate (HRR), and in-cylinder temperature (T), as well as the challenges associated with engine cold-start conditions. The engine configuration is illustrated in Figure 1, while its key specifications are presented in Table 1. A commercial natural gas engine was modified into a heavy-duty methanol-fueled spark-ignition (SI) engine, incorporating an exhaust-heated catalytic methanol cracking unit to produce syngas (H_2/CO) for cold-start assistance. The cracking unit is described in detail by Farooq et al. [46]. The experimental engine model developed by Zhu et al. [47] was extended numerically to investigate cold-start combustion characteristics under pure syngas and syngas–methanol dual-fuel operating conditions. However, the present study focuses exclusively on evaluating the combustion characteristics of pure syngas under cold-start conditions

This study investigated the cold-start combustion characteristics of a syngas–air mixture in a spark-ignition (SI) engine at 700 rpm, near-zero loads, and ignition timings ranging from 24° to 6°CA BTDC. A syngas–air combustion strategy was simulated using Ricardo WAVE to evaluate in-cylinder pressure, heat release rate (HRR), and temperature under varying equivalence ratios, ignition timings, and ambient temperatures (245–293 K). Hydrogen-rich syngas (67% H_2/33% CO by mole fraction), characterized by high laminar flame speed, low ignition energy, and wide flammability limits, promotes rapid ignition, stable combustion, and improved cold-start performance under low-temperature conditions.

The combustion analysis in investigated with the variations in ignition timing ranging between 20 – 6 °CA before top dead center (BTDC), combustion phasing around 120 °CA, fuel injection quantity and lower ambient temperatures ranging between 293 K to 245 K. Subsequently, a lower ambient temperature boundary conditions analysis is conducted with the comparison of fully warmed up engine under steady state conditions.

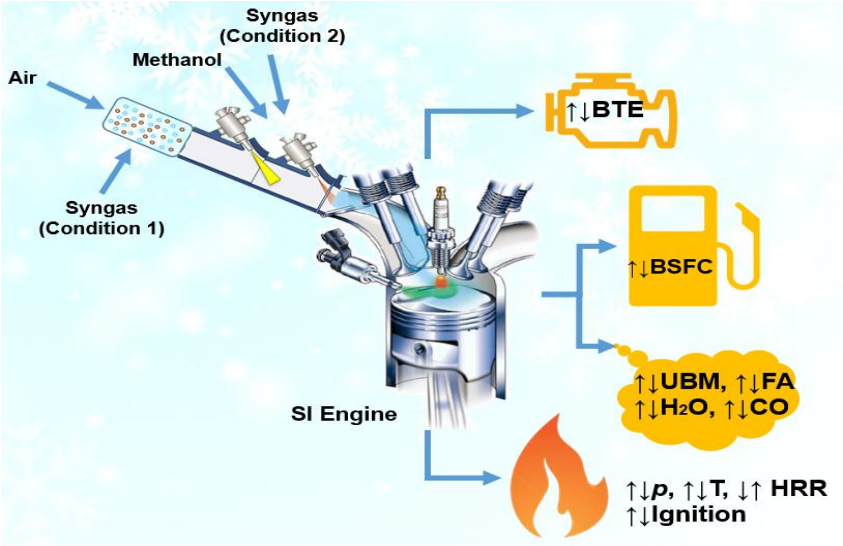


Figure 1 Schematic of the engine operating setup

Table 1 Engine Specifications

No.	Items	Specifications
1	Type	Six-cylinder, turbocharged
2	Bore [mm]/ Stroke [mm]	123/145
3	Displacement [L]	10.3
4	Compression Ratio	11.5
5	Connecting Rod [mm]	218.5
6	Number of valves	4/Cylinder
7	Maximum Power/ kW@rpm	276@1900
8	Maximum torque	1750@ (1200-1500)
9	EVO/EVC (°CA)	50.5 BBDC/11.5 ATDC
10	IVO/IVC (°CA)	12.5 BTDC/17.5 ABDC

2.2 Computational Setup

A one-dimensional Ricardo WAVE model was developed to investigate syngas port fuel injection (PFI) for improving cold-start performance in a spark-ignition (SI) engine, as shown in Figure 2. Hydrogen-rich syngas (67% H_2/33% CO by mole fraction) was injected at 360°CA with an injection duration of 115°CA. Simulations were conducted at 700 rpm, equivalence ratios of 0.9–1.1, and ambient temperatures ranging from 245 to 293 K using the SI-Predictive combustion model. The engine model incorporated intake and exhaust systems, a throttle, injector, cylinder, and

engine block, with cylinder head, piston, and liner temperatures adjusted to cold-start conditions. The numerical analysis focused on evaluating key combustion characteristics, including in-cylinder pressure, heat release rate (HRR), and in-cylinder temperature, under different low-temperature operating conditions. The effects of ambient temperature and equivalence ratio on syngas combustion and cold-start performance were also investigated.

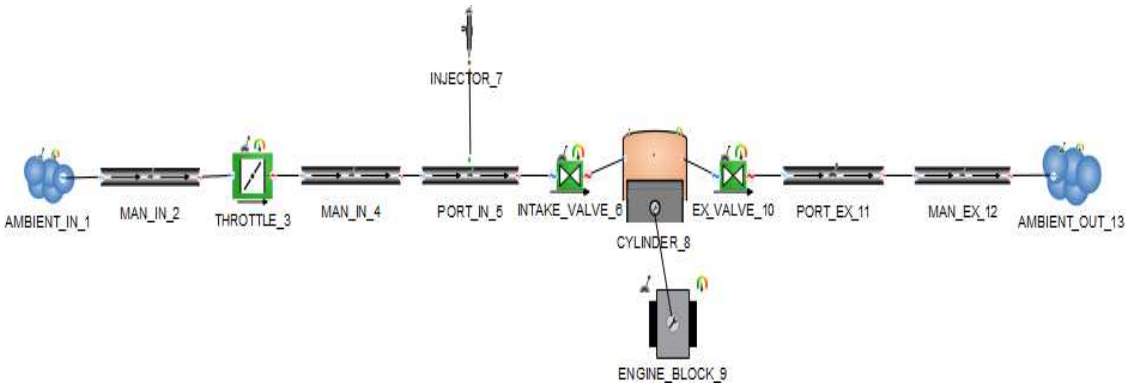
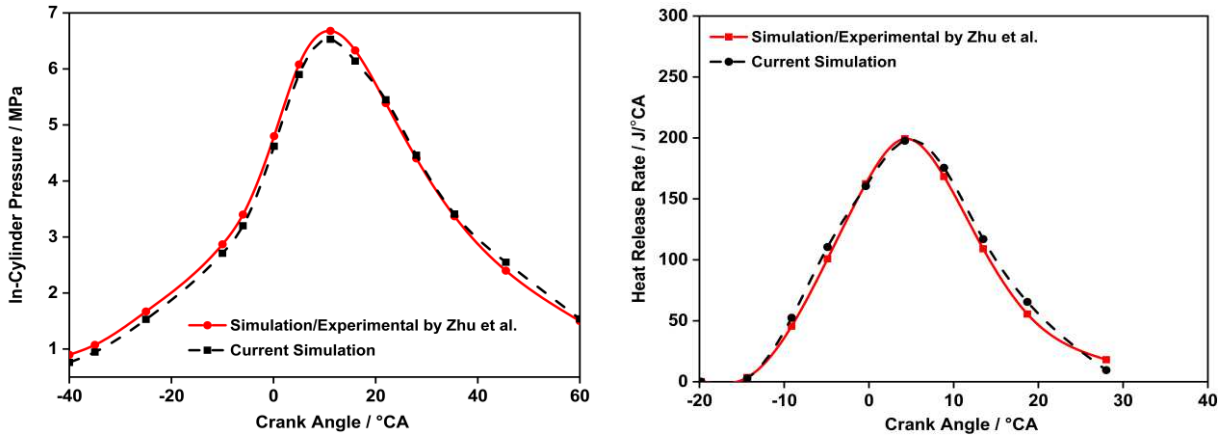


Figure 2 Illustrates the schematic of engine model in Ricardo WAVE

3. Results and Discussion

3.1 Validation of Simulation Results

The simulation model was validated against experimental and numerical results from Zhu et al. [47], demonstrating close agreement (< 6%) in in-cylinder pressure and heat release rate (HRR), as shown in Figure 3 (a, b). Following validation under standard operating conditions, the model was extended to investigate cold-start performance by varying ignition timing, equivalence ratio, and engine wall temperatures. This approach enables the assessment of combustion stability and ignition characteristics under low ambient temperatures, providing insights into strategies for improving cold-start reliability and engine performance.

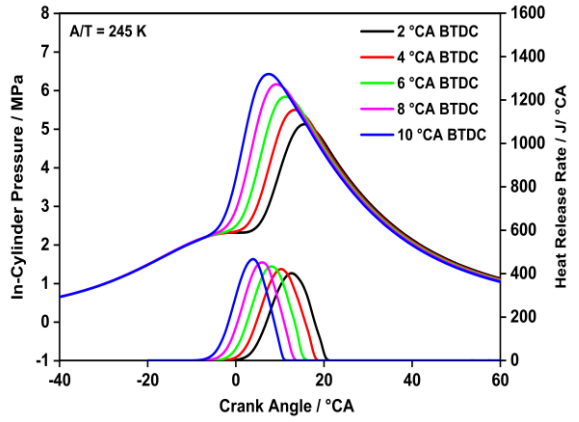


(a) In-cylinder pressure (b) Heat release rate (HRR)

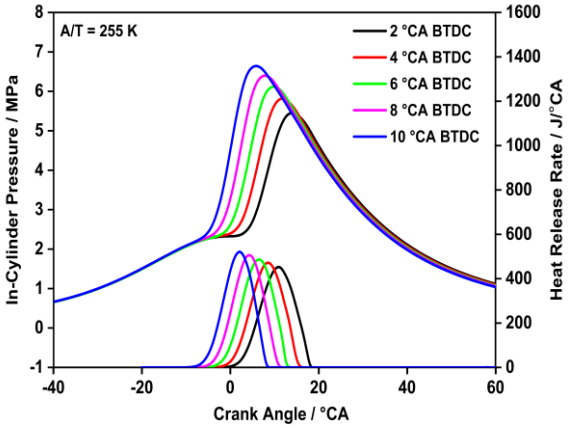
Figure 3 In-cylinder pressure and heat release rate (HRR) validation

3.2 Combustion Characteristics

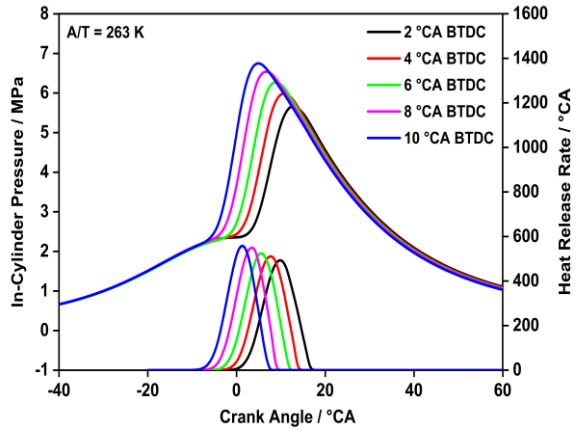
Figure 4 (a–f) illustrates the effects of ambient temperature (245–293 K) and ignition timing (2–10°CA BTDC) on in-cylinder pressure at 700 rpm, 20% throttle opening, and an equivalence ratio of approximately 1. As ambient temperature decreased, syngas laminar flame speed declined from 1.30 to 0.85 m/s, resulting in an ignition delay increase of approximately 1–2°CA. The effects of ambient temperature variations at 245 K, 255 K, 263 K, 273 K, 283 K, and 293 K were investigated to provide a detailed analysis of in-cylinder pressure (P) and heat release rate (HRR) at ignition timings of 2°CA BTDC, 4°CA BTDC, 6°CA BTDC, 8°CA BTDC, and 10°CA BTDC. Nevertheless, peak in-cylinder pressure remained above 5 MPa at lower temperatures, reaching approximately 7 MPa at higher temperatures, with heat release rates exceeding 200 J/°CA. The high hydrogen content and gaseous nature of syngas promoted stable combustion by facilitating ignition and eliminating liquid-fuel vaporization and wall-wetting issues. These findings demonstrate the potential of syngas to improve cold-start reliability, with further optimization possible through spark timing, equivalence ratio, and intake-air preheating.



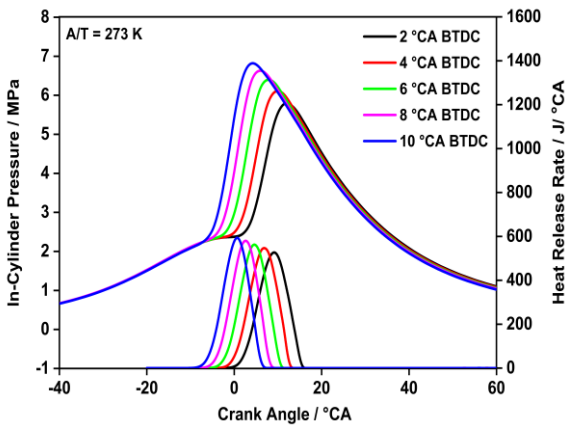
(a) In-cylinder pressure and HRR



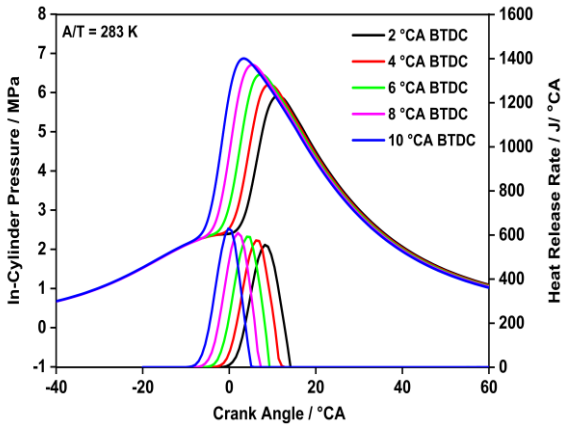
(b) In-cylinder pressure and HRR



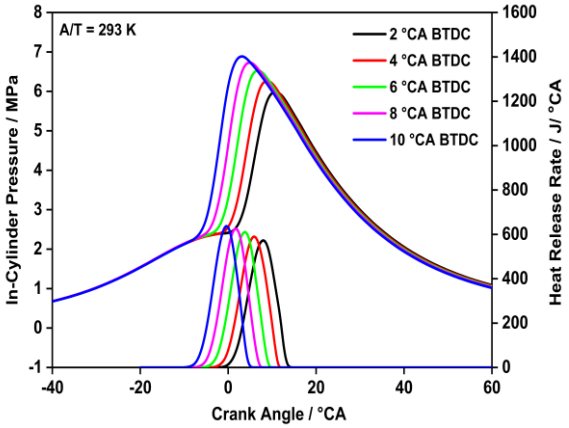
(c) In-cylinder pressure and HRR



(d) In-cylinder pressure and HRR

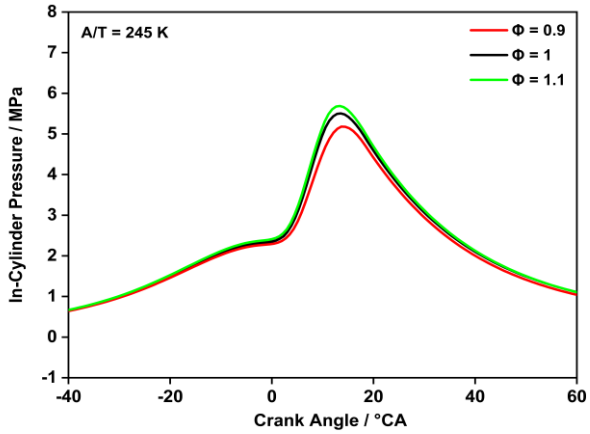


(e) In-cylinder pressure and HRR

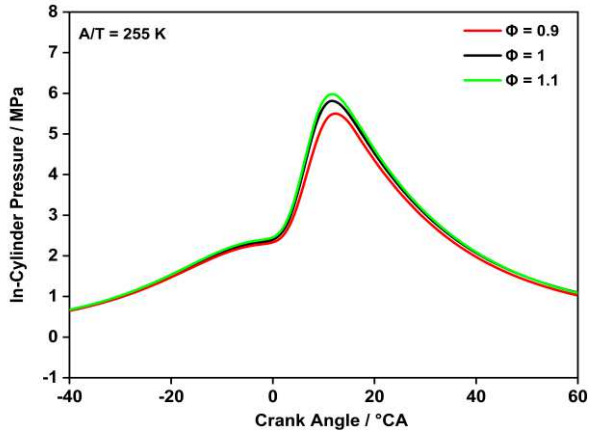


(f) In-cylinder pressure and HRR

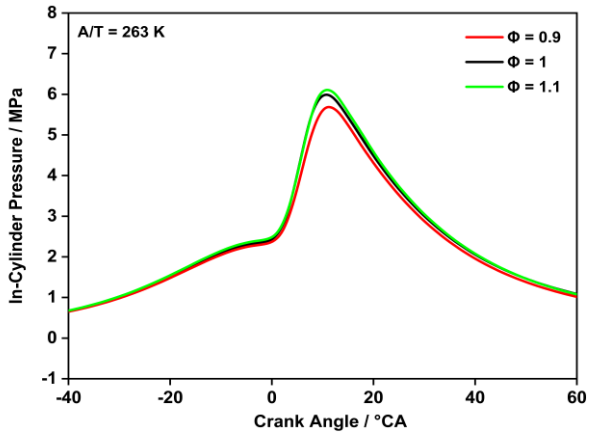
Figure 4 (a–f) Variations in combustion characteristics with ignition timing at ambient temperatures ranging from 298 K to 245 K, including general trends in in-cylinder pressure and heat release rate



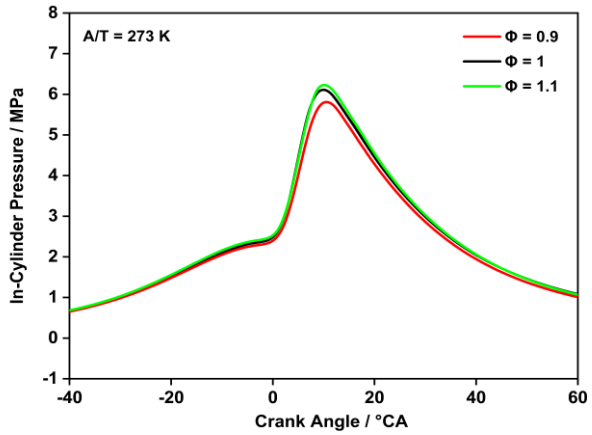
(a) In-cylinder pressure variations /245 K



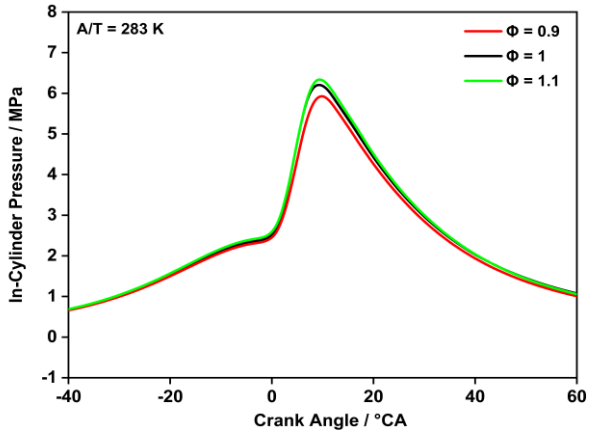
(b) In-cylinder pressure variations /255 K



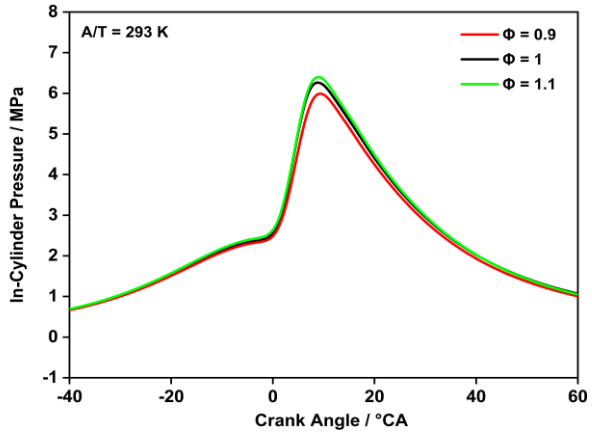
(c) In-cylinder pressure variations /263 K



(d) In-cylinder pressure variations /273 K

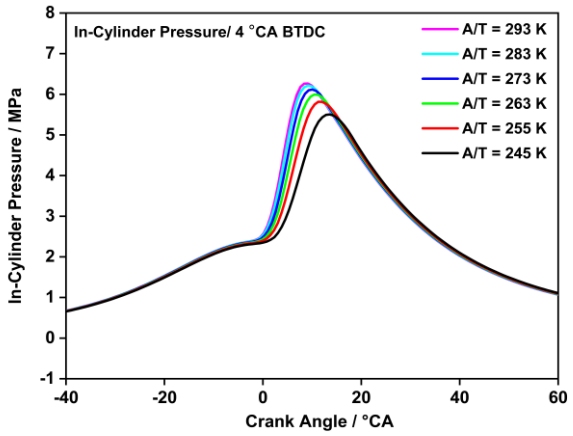


(e) In-cylinder pressure variations /283 K

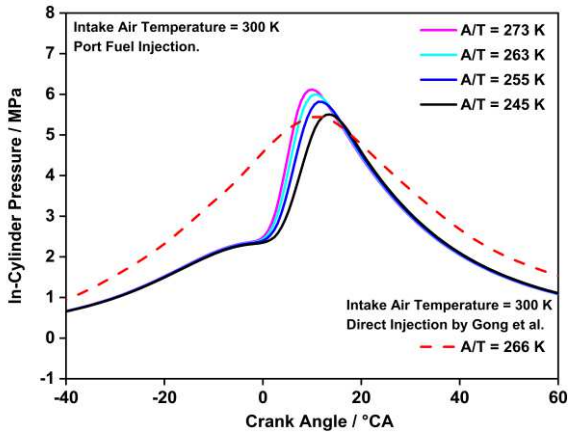


(f) In-cylinder pressure variations /293 K

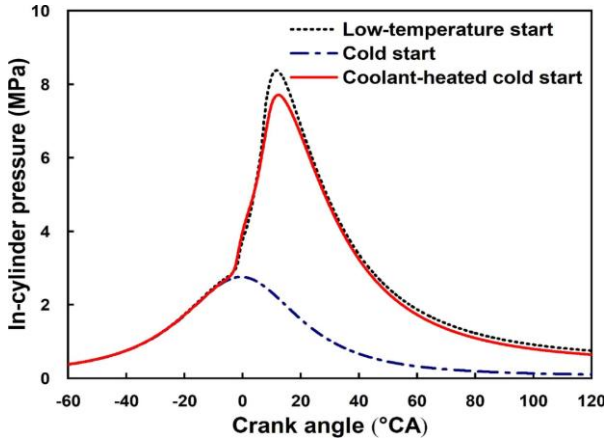
Figure 5(a–f) shows the variations in in-cylinder pressure with changes in equivalence ratio and ambient temperature Figure 5(a–f) illustrates the effect of equivalence ratio (Φ = 0.9–1.1) on syngas combustion under cold-start conditions at 700 rpm and ambient temperatures ranging from 293 K to 245 K. As the ambient temperature decreased, a richer mixture (Φ increasing from 0.9 to 1.1) was required to compensate for reduced flame propagation speed and increased heat losses. With optimized ignition timing, peak in-cylinder pressures remained approximately 5–7 MPa, indicating stable combustion across the investigated temperature range. The high laminar flame speed, low ignition energy requirement, and gaseous nature of hydrogen-rich syngas facilitated reliable ignition and eliminated liquid-fuel wall-wetting issues. Furthermore, combustion phasing (CA50) remained within 5–10°CA after top dead center (ATDC), indicating favorable combustion timing and efficient heat release. These results demonstrate the potential of hydrogen-rich syngas to enhance cold-start combustion stability and engine performance under extremely low ambient temperature conditions. Additionally, the improved combustion characteristics highlight the effectiveness of syngas as an alternative fuel for overcoming cold-start challenges in SI engines. The consistent pressure development and favorable combustion phasing further suggest that appropriate mixture enrichment and ignition timing optimization can improve combustion reliability across a wide range of low ambient temperatures.



(a) In-cylinder pressure variations



(b) In-cylinder pressure variations

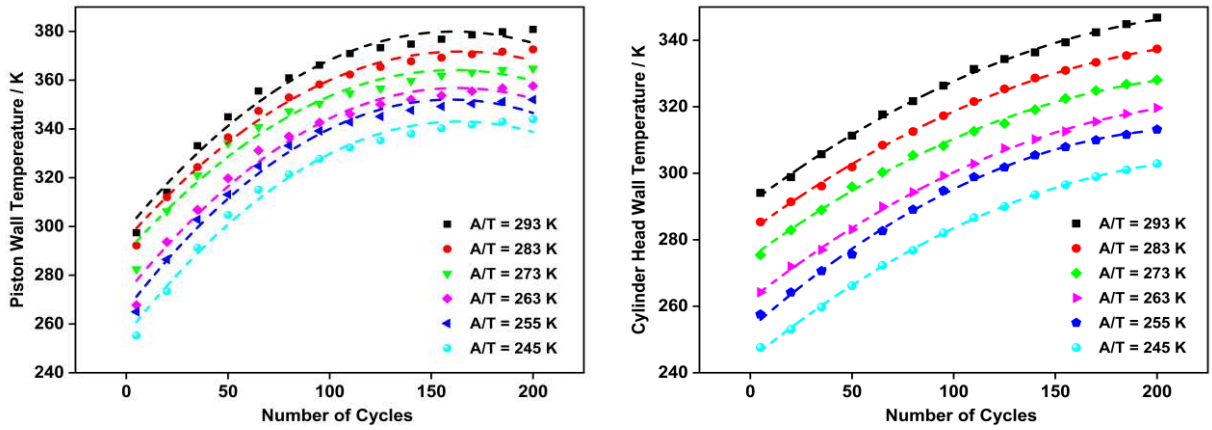


(c) In-cylinder pressure variations for methanol under various conditions, adapted from Liu et al.

Figure 6(a–c) shows in-cylinder pressure variations with changes in ambient temperature and includes a comparison with Gong and Liu et al. under low-temperature conditions

Figure 6(a–c) illustrates the effect of ambient temperature (245–293 K) on cold-start combustion at 700 rpm, with a constant syngas injection of 135 mg/cycle, intake temperature of 300 K, and injection timing of 360°CA for 115°CA. Over 10 engine cycles, peak in-cylinder pressure ranged from 5.5 to 6.3 MPa, with only a modest reduction at lower temperatures. Compared with methanol-fueled engines reported by Gong et al. [32] and Liu et al. [48], which required additional cold-start enhancement techniques, hydrogen-rich syngas demonstrated stable combustion without liquid-fuel vaporization limitations. Its high flame speed, low ignition energy, and gaseous nature highlight its potential as an effective auxiliary fuel for improving cold-start reliability.

Figure 7 (a, b) illustrates the transient temperature rise of engine components during syngas-assisted cold starts at ambient temperatures of 245–293 K. Cylinder head and piston temperatures increased progressively with engine cycles, reaching approximately 330 K and 370 K, respectively, after 200 cycles. Lower ambient temperatures required more cycles to achieve thermal stabilization. The high flame speed, low ignition energy, and gaseous nature of hydrogen-rich syngas promoted stable combustion and accelerated engine warm-up, demonstrating its potential to improve cold-start performance in methanol-fueled SI engines.



(a) Piston wall temperature rise (b) Cylinder wall temperature rise

Figure 7 Cylinder wall temperature and piston wall temperature rise with the variations in ambient temperature

4. Conclusion

This study used Ricardo WAVE simulations to evaluate hydrogen-rich syngas (67% H_2 / 33% CO by volume) as a cold-start aid for methanol-fueled spark-ignition engines. The engine was run at 700 rpm over ambient temperatures of 245–293 K. The main conclusions are as follows:

Hydrogen-rich syngas supported reliable ignition and combustion at all tested ambient temperatures, with peak in-cylinder pressures of 5.5–7.5 MPa. This shows that syngas can overcome the poor fuel evaporation and ignition difficulty that limit pure methanol at low temperatures. The best combustion phasing was obtained with an ignition timing of 4–5°CA BTDC, which placed CA50 at 6–10°CA ATDC. The most favorable mixture was slightly rich, with an equivalence ratio of about 1.1. These values can serve as initial calibration targets for syngas-assisted cold-start strategies.

Lowering the ambient temperature from 293 K to 245 K reduced peak cylinder pressure by only 0.6 MPa. The high flame speed and wide flammability range of hydrogen largely offset the unfavorable thermal conditions, so combustion quality is maintained even in severe cold. Piston and cylinder head temperatures rose substantially within the first 200 cycles. This quick heating improves the in-cylinder conditions needed for methanol vaporization and combustion. Together, stable combustion and fast thermal recovery indicate that the engine can switch from syngas to pure methanol operation within approximately 1–4 minutes of starting.

Overall, hydrogen-rich syngas is a promising cold-start enabler for methanol SI engines. It removes the need for conventional auxiliary starting fuels or external preheating, and it allows the engine to run on methanol alone shortly after startup.

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Ethics and Consent to Participate declarations: NOT APPLICABLE.

Clinical Trial Registration: NOT APPLICABLE.

Consent to Publish declaration: NOT APPLICABLE.

Abbreviations

H_2	Hydrogen,	T	Temperature (K),	DME	Dimethyl Ether,
CA	Crank angle,	PFI	Port fuel injection,	FA	Formaldehydes,

SI	Spark ignition,	DI	Direct injection,	HC	Hydrocarbons,
HRR	Heat release rate,	IVO	Intake valve opening,	ICE	Internal combustion engines,
t	Time,	IVC	Intake valve closing,	H_2/CO	Syngas,
ATDC	After top dead center,	EVO	Exhaust valve opening,	UBM	Unburned methanol,
BTDC	Before top dead center,	EVC	Exhaust valve closing,	LPG	Liquified petroleum gas,
P	Pressure (MPa),	CO	Carbon monoxide,	CNG	Compressed natural gas,

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