

Composition and Combustion Characteristics of LCIG

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To address the high energy demand in the industrialized world and achieve the goal of carbon neutralization, it is also important to make efficient use of low calorific industrial gases (LCIG), in addition to developing the advanced combustion technology of non-carbon fuels such as hydrogen and ammonia.

Keywords: low calorific industrial gases ; opportunity fuels ; hydrogen fuels

1. Introduction

The amount of energy consumed globally has risen 17-fold in the past century, and the primary contributors to air pollution are emissions of CO₂, CO, SO₂, and NO_x from the burning of fossil fuels. Currently, fossil fuels with a carbon footprint, e.g., coal, oil, and natural gas, provide 85% of the world's energy needs [1]. To address the high energy demand in the industrialized world and achieve the goal of carbon neutralization, it is also important to make efficient use of low calorific industrial gases (LCIG), in addition to developing the advanced combustion technology of non-carbon fuels such as hydrogen and ammonia [2][3].

Low calorific industrial gases can be mainly divided into three categories: biogas, syngas, and byproduct gas. Biogas is a clean and sustainable energy source that is often produced from waste treatment, primarily agricultural waste, sewage sludge, and industrial organic waste streams [4]. Methane, hydrogen, carbon dioxide, nitrogen, and hydrogen sulfide are the main components of biogas. Biogas is essentially a low-grade natural gas with a heat value varying from 5.0 to 7.5 kWh/m³, with increased methane concentration, which is the result of organic breakdown in the absence of molecular oxygen. Syngas is often generated by gasifying coal or by reforming biogas, which is mostly made up of hydrogen, carbon monoxide, and carbon dioxide [5]. Since syngas composition varies greatly with different production processes, the low calorific value of syngas varies between 1.0 and 2.6 kWh/m³. Byproduct gas comes from a number of industrial processes in the metallurgy, steel, and chemical industries [6]. Blast furnace gas (BFG), coke oven gas (COG), converter gas, tail gas, cracked gas, pyrolysis gas, and other typical byproduct gases are mostly composed of H₂, CO, CH₄, N₂, and H₂O. In comparison to methane, **Table 1** shows the typical compositions and key characteristics of low calorific industrial gases. Despite being produced from a variety of processes, low calorific industrial gases share similar characteristics in having the major energy sources of H₂, CO, and CH₄.

Table 1. Typical compositions and key characteristics of LCIG compared with methane.

Fuel		Methane	Biogas	Syngas	COG	BFG
Volume fraction (%)	H ₂	/	/	9	62	5
	CH ₄	100	52	7	28	/
	CO	/	/	14	6	23
	CO ₂	/	40	20	4	23
	N ₂	/	8	50	/	49
Calorific Value (kWh/m ³)		9.94	5.17	1.44	4.75	0.95
Density (kg/m ³)		0.67	1.20	1.18	0.38	1.27
Stoichiometric mixture fraction Z _s (l)		0.34	0.48	0.20	0.24	0.88
Ignition delay time at 1200 K (ms)		45.50	51.90	0.93	0.32	0.15
Laminar flame speed (cm/s)		38.28	21.82	14.85	80.07	8.95

The rapid economic expansion in China has led to drastically rising energy consumption, which has led to a significant increase in the production of low calorific industrial gas sources. There are already more than 30.5 million residential biogas digesters in China, and they produce 12.4 billion m³ of biogas annually, which is equal to 19.0 million tons of standard coal [7]. In China, about 600 downdraft biomass gasification facilities are operational, and can provide syngas to over 209,600 households [8]. There are already more than 260 blast furnaces in China with effective volumes of more than 1000 m³, which generate a significant amount of byproduct gases [9]. In this circumstance, China foresees the great opportunity and challenge in the efficient use of low calorific industrial gases.

Considering that low calorific industrial gases contain many combustible components, it is most common and effective to use these gases by direct combustion in gas turbines, internal combustion engines, and specific burners. For example, Blakey [10], Wright [11] et al. reviewed the application of low calorific industrial gases in gas turbines. Singh [12], Pradhan [13] et al. conducted systematic studies on the utilization of low calorific industrial gases in internal combustion engines. Huang [14], Song [15] et al. adopted specific burners to achieve stable and efficient combustion of low calorific industrial gases.

2. Composition and Combustion Characteristics of LCIG

2.1. Composition Characteristics

The fundamental combustion characteristics of LCIG are quite different from those of traditional gaseous fuels, considering their complexity in the mixture composition. Typical composition ranges of biogas, syngas, coke oven gas, and blast furnace gas are listed in **Table 2**. As shown, the variable components in biogas are mainly CH₄ and CO, with a variation range of about 10%. Combustible components (CH₄, H₂, CO) in syngas and byproduct gases from different sources vary significantly, and the variation range of H₂ can reach 20% at most.

Table 2. Typical composition ranges of LCIG.

Fuel		Biogas	Syngas	COG	BFG
Volume fraction (%)	CH ₄	55–65	8–12	20–30	0–3
	H ₂	0–1	35–45	50–70	1–5
	CO	/	20–30	9–20	20–30
	CO ₂	35–45	15–25	0–5	15–25
	N ₂	0–3	3–5	1–11	60–75

Flame structures, such as flame height and standoff distance, have a positive correlation with the H₂ content in LCIG, which contributes to the augmentation of blowoff velocity [16]. CH₄ content in LCIG has more effects on the combustion temperature than CO content. Thermal diffusivity is affected by increasing inert content in LCIG, which also lowers the combustion temperature and laminar flame speed [17]. Differences in CH₄ content and H₂ content in LCIG will cause changes in chemical reaction paths during combustion, and thus affect the ignition delay time and laminar flame speed. For H₂-rich LCIG, it has been discovered that the reactions OH + HO₂ = H₂O + O₂ and HO₂ + H = OH + OH are crucial. For CH₄-rich LCIG, the reactions CH₂O + OH = HCO + H₂O and CH₄ + HO₂ = CH₃ + H₂O₂ are crucial [18]. Increasing the H₂/CO ratio in LCIG causes an increase in flame length and flame temperature.

Since certain LCIG are highly loaded with components containing sulfur and nitrogen, the direct burning of these LCIG generally results in unacceptable emissions. During the combustion process of LCIG, the pollutant emissions are mainly NO_x and CO. Fuel NO_x and thermal NO_x are the two main causes of NO_x emissions. Fuel NO_x is produced by the oxidation of nitrogen-containing compounds, such as HCN and NH₃, which may be formed during gasification. Thermal NO_x is produced in appreciable amounts at high combustion temperatures, when molecular nitrogen in the combustion air is oxidized. The main source of CO emission is from incomplete combustion of LCIG, especially for LCIG with high CO contents.

2.2. Fundamental Combustion Characteristics

Compared with traditional gaseous fuels (CH₄ and H₂), when burning LCIG, the chemical reaction rate is slower and the chemical reaction intensity is lower, resulting in low combustion efficiency, narrow flammable range, and high combustion instability. As for the fundamental combustion characteristics, the impact of LCIG composition on ignition delay time, flame

instability, and laminar and turbulent flame speeds are summarized here. The ignition delay time of low calorific industrial gas is mainly affected by the H_2 content in LCIG. Higher H_2 content leads to shorter ignition delay time. The ignition delay time of LCIG is also sensitive to the initial temperature and pressure of the LCIG combustion system [19].

Laminar flame speed increases nonlinearly with an increase in H_2 concentration in LCIG. Laminar flame speed noticeably increases with equivalence ratio. Flame instability increases with the CO_2 concentration in LCIG, but decreases with a decrease in the equivalency ratio. High pressure, high H_2 concentration, and low equivalence ratio are the conditions under which the cellular flame self-accelerates. Markstein length and hydrodynamic instability both decrease with a rise in LCIG initial pressure, while the thermal mass diffusion instability has no effect [20]. For autoignition-assisted laminar flame propagation, the scaling laws for $H_2/CO/CH_4$ have been developed to characterize the negative temperature coefficient (NTC) behavior, with one branch indicating flame propagation, and the other indicating autoignition-assisted flame propagation [21].

For turbulent flame speed, the ratio of turbulent flame speed to laminar flame speed exhibits a nonlinear declining trend with H_2 concentration in LCIG, and the growth rate progressively declines. The influence of turbulence on the flame speed steadily declines as the H_2 concentration of LCIG approach 50% [22]. CO concentrations in LCIG have a significant impact on the turbulent flame structure. Reduced turbulent flame speed and enhanced combustion instability result from an increase in CO concentration. These effects increase when the equivalence ratio decreases [23].

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