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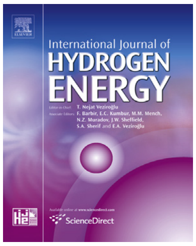

Influence of fuel hydrogen fraction on syngas fueled SI engine: Fuel thermo-physical property analysis and in-cylinder experimental investigations

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ABSTRACT

Hydrogen, either in pure form or as a gaseous fuel mixture specie enhances the fuel conversion efficiency and reduce emissions in an internal combustion engine. This is due to the reduction in combustion duration attributed to higher laminar flame speeds. Hydrogen is also expected to increase the engine convective heat flux, attributed (directly or indirectly) to parameters like higher adiabatic flame temperature, laminar flame speed, thermal conductivity and diffusivity and lower flame quenching distance. These factors (adversely) affect the thermo-kinematic response and offset some of the benefits.

The current work addresses the influence of mixture hydrogen fraction in syngas on the engine energy balance and the thermo-kinematic response for close to stoichiometric operating conditions. Four different bio-derived syngas compositions with fuel calorific value varying from 3.14 MJ/kg to 7.55 MJ/kg and air fuel mixture hydrogen fraction varying from 7.1% to 14.2% by volume are used. The analysis comprises of (a) use of chemical kinetics simulation package CHEMKIN for quantifying the thermo-physical properties (b) 0-D model for engine in-cylinder analysis and (c) in-cylinder investigations on a two-cylinder engine in open loop cooling mode for quantifying the thermo-kinematic response and engine energy balance.

With lower adiabatic flame temperature for Syngas, the in-cylinder heat transfer analysis suggests that temperature has little effect in terms of increasing the heat flux. For typical engine like conditions (700 K and 25 bar at CR of 10), the laminar flame speed for syngas exceeds that of methane (55.5 cm/s) beyond mixture hydrogen fraction of 11% and is attributed to the increase in H based radicals. This leads to a reduction in the effective Lewis number and laminar flame thickness, potentially inducing flame instability and cellularity.

Use of a thermodynamic model to assess the isolated influence of thermal conductivity and diffusivity on heat flux suggests an increase in the peak heat flux between 2% and 15% for the lowest (0.420 MW/m^2) and highest (0.480 MW/m^2) hydrogen containing syngas over methane (0.415 MW/m^2) fueled operation. Experimental investigations indicate the engine cooling load for syngas fueled engine is higher by about 7% and 12% as compared to methane fueled operation; the losses are seen to increase with increasing mixture hydrogen fraction. Increase in the gas to electricity efficiency is observed from 18% to 24%

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as the mixture hydrogen fraction increases from 7.1% to 9.5%. Further increase in mixture hydrogen fraction to 14.2% results in the reduction of efficiency to 23%; argued due to the changes in the initial and terminal stages of combustion. On doubling of mixture hydrogen fraction, the flame kernel development and fast burn phase duration decrease by about 7% and 10% respectively and the terminal combustion duration, corresponding to 90%–98% mass burn, increases by about 23%. This increase in combustion duration arises from the cooling of the near wall mixture in the boundary layer attributed to the presence of hydrogen. The enhancement in engine cooling load and subsequent reduction in the brake thermal efficiency with increasing hydrogen fraction is evident from the engine energy balance along with the cumulative heat release profiles.

Introduction

The primary focus of global research in the field of internal combustion (IC) engines is towards maximizing thermal efficiency and minimizing carbon emissions. Hydrogen as a fuel source, can potentially meet both the objectives. Being a zero carbon fuel, H_2 combustion generates carbon free exhaust. With higher laminar flame speed/adiabatic flame temperature compared to other fuels (refer Table 1) engines fueled with H_2 are expected to have superior thermal efficiency. Towards this, research is being directed at fuelling spark ignited (SI) engines with H_2/H_2 containing mixtures (combustible compounds with H_2 as a constituent) [1–5], the latter being the preferred choice considering the challenges associated with direct H_2 fueled operation like pre-ignition, inlet manifold backfire [4,6], high pressure rise rates [5,7] and NO_x formation [8,9] etc. The basic philosophy is to blend H_2 with other fuels to improve the combustion characteristics, specifically to extend/improve the lean limit operation [9–11] and as a fuel specie as in syngas [12–15]. The use of H_2 with CH_4 (designated hythane), especially under lean operating conditions, is one of the key areas begin exhaustively explored under this philosophy [16–18].

Table 1 – Thermo-physical properties of hydrogen and other fuels.

	Hydrogen H_2	Gasoline C_8H_{18}	Methane CH_4
Stoichiometric A/F (kg/kg)	34.20	17.19	15.08
Flammability limit (ϕ) [1,2]	0.1–7.1	0.7–4.0	0.5–1.67
Lower heating value (MJ/kg) [19]	119.93	44.50	50.02
Minimum ignition energy (mJ) [1,2]	0.02	0.28	0.24
Density (NTP conditions) (kg/m^3)	0.0831	4.4	0.665
Carbon to Hydrogen ratio (mol/mol)	0.0	0.44	0.25
Laminar flame speed (m/s) [19,20]	265–325	37–43	37–45
Adiabatic flame temperature (K) [19]	2318	2470	2148
Flame quenching distance (cm) [19,20]	0.064	0.20	0.20
Thermal conductivity (W/mK) [3]	0.182	0.011	0.034
Diffusion coefficient (cm^2/s) [3,20]	0.61	0.05	0.16

Numbers in square brackets indicate references for the respective properties.

While fuelling engines with H_2 containing mixtures may seem well aligned to satisfy the mandatory requirement of curtailing carbon emissions, either directly through fuel substitution or indirectly by efficiency improvement, analysis of the thermo-physical properties of H_2 containing mixtures suggest challenges towards realization of some of the envisaged benefits. Interestingly, the same thermo-physical characteristics of H_2 that support combustion characteristics also tend to pose challenges in realizing the benefits, especially in the close to stoichiometric operation regime.

The challenges

Certain key thermo-physical properties of H_2 containing mixtures that directly and indirectly enhance the engine efficiency also increase the engine cooling load, potentially offsetting the benefits sought to be derived. The laminar flame speed, adiabatic flame temperature, mixture thermal conductivity/diffusivity (all of which increase with H_2 fraction) and flame quenching distance (which decreases with H_2 fraction) are some of the key thermo-physical properties that potentially have dual influence. While higher laminar flame speed and adiabatic flame temperature influence both the efficiency and heat transfer, the flame quenching distance and mixture thermal conductivity/diffusivity directly influence the convective heat transfer between the working fluid and the containing surface(s). The relevant thermophysical properties of H_2, gasoline and CH_4 are consolidated for comparison in Table 1. While the effect of laminar flame speed and adiabatic flame temperature on the thermal efficiency is well established [9,21,22], the influence of described parameters on engine heat transfer is briefly described as below.

1. *Flame speed*: Hydrogen increases the mixture laminar (and hence turbulent) flame speed [23,24], leading to shorter

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