Combustion and Flame 173 (2016) 245–257

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Investigation of the combustion process of hydrogen jets under argon-circulated hydrogen-engine conditions

Mohd Radzi Abu Mansor [a,b,*], Masahiro Shioji [a]

[a] Graduate School of Energy Science, Kyoto University, Kyoto, Japan
[b] Department of Mechanical and Materials Engineering, Universiti Kebangsaan Malaysia, UKM Bangi, Malaysia

ARTICLE INFO

Article history:
Received 18 February 2015
Revised 27 July 2016
Accepted 27 July 2016
Available online 13 September 2016

Keywords:
Hydrogen
Direct injection
Compression ignition
Argon
Ignition delay
Combustion characteristics

ABSTRACT

The feasibility of argon-circulated hydrogen engines for use in vehicles was recently investigated. The substitution of the noble gas argon (Ar) as the working gas in a hydrogen engine led to the realization of a zero-emission, high-efficiency engine that allows low-ignitability hydrogen to ignite instantaneously after injection. The objective of this study was to investigate the combustion processes of hydrogen jets under argon-circulated hydrogen-engine conditions. Experiments were conducted in a constant-volume combustion vessel under varying conditions with respect to atmosphere, oxygen concentration, injection pressure, ambient temperature, and nozzle-hole diameter. Furthermore, the ignition characteristics and the combustion processes of the hydrogen jets were observed using high-speed shadowgraph images. Under short ignition delay conditions, the experimental results for the Ar–O_2 atmosphere indicated a lower heat-release rate, which continued to the end of the injection and resulted in a longer combustion period, whereas the heat-release rate under the air (N_2–O_2) atmosphere terminated simultaneously with the end of the injection. The ignition delay for the hydrogen jet under an Ar–O_2 atmosphere increased with decreasing ambient temperature, similar to the behaviour observed under the air atmosphere. Other fundamental characteristics that may help control the operation of argon-circulated hydrogen engines were obtained and discussed.

1. Introduction

At present, transportation industries mainly rely on petroleum fuels, resulting in a total daily worldwide consumption of up to 84.52 million barrels (2010 est.) [1]. With the increasing world population comes an increasing demand for fuels in the transportation industry. This trend has a ruthless impact on the environment because 70% of fuel usage is from internal combustion engines, which produce exhaust pollutants and deplete the non-renewable sources of fossil fuel [2,3]. This issue has motivated researchers worldwide to find alternative sources to power vehicle engines with new fuels. Hydrogen is one of the most promising energy carriers for the future [4–10]. It is a highly efficient, low-pollution fuel that can be especially beneficial for use in transportation. Moreover, hydrogen has been characterized by many researchers as the ultimate carbon-free fuel, has a high energy content per unit mass, is easily combustible because of its low ignition energy and produces only water as the major bi-product [11].

A majority of the efforts in hydrogen engine research have focused on spark ignition (SI)-type engines. Various studies have focused on combustion improvements for hydrogen fuel [12], the influence of the injection timing under various equivalence ratios [13], and knocking in SI engines [14]. Although hydrogen can be stably utilized using super-lean fuel mixtures, lean operations can significantly reduce the power output because of reductions in the volumetric heating and the low energy density of hydrogen in air-fuel mixture [15]. Furthermore, the low ignition energy of hydrogen can cause abnormal combustion, such as backfiring, pre-ignition, and knocking; these effects are the primary obstacles to the operation of hydrogen premixed charge SI engines, in addition to their low output [12–15]. These issues can be resolved by directly injecting the fuel gas into the cylinder. Studies have investigated the effects of the compression ratio, equivalence ratio, and engine speed on the performance and combustion characteristics of direct-injection SI engines [16]. Backfiring, pre-ignition, and knocking events can probably be eliminated by utilizing a late injection timing [11,16]. The challenge here is that this process requires hydrogen–air mixing in a very short time and has a high probability of incomplete mixing. Furthermore, late start of injection (SOI) will result in the production of substantial amounts of NO_x and reduce the indicated thermal efficiency at high load [15].

* Corresponding author at: Department of Mechanical and Materials Engineering, Universiti Kebangsaan Malaysia, UKM Bangi, Malaysia Fax: +603 89259659.
E-mail addresses: radzi@ukm.edu.my, mradzi@gmail.com (M.R.A. Mansor).

http://dx.doi.org/10.1016/j.combustflame.2016.07.032
0010-2180/

To achieve high thermal and volumetric efficiency and simultaneously eliminate combustion abnormalities, compression ignition (CI) engines operating with hydrogen fuel are considered a promising approach [11]. An engine that can operate at a high compression ratio would obtain higher power outputs than would SI engines. With high-pressure gas fuel directly injected into the hot atmosphere, the fuel will mix by entrainment and turbulence in a high-speed unsteady jet rather than by in-cylinder flow [17]. However, the relatively high auto-ignition temperature of hydrogen makes it difficult to ignite for combustion. An experiment has been performed by Shioji [18] to investigate the possibility of hydrogen ignition in CI engines. The experiment was conducted with an SOI time $\theta_j = 80°$CA, equivalence ratio $\phi = 0.35$ and compression ratio $\varepsilon = 22$. According to the results, stable combustion and ignition are not obtained in the combustion chamber with $\varepsilon = 22$ because of the high auto-ignition temperature of hydrogen.

Theoretically, there are two options for solving the problem of igniting hydrogen fuel in an internal combustion engine: increasing the compression ratio or using gases with a low specific heat capacity together with oxygen as a diluent to replace air during the combustion process. By increasing the compression ratio, the air and fuel will blend better, thus causing the engine to perform better without using too much extra energy to gain additional power. In the experiment by Shioji [18], $\varepsilon = 30$ was found to be a suitable compression ratio for achieving the auto-ignition temperature of hydrogen and producing stable combustion. This value is considered high and disadvantageous for the engine. Such a value will lead to the possibility of engine knocking. Moreover, a high compression ratio requires proportionally increasing the size of the engine, which is not practical for engine design.

In contrast, the approach of using gases with a low specific heat capacity, specifically using a monoatomic noble gas as a diluent to replace nitrogen from the air to generate a high temperature for the purpose of hydrogen ignition [11,19], is a promising alternative. This technique would not only eliminate the difficulty of CI for the hydrogen fuel but also be advantageous for achieving thermal efficiencies higher than those provided by normal air. The engine efficiency for an ideal diesel cycle can be written as a function of the engine's compression ratio (r), the cut-off ratio (r_c) and the specific heat ratio (κ) of the in-cylinder gas [20], as shown in Eq. (1).

$$\eta_{th} = 1 - \frac{r^{1-\kappa}\ (r_c^{\kappa} - 1)}{\kappa\,(r_c - 1)} \tag{1}$$

This relationship suggests replacing nitrogen from the air with an optimal diluent. Noble gases such as helium and argon are promising diluents because of their monatomic structure. These gases are nonreactive and have a high specific heat ratio ($\kappa = 1.67$, compared to $\kappa < 1.4$ for air) because noble gas molecules only have the translational mode of energy storage [21]. Therefore, attention is now being paid to CI engines that operate using a mixture of oxygen and argon. Argon was selected because this gas is plentiful, easy to obtain on the market (compared with other noble gases), and facilitates the creation of gas-tight seals [19]. This great concept encouraged a patent by Lauman et al. [22] in which argon is utilized in an IC engine; the patent proposes that the water from the exhaust can be condensed out and that the remaining argon can then be recycled in a closed-loop system. The feasibility of using this concept in a vehicle has been studied by many researchers [11,19,22], and a detailed study of separating argon and steam (H_2O) from exhaust gas from a system was performed by Kuroki et al. [19].

Direct injection CI engines do not suffer from knock and represent a better solution for taking advantage of the thermodynamic properties of noble gases. It has been experimentally demonstrated that this approach is able to achieve indicated thermal efficiencies close to 50% using compression ratios between 10 and 16 [11]. However, the new challenge is that the amount of hydrogen gas that can be injected at higher compression ratios is limited by the injection pressure of the system. High-pressure hydrogen gas injection is difficult because of the high diffusivity and low lubricity of H_2 gas [23]. With the new generation of solenoid injectors equipped with pressure balances, the energy and dynamic response of the injectors can be reduced [24]. However, issues related to the use of hydrogen, oxygen and argon in terms of transportation, production, storage, and portability continue to represent barriers to their utilization. These obstacles reduce the overall efficiency of hydrogen fuel, especially during production and filling of the gas into a tank for on-board purposes. This topic has attracted many researchers, who are performing detailed studies of and attempting to solve this problem [19,23,24]. Currently, only limited fundamental data can be obtained for this type of hydrogen combustion. In this study, the ignition delay and the combustion characteristics of hydrogen jets in an Ar–O_2 atmosphere were investigated using a constant-volume combustion vessel. The effects of ambient temperature, oxygen concentration, ambient pressure, injection pressure, and nozzle-hole diameter were investigated in a pre-burning system to determine the optimal design and operating conditions for argon-circulated hydrogen engines. To further investigate the combustion process of a hydrogen jet in an Ar–O_2 atmosphere, high-speed shadowgraph images were collected. Experiments were first conducted under standard conditions in an Ar–O_2 atmosphere (underlined in Table 1), and the results were compared to the combustion process of a hydrogen jet in an air atmosphere to validate the improvement in the combustion process achieved using a working gas with a high specific heat ratio.

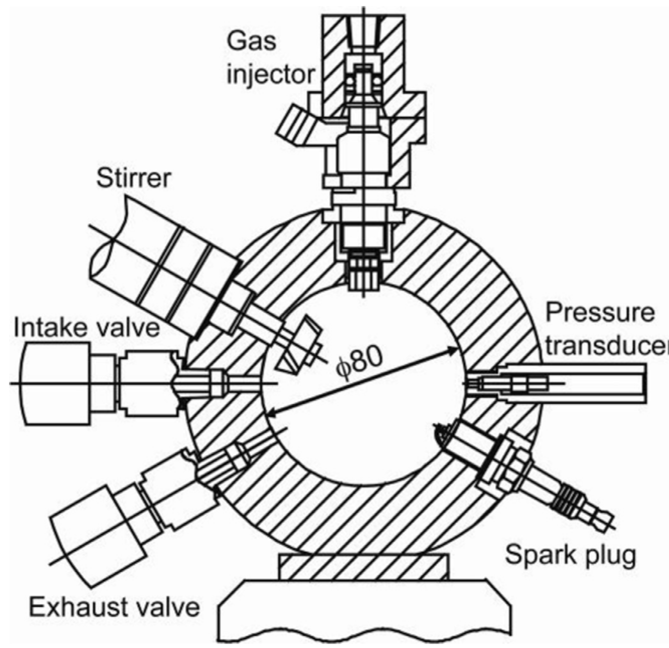

Fig. 1. Constant-volume vessel.

2. Methodology

2.1. Experimental setup and procedure

In this study, the ignition and combustion characteristics of a hydrogen jet were investigated in a constant-volume vessel. The combustion chamber, illustrated schematically in Fig. 1, was built in a manner similar to that reported in previous studies [25,26].