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Full Length Article

Study on the combustion characteristics and ignition limits of the methane homogeneous charge compression ignition with hydrogen addition in micro-power devices

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ABSTRACT

Based on the single process of free piston in micro HCCI free piston power device, the parameters such as the combustion characteristics of methane hydrogenation homogeneous charge compression ignition, the free piston movement process, the ignition time of the mixture gas, the changes of temperature and pressure in micro-combustion chamber, and the power capability of the device are compared and analyzed by combining the experiment method with the numerical simulation method. The experimental results are basically consistent with the numerical results. The research shows: when the initial equivalence ratio is 0.5, the blending of hydrogen can widen the ignition limit of mixed fuel, advance the ignition time of the mixture gas and reduce the starting energy needed for the device. At the same time, adding hydrogen to methane will reduce the maximum temperature and the maximum pressure of the micro-combustion chamber, make the burning flame more stable and alleviate the detonation phenomenon of the combustion of mixture gas. However, the addition of hydrogen to methane will result in the decrease of the final speed of the free piston, the increase of the time required for a single stroke, the decrease of the power capacity of the device, and the indicator thermal efficiency is also reduced. Only the proper hydrogen blending ratio can be used to expand the combustion boundary and improve the reliability of the combustion process while ensuring the capability of the micro power device.

1. Introduction

With the rapid development of Micro-Electro-Mechanical System (MEMS), as the core component of MEMS, the micro-power devices with high energy density, low pollution, low emission and using hydrocarbon fuel as the power source has become a research hot spot at home and abroad [1–3]. The micro free piston power device is a kind of micro power devices, its structure is simple, compact and has no other mechanical devices, which is more suitable for miniaturization [4,5]. Under normal circumstances, the maximum instantaneous pressure will not exceed 150 MPa and the maximum instantaneous temperature is less than 3500 K in the micro-free piston power device. The operating frequency of the micro-free piston power device is usually in the range of 300–1000 HZ. At the same time, it can achieve controllable combustion with variable compression ratio and it can be combined with various gaseous fuels and HCCI [6].

American Honeywell Corporation and Minnesota University proposed the concept of micro free-piston engines firstly [7,8]. Subsequently, H.T. Aichlmayrl et al. [9,10] studied the single compression ignition of a micro free piston engine, and proved the feasibility of micro HCCI free piston engine. Wang et al. [11–15] adopted experiment and numerical simulation methods to study the influence of variable parameters such as the initial momentum of the free piston, the equivalence ratio of the premixed gas, and the compression ratio on the combustion process of mixture gas in the micro-free piston power device under a single stroke. Homogeneous Charge Compression Ignition (HCCI) can achieve higher thermal efficiency and lower NO_x and soot emissions [16,17], by combining with the micro-free piston power device, it can overcome the flame quenching, combustion instability and other issues of the micro-free piston power device [18]. The intensive development of the micro HCCI free piston power device not only has made great and profound changes to the MEMS industry, but also to the pillar industries such as information, biology and modern microelectronics technology [19]. However, the combustion process of HCCI is controlled by chemical kinetics. How to control the combustion time of HCCI engine and realize the stable and reliable combustion of mixed gas is an urgent problem to be solved [20].

Current studies on conventional-scale combustion processes show

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Nomenclature

T_0	initial temperature
P_0	initial pressure
ϕ	initial equivalent ratio
L	length of micro-combustion chamber
d_1	diameter of micro-combustion chamber
h	length of free piston
l	the distance from the bottom of the piston to the bottom of the micro-combustion chamber
m	mass of free piston
v_0	initial speed of free piston
v_1	final speed of free piston
α	hydrogen blending ratio
v_{H_2}	the volume of hydrogen in the methane mixed with hydrogen
v_{CH_4}	the volume of methane in methane mixed with hydrogen
$T_t(x, y, z)$	temperature of micro-combustion chamber
$P_t(x, y, z)$	pressure of micro-combustion chamber
$Y_{nt}(x, y, z)$	concentration of each component
V_s	chamber volume
t_1	Piston stroke time
m_{H_2}	the mass of hydrogen in the methane mixed with hydrogen
m_{CH_4}	the mass of methane in the methane mixed with hydrogen
Q	the amount of heat released by the fuel
W_e	net output power
T_R	room temperature and it is set to 25 °C
n	the normal vector outside the boundary surface
k	the thermal diffusivity
A	cross-sectional area of the free piston
t	time
u_i	absolute velocity in the x_i direction
x_i	Cartesian coordinate (i = 1, 2, 3)
ρ	fluid density
s_m	quality generation source
τ_{ij}	stress tensor
s_i	energy generation source
e	unit mass with fluid internal energy
q_i	Energy flux of x_i direction
s_h	energy generation source
$F_{s,j}$	diffusion flow
R_s	reaction rate of mass of the component
P_∞	ambient pressure
T_∞	ambient temperature
p	absolute pressure of gas in the micro-combustion chamber
W	indicated power
H_{u,H_2}	low heat value of hydrogen
ΔE	Piston kinetic energy increment
H_{u,CH_4}	low calorific value of methane
η	indicated thermal efficiency
N_e	net power
P_A	atmospheric pressure and it is set to 0.1 MPa.
q_s	he heat flow intensity generated by the combustion of the mixed gas
λ	the surface heat transfer coefficient

that fuel blending can greatly improve the combustion characteristics of hydrocarbon fuels and achieve stable combustion. Wang et al. [21] concluded that when the concentration of hydrogen is increased, the percentage of the three kinds of intermediate free radicals, H, O and OH will increase, while the intermediate products of methane, CH_2O and CH_3CHO are gradually reduced, and the methane oxidation reaction proceeds in the direction of the low carbon reaction through the numerical simulation of methane, oxygen and air mixture combustion. Zhong [22] used chemical reaction kinetics to study the ignition and burning characteristics of H_2 in a methane-air premixed flame, and found that the presence of a small amount of hydrogen in the methane flame not only can reduce the ignition temperature of methane, but also can significantly increase burning rate and shorten burning time. Boushaki, T et al. [23] studied the effects of hydrogenation and steam on the laminar combustion velocity of methane-air premixed flames by experiments and numerical simulations. Sarlia V D et al. [24–26] used the CHEMKIN PREMIX code with the GRI kinetic mechanism to calculate the laminar burning velocities of hydrogen–methane/air mixtures at NTP conditions and Time-Resolved Particle Image Velocimetry to study transient interactions between hydrogen-enriched methane/air premixed flames and toroidal vortex structures, and developed a Large Eddy Simulation (LES) model to simulate the unsteady propagation of hydrogen-enriched methane/air premixed flames around toroidal vortices. They found that As the H radicals concentration and the reactions involving such atoms, in lean mixtures the hydrogen addition enhances the methane reactivity slightly, while a strong inhibiting effect of the hydrogen substitution by methane is observed at rich conditions. The hydrogen presence affects the flow field both quantitatively (increase of the velocity of the main toroidal vortex) and qualitatively (generation of different sub-vortices within the main vortex), enhancing the intensity of the interaction. The characteristic time of hydrogen diffusion is one order of magnitude higher than the characteristic time of flame roll-up around the vortex. Di S et al. [27] developed a reactor network model to study homogeneous gas-phase methane combustion taking place under typical operating conditions of lean premixed combustors piloted by rich catalytic/lean-burn (RCL) systems. Numerical results have shown that the opportunity to stabilize combustion is strongly linked to the presence of hydrogen in the -pilot stream. In the field of micro-scale combustion, Yan et al. [28] carried out the two-dimensional numerical simulation of the catalytic combustion of the methane mixed with hydrogen in a flat type micro channel. The results showed that the ignition time can be advanced and the combustion stability can be improved by adding hydrogen, and the mole fraction of H, OH and C(s) increases with the increase of hydrogen. In this paper, the combustion characteristics of the methane mixed with different proportions of hydrogen in the micro HCCI free piston power device are studied by the combination of experiment and numerical simulation to provide a theoretical basis for stabilizing the ignition of the device, controlling the ignition time of the fuel and expanding the operating conditions of the HCCI engine.

2. Experimental device and working principle

In order to study the combustion characteristics of the methane mixed with hydrogen and the movement of the free piston in the micro free piston power device, a visual experiment bench for free piston single stroke process was established, and the experiment bench is shown in Fig. 1. The methane/oxygen mixture with different proportions of H_2 is prepared by the MKS1179A flow meter and the MKS247D high-precision mass flow controller, and introduce it into a visual micro-combustion chamber made by borosilicate. The MKS247D high-precision mass flow controller can control four different gases simultaneously. High-pressure nitrogen gas provides different initial speeds for the piston through the pneumatic device. The fuel and the air are controlled by the mass flow meter to determine different equivalence ratios, after which the various gases are uniformly mixed into the micro-combustion chamber, and the piston is moved to compress the mixture gas by giving the initial velocity to achieve HCCI combustion of fuel. The mixture gas is ignited in the micro-combustion chamber. In the single impact process of free piston, a high-speed digital camera is