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Full Length Article

Experimental study of the combustion and emission characteristics of ethanol, diesel-gasoline, *n*-heptane-iso-octane, *n*-heptane-ethanol and decane-ethanol in a constant volume vessel

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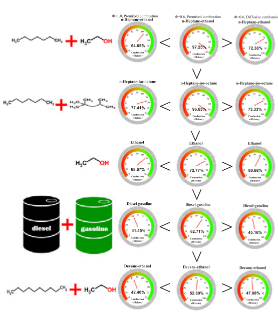
GRAPHICAL ABSTRACT



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ABSTRACT

This work investigates the effect of fuel reactivity, mixture preparation (premixed or diffusive) and equivalence ratio (φ = 0.6, 1.0) on the combustion and emission characteristics of ethanol, diesel-gasoline, *n*-heptane-iso-octane, *n*-heptane-ethanol and decane-ethanol in a constant volume bomb. It provides the direction to improve the combustion efficiency and reduce the pollutant emissions for the internal combustion engines. The fuel selection criterion is to establish the fuel reactivity gradient by blending the high and low octane number fuels. The main conclusions are summarized below: First, the premixed fuel-lean combustion, also known as homogeneous charge autoignition (HCAI), can improve the combustion efficiency by elevating the peak pressure and reducing the combustion duration. The ethanol combustion efficiency increases from 41.0% at 1.0-D condition to 68.7% at 1.0-P condition by breaking the limit of the fuel-air mixing rate, and finally reaches 72.8% at 0.6-P condition through increasing the oxygen concentration and facilitating the hydrocarbon oxidation. Second, the combination of the high reactivity (low RON) and high volatility fuels can further improve the combustion efficiency that the former acts as the distributed ignition source and the latter forms the homogeneous charge. The combustion efficiency of *n*-heptane-ethanol at 0.6-P condition reaches 97.2%. Third, the HCAI can reduce the NO_x emission by enhancing the mixture uniformity, constructing high dilution to lower the peak combustion temperature. Fourth, the premixed fuel-lean combustion produces higher CO and HC emission compared to diffusive combustion due to the relatively low reaction temperature. Fifth, the premixed fuel-lean combustion can significantly reduce the particle mass and number concentration by decreasing the production of the accumulation mode particles. Sixth, the high volatility/RON fuel (such as ethanol) alone is not the best candidate for HCAI combustion because their high autoignition resistance makes it difficult to ignite spontaneously and

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produce a large number of unburned hydrocarbons. Then they nucleate to form new particles or condense on solid particles.

Nomenclature

c_v	the specific heat capacity at constant volume
cov	the covariance
Dp	the particle diameter
ΔH_c	the heat of combustion
$H_P(T_A)$	the enthalpy of the products at ambient temperature T_A
$H_R(T_A)$	the enthalpy of the reactants at ambient temperature T_A
$\Delta h_{f,i}$	the standard enthalpy of formation of species i at ambient temperature T_A
m	mass
N_i	the number of the particle
N_i	the number of the particle of specific diameter
n_f	the fuel molar quantities
n_i	the number of moles of species i in the reactants or products
P_{init}	the initial mixture pressure
P	the mixture pressure
P_{max}	the maximum mixture pressure
p	pressure
$\frac{dQ_g}{dt}$	the gross heat release rate
$\frac{dQ_{ht}}{dt}$	the heat transfer rate from the system to the walls
$\frac{dQ_n}{dt}$	the net heat release rate
R	the sphere radius or the gas constant
r	the radius of the spherical flame at any moment
T_A	ambient temperature
U_s	the sensible internal energy of the charge
V	volume

Greek letters

φ	the equivalence ratio
γ	the ratio of specific heat capacity
γ_u	the ratio of the specific heat capacity of the unburned mixture
η_c	the combustion efficiency
ψ	the symmetric coefficient
σ^2	the variance of variables

Abbreviations

AIT	autoignition temperature
CCD	charge coupled device
CDDR	combustion duration decreasing rate
CVV	constant volume vessel
CFD	computational fluid dynamics
CLD	chemiluminescence detector
FID	hydrogen flame ionization detector
FILE	forward illumination light extinction
HCCI	homogeneous charge compression ignition
HCNG	hydrogen compressed natural gas
HRR	heat release rate
LDV	laser Doppler velocimetry
LEM	laser extinction method
LIBS	laser-induced breakdown spectroscopy
LIF	laser-induced fluorescence
LII	laser-induced incandescence
LPG	liquefied propane gas
MFB	mass fraction burned
MON	motor octane number
N/A	not available or not applicable
NDIR	non-dispersive infrared
PCCI	premixed charge compression ignition
RCCI	reactivity controlled compression ignition
RON	research octane number

1. Introduction

The compression ignition engine has the advantage of high thermal efficiency because the high compression ratio ensures a larger proportion of energy can be extracted from the fuel. However, the diffusive (mixing controlled) combustion mode generates many over-lean and over-rich regions [1]. The fuel/air ratio nonuniformity seriously deteriorates the NO_x, HC and particulate emission which offsets the advantage of lean combustion [2]. The spark ignition engine usually adopts uniform fuel-air mixture which is induced ignition by the spark plug. The premixed combustion greatly reduces the particle emission but the NO_x emission rises due to the high reaction temperature of the flame front and post flame products [3,4]. In addition, the HC and CO emissions also need to be controlled. In order to further increase the thermal efficiency and reduce the NO_x/soot emissions simultaneously, some new combustion modes like HCCI (homogeneous charge compression ignition), PCCI (premixed charge compression ignition) and RCCI (reactivity controlled compression ignition) etc. are proposed [5–7]. In essence, the burning rate of these combustion modes is chemical kinetic controlled because the fuel-air mixture is premixed and external ignition source is not available [8,9].

The HCCI and PCCI combustion mode drive innovation particularly in the combustion process. The HCCI directs the pathway to increase the combustion efficiency and simultaneously reduce NO_x and particulate matter emission by premixed fuel-lean combustion. However, the homogeneous charge autoignition produces unacceptable high heat release rate and thus a high pressure rise rate which constrains the engine operation on the moderate to high load condition [5,8]. In order to mitigate the high heat release rate, the PCCI combustion mode is proposed that creating the partially premixed charge by appropriate injection strategy. The in-cylinder charge stratification lowers the peak heat release rate and extends the operation load to a certain extent [6]. However, these innovations still focus on the combustion mode itself and do not involve the importance of the fuel design [10]. The fuels physical (e.g. volatility, viscosity) and chemical (e.g. autoignition temperature, chemical group) properties have an important impact on the combustion process which is the key to improve the combustion efficiency and reduce pollutant emission [10]. In order to actively control the heat release rate, the concept of the dual fuel HCCI [11] and the RCCI [7,9] are proposed. Their fuel design principles are similar: establishing fuel reactivity gradient in the combustion chamber by adopting at least two fuels of different reactivity. For dual fuel HCCI, the combustion phasing can be adjusted by varying the ratio of high reactivity (low RON) fuel to the low reactivity (high RON) fuel. In addition, to vary the fuel blending ratio, the RCCI can also use the in-cylinder charge stratification to control the heat release rate by adjusting the injection strategy. The nature of these fuel reactivity controlled combustion mode is that the chemical kinetic controls the reaction rate. However, it is very difficult to investigate the effect of chemical kinetics on the combustion and emission characteristics in the