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Research Paper

Study on the synthetic scavenging model validation method of opposed-piston two-stroke diesel engine

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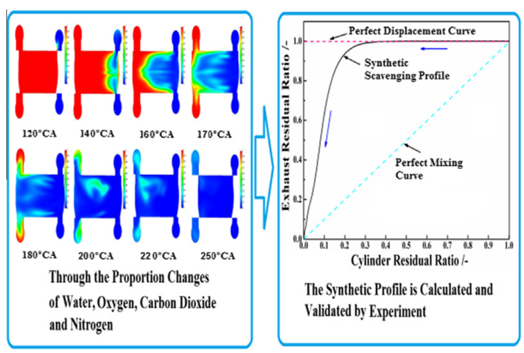
HIGHLIGHTS

- Scavenging parameters of the OP2S diesel engine are investigated respectively by simulation and experiment.
- Detailed calculation process of the synthetic scavenging profile was given.
- Tracer gas technique is used in experimental validation process.
- Validation method of the synthetic model was presented.
- Delivery ratio range of the OP2S diesel engine was given.

GRAPHICAL ABSTRACT



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ABSTRACT

The scavenging process of two stroke engines is a complex phenomenon. In two stroke engines, each outward stroke of the piston is a power stroke. This means the operation of clearing the burned gas in cylinder and obtaining fresh air for next cycle must accomplish at same time. The combined intake and exhaust process in two stroke engine is called scavenging. Nowadays, a synthetic scavenging model is widely used to describe the scavenging process of two stroke engines. It represents the time evolution of the in-cylinder residual gas rate and the exhaust residual gas rate. An opposed two stroke diesel engine's (OP2S) synthetic scavenging profile is calculated through the changes of gas compositions in-cylinder and exhaust pipe by CFD simulation. To validate the accuracy of this profile, a validation method based on tracer gas technique is proposed. First, scavenging parameters including scavenging efficiency and trapping efficiency are calculated by 1D software using the synthetic scavenging profile as a vital boundary condition. The results reveal that the delivery ratio of the OP2S diesel engine should below 140%. Second, use tracer gas technique to measure the scavenging parameters of OP2S diesel engine. In the experimental process, we find the OP2S diesel engine operates steady only if the delivery ratio is higher 50%. The scavenging parameters from 1D simulation and experiment match well which means the synthetic scavenging model received by CFD simulation performs well and validating its effectiveness through tracer gas technique is available.

1. Introduction

The opposed-piston two-stroke engine (OP2S) concept came into being in 1850's. Witting, a German engineer, designed and manufactured the world's first coal gas fuel opposed-piston engine

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Nomenclature

1D	mono-dimensional
3D	three-dimensional
A	intake air
CFD	computational fluid dynamics
$CO_{2,cyl}\%$	mass percentage of carbon dioxide in cylinder
$CO_{2,exh}\%$	mass percentage of carbon dioxide in exhaust chamber
EGR	exhaust gas recirculation
F	fuel
$(F/A)_{ov}$	global fuel–air ratio
G_0	mass of delivered (or mixture) air retained
G_R	reference mass
G_S	mass of delivered air (or mixture) per cycle
g_s	intake flow rate
$H_2O_{cyl}\%$	mass percentage of water in cylinder
$H_2O_{exh}\%$	mass percentage of water in exhaust chamber
l_0	delivery ratio
m_{air}	mass of scavenging gas
m_{exh}	mass of tracer gas in exhaust gas
m_{fuel}	mass of fuel
m_{scav}	mass of short circuit gas
$m_{tracer,air}$	mass of tracer gas in total scavenging air
$m_{tracer,exh}$	mass of tracer gas in exhaust gas
$W_{tracer,air}$	mass fraction of tracer gas in total scavenging air
$W_{tracer,exh}$	mass fraction of tracer gas in exhaust gas
$W_{tracer,scav}$	mass fraction of tracer gas that circuited
$X_{t\cdot e}$	molar concentration of tracer gas in intake pipe
$X_{t\cdot i}$	molar concentration of tracer gas in exhaust pipe
m_{trap}	mass of trapped gas
$m_{trap,tracer}$	mass of tracer gas that captured in cylinder
M	molar mass
M_{air}	molar mass of intake air
M_{exh}	molar mass of exhaust air
$M_{tracer,air}$	molar mass of tracer gas in total scavenging air
$M_{tracer,exh}$	molar mass of tracer gas in exhaust gas
n	engine speed
n_{air}	molarity of intake air
n_{exh}	molarity of exhaust gas
$n_{tracer,air}$	molarity of tracer gas in total scavenging air
$n_{tracer,exh}$	molarity of tracer gas in exhaust gas
$N_{2,cyl}\%$	mass percentage of nitrogen in cylinder
$N_{2,exh}\%$	mass percentage of nitrogen in exhaust chamber
N_{cyl}	engine cylinder number
$O_{2,cyl}\%$	mass percentage of oxygen in cylinder
$O_{2,exh}\%$	mass percentage of oxygen in exhaust chamber
OP2S	opposed-piston two-stroke
p_s	intake pressure
R	molar gas constant
T_s	intake temperature
V_h	displacement per cylinder
ρ_s	intake density
η_R	cylinder residual ratio
$\eta_{R,exh}$	exhaust chamber residual ratio
η_s	scavenging efficiency
η_{tr}	trapping efficiency

[1]. From then on, many novel designs were brought out on aircrafts, marines and vehicles such as TS-3 engine manufactured by British Rootes Company and 6-TD engine from Ukraine. However, rigid emission legislations slowed down the development of opposed-piston engines after 1970's. In recent years, with the improvement of modern analytical tools, materials, and fuel supply system, OP2S engines from FEV, EcoMotor and Achates Power Company have performed well in many fields [2–6]. OP2S draws more and more attention once again because of its high efficiency and high power density [7,8].

The OP2S engines have the potential for higher power density than four-stroke engines if the scavenging process is well investigated to fill the cylinder with fresh air. Depend on the port timing, the gas exchange process of OP2S cycle can be comprised of 3 phases [9]. At first phase, the pressure in cylinder is released near the expansion stroke by opening the exhaust port. At second phase, the intake ports are opened, the burned gas is replaced by fresh gas continuously. At last phase, after the exhaust port is closed, a portion of fresh air is blown into cylinder by scavenging blower or turbocharger compressor until the intake port is closed. Different from four stroke engines, the scavenging process of two stroke engines is always evaluated by the trapping efficiency, the scavenging efficiency and the delivery ratio.

In real scavenging processes, mixing occurs as the fresh air displaces the burned gases and some of the fresh air may be expelled. Two vital ideal models must be firstly introduced: perfect displacement model and perfect mixing model. Perfect displacement model is used to describe if the burned gases were pushed out by the fresh gases without any mixing. Perfect mixing model would occur if entering fresh mixture mixes instantaneously and uniformly with the cylinder contents. Since 1914, HOPKINS [10] have proposed a perfect mixing scavenging model, lots of different models have been offered to draw conclusions about the quality of the scavenging process. A model with good ability to reproduce the real process as well as low mathematical expenditure is always needed. Merker and Gerstle [11] classified these models into the single-zone, the multi zone and the fluid mechanical models. In single-zone models, Benson and Brandham [12] assume that the cylinder content can be divided into two zones, a perfect displacement and a perfect mixing zone. In the first phase, scavenging process works as perfect displacement while the second phase takes place as a perfect mixing process. Dang and Wallace [13] combines perfect displacement with perfect mixing and short circuiting. Multi zone models divide the cylinder volume into two or more sub-volumes or systems. All sub-volumes or systems share constant pressure but different zones can have different temperatures. The temperature of each sub-volume is constant and no heat transfer between zones. Many models are proposed by such as Sher [14], Streit and Borman [15] and Wallace and Cave [16]. In recent years, a synthetic scavenging model for the overall characterization of the scavenging process of two-stroke engines is widely used. It gives the mass fraction of burned gases exhausted as a function of the mass fraction of burned gases in cylinder. The model usually assigned as input data in many 1D software [17]. Ferrara et al. [18] present an innovation solution to reduce the short-circuit by designing a rotating valve positioned in correspondence with the exhaust port. The synthetic scavenging model is used as input data for the second step of the 1D simulation. The new solution was analyzed both in terms of global performance with 1D code, and of fluid dynamics behavior of the system through CFD simulations. Laget et al. [19] used the synthetic scavenging model to research the influence of intake and exhaust pressure to the scavenging process in their preliminary design of a two-stroke uniflow diesel engine for passenger car. Tribotte et al. [20] compared three kinds of cylinder heads with the guideline of the synthetic scavenging model. The results were satisfied after redesigning. Pohorelsky et al. [21] also used the synthetic scavenging model as a part of their 1D engine model to determine the requirements on the air