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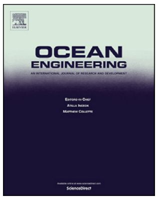

Numerical investigation of two-stroke marine diesel engine emissions using exhaust gas recirculation at different injection time

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A R T I C L E I N F O

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A B S T R A C T

The computational fluid dynamic (CFD) model was established for a two-stroke marine diesel engine. The detailed chemical solver was adopted as combustion model. *n*-tetradecane was used as an alternative fuel. The simulation model was validated using experimental data. The effects of inlet pressure, exhaust gas recirculation (EGR) and start of injection (SOI) time were investigated on the emission of marine diesel engine. The base parameters were compared, including mean in-cylinder pressure, indicated power and indicated specific fuel consumption (ISFC). The trade-off between NO_x and ISFC was also researched. Results show that NO_x emissions become less and less when the inlet pressure exceeds 0.369 MPa. NO_x emissions reduce strongly when the EGR is used. The quantity of NO_x emissions meets the requirement of Tier III when the EGR rate reaches 20%. Analysis results reveal that the quantity of NO_x emissions declined with retarded SOI; however, ISFC increases. The decrement in NO_x emissions is quite small under high EGR rate; however, the associated increase in ISFC is large. Coupling EGR with SOI not only decreases NO_x, emissions but also lowers ISFC. This paper provides a workable technological method to optimize marine diesel engine emissions.

1. Introduction

Environmental pollution is of global concern. Marine diesel engines produce more emissions than do vehicle engines. Emission regulations have recently become more stringent for marine engines. The International Maritime Organization Tier III requires NO_x emissions not exceed 3.4 g/kWh, when operating inside an emission control area (Emission Standards, 2016). Many technologies have been proposed to make marine engines meet these requirements, such as alternative fuels, internal engine modifications, humid air motors, exhaust gas recirculation (EGR), and selective catalytic reduction (Yang et al., 2012; Roskilly et al., 2015; Zhou et al., 2013).

Diesel engines commonly employ EGR to lower NO_x emissions. Raptotasios et al. (2015a) showed that NOx emissions meet the Tier III requirement when the EGR rate exceeds 35% for the two-stroke 4T50ME-X test marine diesel engine. Deepak et al. (Agarwal et al., 2011) studied the effect of EGR on the performance, emission, deposits and durability for a constant speed compression ignition engine. Decreases in NO_x and exhaust gas temperature were observed but emissions of particulate matter (PM), HC, and CO were found to increase with EGR use. At the same time, higher carbon deposits and higher wear of piston rings were observed on the engine parts operating with EGR. The EGR temperature also effects the performance and emissions of heavy duty direct injection diesel engines (Hountalas et al., 2008). The low temperature EGR improves brake specific fuel consumption (BSFC) and lowers soot, but has only a small positive effect on NO_x emissions. Low EGR temperature has a stronger effect at higher EGR rates. Yu et al. (2014) showed that with increasing EGR rate, the cylinder pressure and combustion temperature reduces and the peak of soot also shows a downward but more gentle trend, under the same load conditions. Although EGR is a useful technology for diminishing NO_x emissions, it is necessary to use other methods to limit the associated reduce in BSFC.

Wagner et al. (2003) described the simultaneous decreases of NO_x and PM emissions in a modern light-duty diesel engine under high EGR levels. They used a combination of EGR and manipulation of injection parameters. Their results showed that improved understanding of this combustion regime will lead to wider EGR utilization to meet the lower performance requirements of post-combustion emissions controls. Verschaeren et al. (2014) investigated NO_x emissions in a medium-speed heavy-duty diesel engine using EGR and Miller timing. An injection advance during low-load operation raised combustion pressures and shortened combustion duration. Chen et al. (2014) studied pilot injection for improvement of combustion characteristics in a heavy-duty diesel engine. Their results demonstrated that with the advance of pilot

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injection timing, the peak in-cylinder pressure dropped down, the ignition delay of the main combustion is shortened, and the NO_x and soot emissions are reduced, whereas the HC and CO emissions are increased. Tadros et al. (2016) studied the effect of different start angles of combustion on performance and the exhaust emissions of a marine diesel engine. The start angles of combustion at the lowest speed of the engine are retarded top dead center, which reduces the exhaust emissions and decreases the brake power a little bit. Saravanan (2015) studied the effect of EGR and advanced injection timing on the combustion characteristics of a diesel engine. From their experimental results it can be concluded that NO_x and smoke emissions can be controlled simultaneously with less variation in the combustion characteristics of the engine. The trade-off relationship between BSFC and NO_x can be improved by applying EGR and adjusting the injection timing (Verschaeren et al., 2014; Aldajah et al., 2007; Thangaraja and Kannan, 2016; Li et al., 2014).

Computer simulations have increased in potential applications with the development of computers. It is now practical to use computer simulations to model marine diesel engines. Owing to the large volume of a marine engine, experimental research is difficult and expensive. Pang et al. (2016) investigated soot formation and oxidation processes in a large two-stroke marine diesel engine using integrated computational fluid dynamic (CFD)-chemical kinetics. They developed a new *n*-heptane skeletal diesel surrogate model for analyzing combustion and soot. Panagiotis et al. (Kontoulis et al., 2008) used the KIVA-3 code as the modeling platform to study the effects of advanced injection strategies. They demonstrated that by adding an appropriately timed pilot injection, fuel savings of the order of 1.7% can be achieved, without increasing NO_x emissions. They used *n*-tetradecane as an alternative fuel. Sun et al. (2017a) compared the performance of *n*-heptane and *n*-tetradecane as alternative fuels in a marine diesel engine. The quantity of emissions is related to the combustion models and alternative fuels. It is important to choose an appropriate combustion model and alternative fuel for the simulation of a marine diesel engine.

In this paper, a CFD model of a two-stroke marine diesel engine is established and validated using experimental data. The effects of inlet pressure, EGR rate and injection time on the performance of marine diesel engines are studied. The optimal method is proposed to lower NO_x emissions while minimizing the increase in indicated specific fuel consumption. This paper provides a solution to make a two-stroke marine diesel engine meet the requirement of Tier III.

2. Brief description of the model

The CFD model is based on a marine diesel engine (6S35ME-B9). The main particulars are listed in Table 1. The engine speed is 142 r/min when operated at 100% load. The in-cylinder pressure and emission products were tested and used to validate the accuracy of the model.

The engine simulation is performed using the commercial CFD software package CONVERGE 2.3. Fig. 1 shows the three-dimensional structure of model. This model includes a scavenge box, cylinder and exhaust port. The k-ε two-equation mode is used as turbulence model. Kelvin Helmholtz-Rayleigh Taylor model is applied to the simulation of spray breakup. The NTC collision model is implemented to simulate the fuel collision. The wall splash model is used in the O'Rourke model based on Weber number, film thickness and viscosity. The detailed chemical solver combustion model is used to simulate the fuel ignition. For the emissions generate models, the Extended Zeldovich NO_x mechanism is applied to simulate the production of NO_x. Hiroyasu-NSC Model is used to simulate soot production respectively. The injected liquid temperature is set to 345 K. The injection duration is 15.36 °C A and the total injection mass is 0.0126 kg, which was obtained from experimental data.

Table 1
6S35ME-B9 test engine specifications.

cylinder number	6
Bore (mm)	350
Stroke (mm)	1550
Displacement (L)	149
Connecting rod length (mm)	1550
Speed (r/min)	142
Power (kW)	3575

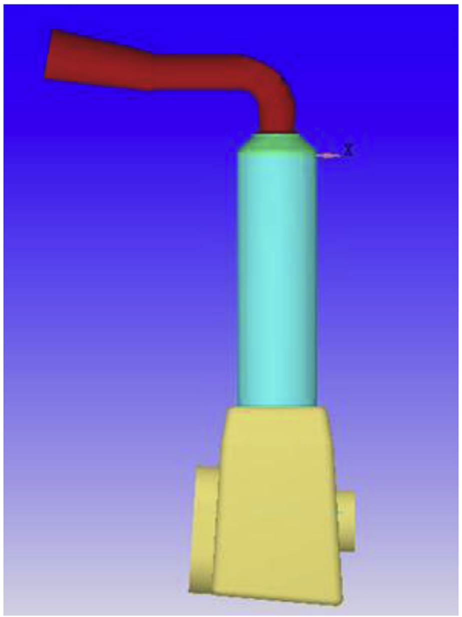

Fig. 1. The three-dimensional geometric structure.

These models participate in calculated process of CFD model. In addition to these, the marine engine numerical simulation also is based upon continuity, momentum and energy conservation laws (Amsden et al., 1989).

The continuity equation of flow field is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u} \right) = \dot{\rho}^s \tag{1}$$

$\vec{u}$ is the velocity vector, ρ is the fluid density. $\dot{\rho}^s$ is the source item.

The equations of momentum conservation law on the *x, y*, and *z* directions as follows:

$$\frac{\partial \left(\rho \vec{u} \right)}{\partial t} + \nabla \cdot \left(\rho \vec{u} \vec{u} \right) = -\frac{1}{a^2} \nabla P - A_0 \nabla \left(\frac{2}{3} \rho k \right) + \nabla \cdot \sigma + \vec{F}^s + Pg \tag{2}$$

a is the dimensionless quantity of different fluid properties. *P* is the pressure; *g* represents the gravity; *k* is the turbulence energy; A_0 has relationship with turbulence model (laminar flow $A_0 = 0$, turbulent flow $A_0 = 1$); σ is the viscous stress.

The equation of energy conservation law as follow:

$$\frac{\partial (\rho I)}{\partial t} + \nabla \cdot \left(\rho \vec{u} I \right) = -P \nabla \cdot \vec{u} + (1 - A_0) \sigma \cdot \nabla \cdot \vec{J} + A_0 \rho \varepsilon + \dot{Q}^C + \dot{Q}^S \tag{3}$$

I is the specific heat energy including chemical energy; $\vec{J}$is the heat equator flux vector.

3. Model validation

n-tetradecane is often used as an alternative fuel for the simulation of marine diesel engines Struckmeier et al. (2009) research the multi-component modeling of evaporation, ignition and combustion processes. The effects of fuel component properties on the ignition and combustion properties of the fuel blend have been investigated. The