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Numerical analysis of the influence of the fuel injection timing and ignition position in a direct-injection natural gas engine

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ABSTRACT

Large-eddy simulation of fuel injection and combustion in a direct-injection natural gas engine was conducted. The influence of the fuel injection timing and ignition position was numerically analyzed. The engine used in this study operates in lean burn mode with a fuel-air equivalence ratio of approximately 0.72. The combustion pressure and in-cylinder burned volume decrease as fuel is injected earlier using the same ignition timing, and the fuel consumption rate also decreases. As ignition is delayed, the influence of the fuel injection timing is weakened because of the over-mixed mixture during the late compression stoke. Fuel injection timing changes the global fuel-air equivalence ratio, which is not the primary cause of its effect on combustion. As fuel is injected later, the in-cylinder velocity magnitude increases and a relatively richer mixture is distributed around the ignition position, which contributes to better combustion. This is the main mechanism of how fuel injection timing influences combustion. The ignition position determines the background distribution of the velocity magnitude and mixture and confines the available space for flame development. Central ignition is the best choice for the engine used in this study.

1. Introduction

Crude oil shortages and greenhouse gases have become two serious problems worldwide [1] that must be resolved immediately. Many countries have released increasingly stringent emissions rules [2]. Therefore, scholars and automotive manufacturers are seeking to promote broad studies and to develop alternative fuel engines. Natural gas is one of the most promising alternative fuels because of its chemical properties. Natural gas has high knock resistance, which allows more power for a given engine displacement and increases thermal efficiency. Furthermore, natural gas has a low carbon content, which results in a significant reduction in pollutant emissions [3].

Although natural gas engines can produce the same high torque output as gasoline engines and increase the thermal efficiency through a combination of a high engine compression ratio and lean combustion mode, the in-cylinder combustion duration is prolonged, which leads to serious liner heat loss [4] and high cycle-to-cycle variation [5] because natural gas has low charge efficiency and laminar flame speed. The performance of natural gas engines can be improved through direct injection owing to the increased volumetric efficiency and low detonation limits. There are currently two main engine types that use direct-injection natural gas, namely, purely direct-injection natural gas engines and dual-fuel engines [6]. There is considerable literature on both branches. Douailler [7] converted a diesel engine to a high-compression-ratio direct-injection natural gas engine. They demonstrated that the injection duration is shortest and that the engine has the highest volumetric efficiency when natural gas is injected close to the timing of intake valve closure. Zoldak [8] experimentally found that injection timing is crucial to engine performance. When fuel is injected during the compression stoke, the injection process leads to a heterogeneous fuel-air mixture, which can be characterized as a partially stratified combustion process. The combustion is sufficiently mixed and phased for optimal fuel consumption, in contrast to the situation where fuel is injected before intake valve closure. This conclusion agrees well with Mindaugas's [9] study in low-pressure direct-injection natural gas engines. Ali [10] proposed a gas-jet ignition method with two-stage injection and demonstrated that natural gas engines operate in a wide range of equivalence ratios from 0.3 to 0.7. Literature review shows that the direct injection of natural gas has great potential, and fuel injection timing plays an important role.

Numerical methods might be a good way to investigate the intrinsic mechanism of direct-injection natural gas engines. The

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Nomenclature

$\overline{\rho}$	favre averaging density
$\tilde{\mathbf{u}}$	filtered velocity vector
p	pressure
$\overline{\mathbf{S}}$	strain rate tensor
$\boldsymbol{\tau}$	sub-grid Reynolds stress tensor
$\mathbf{I}$	unit tensor
ν_{sgs}	sub-grid viscosity
ν	laminar viscosity
$\overline{\mathbf{D}}$	large-scale strain rate tensor
k_{sgs}	sub-grid turbulent kinetic energy
ε	dissipation rate
C_k	model constant
C_ε	model constant
Δ	space filter scale
P_0	stagnant/injection pressure
P_{ch}	chamber pressure
ρ_0	stagnant density
d_{eq}	equivalent diameter
l_{spk}	electric spark length
t_{spk}	spark timing
TDC	top dead center
CNG	compressed natural gas
DI	direct injection
PaSR	partially stirred reactor model
m_b^{ign}	burned fuel mass
$\overline{\rho}_u$	favre averaging unburned mixture density
δ_L	laminar flame thickness
$\overline{C}_{ign}$	filtering variable
C_{init}	ignition model constant
$\mathbf{x}$	displacement vector
$\mathbf{x}_{spk}$	spark displacement vector
$\overline{\dot{w}}_i$	mean reaction rate of the ith reaction
Y	specie mass fraction
T	temperature
k	reacting sub-grid volume fraction
τ_{mix}	turbulent mixing time
τ_c	chemical reaction time
C_{mix}	model constant
γ	node diffusivity
u_c	velocity of cell center
u_p	velocity of grid node
$\mathbf{x}_{old}$	old displacement of grid node
$\mathbf{x}_{new}$	new displacement of grid node
BTDC	Before Top Dead Center
DNS	Direct Numerical Simulation
LES	Large-eddy Simulation
RANS	Reynolds-Average Navier–Stokes

first challenge is simulation of high-pressure gaseous injection. In the direct-injection natural gas engine, the pressure at the nozzle exit is generally larger than ambient pressure, and the generated flow is characterized as under-expanded flow. At the nozzle exit, flow is believed to be choked, and velocity equals the local speed of sound. At this time, the mass flow rate mainly depends on the upstream injection pressure. Provided that the Reynolds number of the near-nozzle region is high, i.e., greater ten thousand, it is necessary to select a fine grid and small time step to calculate the intricate turbulence eddy structure. In addition, the difference of flow scales between the nozzle and cylinder is approximately 100 times, which makes detailed numerical calculation of the injection process in an engine computationally expensive.

Some scholars are attempting to use detailed numerical methods to conduct their research. Yadollahi [11] established a detailed numerical model of a direct-injection natural gas engine with a centrally mounted injector. The calculation domain included the engine cylinder and injector region. The detailed simulation of the high-pressure methane jet was sensitive to grid scales and preferred to be numerically unstable. The effect of the chamber geometry on mixture formation and combustion was also involved. A narrow bowl chamber produced a relatively better stratified mixture. It has been shown that advanced ignition timing of up to 50 degree crank angle should be used to obtain better combustion performance [12]. Riccardo [13] concluded that multi-hole jets interact and emerge into a single fuel jet in the downstream of an under-expanded region. Bialy [14] studied the effect of injector position on the in-cylinder degree of mixture stratification and determined the optimal injector position for the engine in this study. However, these authors all stated that detailed numerical simulation of the in-cylinder injection process and mixture formation remained too computationally expensive.

Some virtual injector methods were proposed to avoid near-nozzle field simulation. These virtual injector methods aimed to provide an applicable inlet boundary condition that could reproduce the mass flow rate and momentum flow rate of the real injector. The fuel penetration upstream was then calculated using a relatively coarse grid. The early notional nozzle approaches, which belong to family of virtual injector methods, were proposed by Birch [15], Ewan [16] and Schefer [17]. In these methods, the inlet boundary conditions are obtained through one-dimensional theoretical calculation. The expansion process between the gas reservoir and the Mach disk is assumed to occur isentropically. The numerical simulation begins downstream from the Mach disk. Furthermore, Baratta [18] proposed a virtual injector model based on detailed calculations. The inlet velocity, temperature and mass flow rate of the virtual injector model are calculated by processing the results of previous detailed calculations. The virtual injector model has been successfully applied to real engines. However, large amounts of prior detailed calculations are highly time-consuming. Luca and co-workers [19] combined gas jet similarity theory and experimental results to propose a phenomenal model, which has been validated by experimental results using a constant chamber. Hessel [20] proposed a gaseous sphere injection model based on a liquid spray model using a coarse grid and then extended it to a model of under-expanded gaseous injection [21]. Zoldak et al. [22] applied the gas sphere injection model in a dual-fuel engine and demonstrated that the gas sphere injection model can reproduce the mass and momentum flow rates. Numerical simulation of engine performance prediction was achieved. Recently, Mingi [23]applied the gaseous sphere injection model to a constant volume bomb and a real direct-injection natural gas engine. Reasonable results were produced for natural gas direct injection and mixture formation without a fine mesh near the inlet boundary.

From the literature of view, it was concluded that injection timing is the key factor affecting the performance of direct-injection natural gas engines. Numerical simulation is a powerful and economical tool to guide the design and optimization of in-cylinder mixture formation and combustion. Detailed numerical simulation can capture delicate microcosmic flow structures with high resolution, such as normal shock and reflected shock, but it is computationally expensive. The virtual injector model is more feasible in engineering prediction. There are studies on the numerical investigation of high-pressure injection and cold-mixture preparation for direct-injection natural gas engines. However, to the best of our

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