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The effects of intake backflow on in-cylinder situation and auto ignition in a gasoline controlled auto ignition engine

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HIGHLIGHTS

- The intake backflow decreases as the intake valve open timing delays until it disappears.
- The in-cylinder mean temperature reduces as the intake backflow increases.
- Intake backflow lowers the hot zone temperature with more uniformed distribution in the cylinder.
- The hot and relatively low residual gas fraction zone grows up as the intake backflow increases.
- The experiment results validate the effects of intake backflow on auto ignition.

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ABSTRACT

The inability to control the auto ignition in CAI combustion is an obstacle against its practical use, and the in-cylinder thermal and component distributions are being investigated in more depth as a way to control auto ignition. A 3D simulation using KIVA code is applied to study the effects of intake backflow on the in-cylinder situation. When the intake backflow is increased, the mean temperature is found to be significantly lower. In addition, the difference in the mean temperature of the cylinder reaches 40 K at 320° CA ATDC for a 73–75.8% residual gas fraction. The in-cylinder temperature distribution becomes concentrative and the highest temperature in the cylinder decreases as the intake backflow increases. In this paper, the characteristics of the hot zone are studied, and the superposition ratio of the hot zone and the high residual gas fraction zone is proposed to represent the temperature and residual gas fraction of the mixture in the cylinder. The hot and relatively low residual gas fraction zone increases as the intake backflow increases. Experiments were performed on a single-cylinder engine with a variable valve system. Results indicated that the autoignition timing first delays and then advances as the intake backflow increases. The autoignition changes 3.7° CA at a 58.1–60.6% residual gas fraction. The intake backflow is a potential means of controlling auto ignition timing for CAI.

1. Introduction

Controlled auto ignition (CAI) combustion is studied for its potential to improve fuel economy and reduce NOx emissions simultaneously [1]. However, the inability to control auto ignition is an obstacle against its practical use. It is difficult to find a direct way to control the autoignition for CAI as the spark timing for the traditional SI engines or the spray timing for CI engines.

Many studies indicate that ignition and combustion can be affected by the temperature and components distributions in the cylinder. Yang et al. applied partial fuel stratification, in which most fuel was premixed with intake air and the rest of the fuel was directly injected during the compression stroke to form partial fuel stratification. The PRF73 exhibited two-stage ignition under these conditions, meaning that control of the combustion heat-release rate was possible with properly adjusted injection parameters [2]. Thirouard and Cherel investigated the combustion process using optical diagnostics, focusing on the correlation between the fuel/air mixture quality and the CAI combustion process,

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Abbreviations: ATDC, after top dead centre; CAI, controlled auto ignition; CA10, crank angle of 10% burned mass fraction; CFD, computational fluid dynamics; CI, compression ignition; CMCVs, charge motion control valves; EVC, exhaust valve closing; EVO, exhaust valve opening; HCCI, homogenous charge compression ignition; IMEP, indicated mean effective pressure; ISFC, indicated specific fuel consumption; IVC, intake valve closing; IVO, intake valve opening; LIF, laser induced fluorescence; NOx, nitrogen oxides; PRFs, primary reference fuels; RGF, residual gas fraction; SI, spark ignition; WOT, wide open throttle; 4VVASs, 4 variable valve actuation systems.

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and found that limiting the volume of the reaction zone by charge stratification and decreasing the reaction rate by increasing the dilution could control the heat release rate in CAI operation. They also found that local fuel-rich inhomogeneities were favorable to autoignition and that their locations correlate well with the position of initial reaction zones [3,4]. Kengo et al. varied inhomogeneity in the fuel distribution by mixing air and fuel in the intake manifold through a special device and found that this practice of varying the inhomogeneity in the fuel distribution in the premixture was an effective method for controlling the combustion duration in HCCI engines [5]. Reuss and Sick applied a binarization scheme and a statistical analysis of the LIF images to per-cycle planar LIF images, revealing inhomogeneities both from cycle to cycle and within the regions of individual cycles that track with the average heat release rate [6]. Dec et al. investigated the naturally occurring charge stratification in an HCCI engine using chemiluminescence imaging and found that the stratification slows the pressure-rise rate (PRR) during combustion [7]. It appears that an inhomogeneous composition and thermal distribution dictate the spatial and temporal distribution of auto ignition sites in the cylinder. Hence, in-cylinder stratification provides the potential to control the ignition timing and combustion process of an HCCI engine.

Recently, the thermal and component distributions have been determined to be important for HCCI combustion, and methods to obtain in-cylinder stratification have been investigated. Herold et al. obtained stratification by independently feeding the intake valves of a four-valve engine with thermally and compositionally different mixtures of air, vaporized fuel, and argon [8]. Knop et al. induced some mixture stratification by re-breathing burnt gases through the exhaust ports during the intake stroke using a 2-step exhaust valve lift profile in a port fuel injection engine [9]. Choi et al. applied nonsymmetrical fuel injection to the intake port and completed fuel stratification in a port fuel injection engine [10]. Berntsson et al. used an orbital injector to carry out charge stratification in the cylinder and found that it was possible to influence and control the HCCI combustion by using charge stratification [11].

It is well known that in-cylinder flow has a fundamental influence on the combustion process, and hence, the flow affects the engine performance. The flow controls the fuel–air mixing, governs the flame propagation, and affects the burning rates inside an engine cylinder during the combustion process [12]. Kim et al. investigated the effects of injection timing and intake port flow control on fuel wetting inside the engine cylinder. They found that a tumble mixture-motion plate inside the intake port significantly reduced cylinder liner and piston top fuel wetting. This is because the use of a tumble mixture-motion plate provided more turbulence, which effectively enhanced the mixing during the intake process [13]. Lee and Heywood studied the effects of CMCV on combustion characteristics and hydrocarbon emissions [14]. They concluded that CMCV improved mixture preparation due to increased swirl and tumble intensities, which enhanced fuel transport, distribution, and evaporation. CMCV in the closed condition allowed reduced fuel injection and retarded spark timing strategies that reduced hydrocarbon emissions significantly during the cold start due to greater fuel evaporation and faster burning rate. Mittal and Schock investigated the cycle-to-cycle variations and the influence of charge motion control on in-cylinder flow inside an internal combustion engine assembly and found that the charge motion control used in their study had a profound effect on cycle-to-cycle variations during the intake and early compression; however, its influence decreases during the late compression [15].

Because the in-cylinder situation plays an important role in autoignition and combustion in CAI engines, the authors have performed some research in this field. Li et al. investigated the mixing process of a single-cylinder gasoline engine equipped with 4VVAS with numerical simulation, proposed and quantified the definitions of RGF/temperature statistical distribution and inhomogeneity, and analyzed the influences of the aforementioned valve parameters [16]. Li et al. investigated the management ability of the intake valve on the distribution, and its effects on autoignition were investigated via KIVA code. Results indicated that a higher thermal inhomogeneity leads to earlier autoignition timing, and the autoignition timing is more sensitive at high residual gas fractions than at low residual gas fractions [17]. The intake flow provides the initial conditions for the autoignition and combustion events in the CAI engine. Control of the intake flow is an important means by which an engine designer can attempt to optimize combustion characteristics. Cao et al. studied the effect of intake valve timing on a premixed gasoline engine, and the analyses showed that the amount of backflow and flow patterns were dependent on IVO and that early backflow decreased the mixture temperature at IVC due to heat loss [18]. The studies indicated that the flow can influence the in-cylinder situation and that regulating the flow might be potential method to control the auto ignition of CAI.

Therefore, in this paper, intake backflow is proposed as a means to control autoignition of CAI combustion. The influences of the intake backflow on the in-cylinder mean temperature, the in-cylinder temperature distribution, and the characteristics of the hot zone are investigated. Effects of intake backflow on autoignition were obtained from experiments on a single-cylinder engine with variable valve system. Results indicate that the intake backflow can be used to control auto ignition timing.

2. Engine model

The research is based on a port fuel injection gasoline engine with a pent roof combustion chamber. The details of the engine are summarized in Table 1. The engine computational mesh with the intake and exhaust ports is shown in Fig. 1. The number of mesh cells is approximately 60,000. The intake valve and exhaust valve timings and lifts can be varied. Negative valve overlap is used to trap residual gas inside the cylinder. Although gasoline is a kind

Table 1
Specifications of the engine model.

Bore	80 mm
Stroke	83.5 mm
Displacement	419.75 cm^3
Compression ratio	10.3
Connecting rod length	133 mm
Intake valve diameter	30 mm
Exhaust valve diameter	26 mm

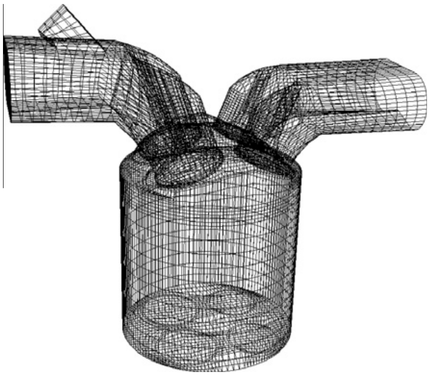

Fig. 1. Engine computational mesh.