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Effect of engine parameters on in-cylinder flows in a two-stroke gasoline direct injection engine

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HIGHLIGHTS

- Effect of engine parameters on in-cylinder fluid flow structure in a two-stroke loop-scavenged engine is studied.
- Port area ratio does not affect the in-cylinder flow significantly.
- Booster port orientation effects TR and SR without affecting the TKE.

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ABSTRACT

This paper deals with the in-cylinder flow field analysis in a two-stroke engine under motoring conditions by particle image velocimetry (PIV) and computational fluid dynamics (CFD). The main objective is to analyze the effect of engine parameters viz., engine speed, compression ratio (CR) and port orientation on the in-cylinder flows in a loop-scavenged two-stroke gasoline direct injection (GDI) engine, with an aim to help researchers to design fuel efficient and less polluting two-stroke engines. In this study, a single-cylinder 70 cm^3 two-stroke engine which is very commonly used for the two-wheeler application, is considered. The engine cylinder is modified to provide optical access into the in-cylinder region. The PIV experiments are conducted at various engine speeds viz., 500, 1000 and 1500 rev/min, and the plane averaged velocity vector fields obtained, are analyzed to understand the in-cylinder flow behavior. The CFD study is also carried out using the commercial CFD code, STARCD, to study and compare the in-cylinder flow parameters at various engine operating conditions. The CFD results are compared with the experimental results to the extent possible. The CFD predictions are found to be in good agreement with the experimental results. Therefore, the CFD analysis has been extended further to understand the effect of various engine parameters on the in-cylinder flows. We found that the turbulent kinetic energy and tumble ratio increased by about 25% and 20% respectively, when the engine speed was increased from 1000 to 1500 rev/min. Also, we found that the turbulent kinetic energy and tumble ratio decreased by about 13% and 26% when the compression ratio was increased from 7 to 8. In addition, we found that the port orientation, rather than port areas had a greater influence on the in-cylinder flow parameters.

1. Introduction

Two-stroke engines were widely used because of high power density and potentially lower mechanical losses as compared to their four-stroke counterparts [1]. Conventional two-stroke engines have a number of advantages over four-stroke engines [2,3]. The two-stroke engines have high mechanical efficiency due to the absence of poppet valves and the associated driving system [4]. The double firing frequency and lower part-load pumping losses in them result in higher specific output and lesser indicated mean effective pressure for a given torque compared to four stroke engines [5]. However, two-stroke engines suffer from low scavenging and trapping efficiencies which lead to poor performance and high exhaust emissions. Two-wheelers with two-stroke engines are reported to emit as much as five times more HC and 1.5 times more CO emissions per kilometer of distance than two-wheelers with four-stroke engines [6,7]. Scavenging in two-stroke engines is a very important process which affects the quality of trapped charge and hence emissions and power output [8].

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Today, two-stroke engines are regaining their popularity due to the adaptation of gasoline direct injection (GDI) technology. The GDI engines have several advantages as compared to those of conventional SI engines viz., better fuel economy, good transient response, and high power output and low emissions [9–13]. As of now, in-cylinder flows, which affect the scavenging and emissions in two-stroke engines, are poorly understood [14]. The most efficient scavenging occurs when there is no mixing of the burnt and unburnt gases [15]. The GDI technology helps better scavenging compared to conventional two-stroke engines. The direct injection of fuel into the cylinder after closure of the ports can eliminate short-circuiting [16]. It is also a better choice for achieving superior fuel economy and reduced emissions in spark ignition (SI) engines [17]. In GDI engines, the in-cylinder flow field plays a major role in fuel–air mixing [18,19]. Adopting GDI technology to conventional two-stroke engines will improve their energy efficiency and reduce the fuel consumption. Understanding the various aspects of in-cylinder flows in a two-stroke engine and the effect of various engine parameters on them helps design the engines with better scavenging. The in-cylinder flow structures in two-stroke engines are affected by the engine geometric parameters viz., piston shape, port areas and orientations as well as operating conditions viz., engine speed and compression ratio. Therefore, it is very essential to understand the in-cylinder flows in two-stroke engines in various engine conditions in order to optimize the engine performance [20]. The engine parameters that are addressed in the work have a significant impact on preparing a proper fuel air mixture in the cylinder in order to achieve the desired results viz., faster combustion, improved fuel economy and reduced emissions. All the parameters that are studied in this work have direct impact on energy efficiency of the engine. In order to understand the in-cylinder flow structure in the engine and its implication on mixture preparation, emissions and performance, many researchers in the past used numerical tools as well as flow visualization techniques like PIV, PLIF etc.

Computational fluid dynamics (CFD) has been widely accepted and indispensable tool for the analysis of the in-cylinder flows of internal combustion (IC) engines [21]. With the increase in computing power over the years, the role of CFD in engine studies gained wide popularity, because of the use of detailed sub-models for the various processes and finer grids; together with high quality dynamic mesh techniques [22]. Previously, many researchers have developed and used various sub-models to study a wide range of engine processes like in-cylinder flow phenomenon and turbulence [22–25], combustion process and heat transfer [26–29], flame initiation and kernel growth rate [21,29] etc., which are aided with visualization studies. Computer simulation models are also useful to understand the effect of various design parameters and operating conditions on the in-cylinder flows and investigate into alternate design concepts [30,31]. The CFD analysis of the in-cylinder flows and fuel sprays are highly complicated and its accuracy depends on the selection of appropriate models, which remains the responsibility of the user [32]. As the CFD uses mass and momentum conservation equations, and mathematical models with simplified assumptions, there are many possible sources of errors. Hence, the validation of the CFD results is very vital for the effective usage of such models [32]. Many non-intrusive experimental techniques viz., laser doppler velocimetry (LDV) [33,34], PIV [35–38] etc., have been extensively used in order to get detailed information on the in-cylinder flow fields in IC engines [38,39]. This information in turn has been used to validate the results obtained from CFD studies [40].

In-cylinder flow of an engine is a periodic phenomenon, and its nature changes considerably with time. The flow characteristics cannot be discussed on the basis of data over only one cycle, because of the cycle-by-cycle variations. Therefore, a statistical procedure should be applied to a large data obtained at the same engine crank angle [41]. The PIV is a well-established technique to capture the instantaneous planar flow field in IC engines [42,43]. The PIV enables us to capture planar instantaneous velocity vector field at any given crank angle unlike LDV or hot wire anemometer (HWA) technique [38]. The PIV technique has been used to measure various IC engine flow characteristics like the turbulence properties [40,44–46], cycle-to-cycle variations [47], flow during injection and ignition [42], flow during the intake stroke under different conditions [20], tumble and swirl measurements [45,46], etc. The stereoscopic PIV has also been used for engine studies to resolve the third component of velocity in the engine cylinder [48]. Voisine et al. [49] carried out two-component (2C) PIV in a horizontal and vertical symmetry planes of the engine cylinder, and reconstructed the quasi 3D flow from the phase averaged flow images to understand the complex 3D structures Dannemann et al. [50] extended this study to eight planes, resolving the flow structures between different planes, for a more detailed view. In most of the previous studies, the PIV technique has been found to be applied to study the in-cylinder flows of four-stroke engines, whereas the literature available to study the in-cylinder flows of two stroke engines with PIV technique is limited.

Most of the available literature on the two-stroke engines is pertinent to conventional SI and CI engines only. However, today two-stroke GDI engines are becoming popular, because of reduced short circuiting losses and better control of mixture.

Pradeep et al. [51] directly injected liquefied petroleum gas (LPG) in a two-stroke SI engine to improve the performance and reduce exhaust emissions. For this purpose, they modified a manifold injected two-stroke SI engine for direct injection of LPG, in gaseous form, from the cylinder head. They concluded that the LPG direct injection could reduce the HC emissions by 93% at 25% throttle, and by about 88% at 100% throttle operation respectively. However, they reported that, there was a significant increase of CO emissions, possibility because of the presence of rich in-cylinder trapped mixtures and charge stratification.

Ghazikhani et al. [52] investigated the effect of exhaust temperature and delivery ratio on emissions and performance of a gasoline–ethanol two-stroke SI engine at different engine loads and speeds. All the experiments were performed without any modification on the engine at 25%, 50% and 75% of full load and with ethanol addition of 5%, 10% and 15% by volume. From the experimental results, they found that, the scavenging and trapping efficiencies were more in accordance with the perfect mixing model because of rapid evaporation of ethanol at the entrance of the cylinder and better mixing. They also found that increasing the delivery ratio, increased the scavenging efficiency because of increase in the inlet mass, but reduced the trapping efficiency.

Andwari et al. [53] investigated the influence of internal and external EGR, and fuel octane number on the combustion phasing and cyclic variability in a CAI two-stroke cycle engine. They found that the external EGR varied the magnitude of cool flame while the internal-EGR varied its timing. They also found that the behavior of hot flame was more affected by the internal EGR, compared to the external EGR. They also concluded that the effect of fuel octane number on the cyclic variability of CAI combustion was significant when either the concentration of internal EGR was high or external-EGR was low.

Mattarelli et al. [54] compared a four-stroke diesel engine with a two-stroke GDI engine in terms of fuel economy, emissions, weight, performance, cost etc. In order to keep the conditions of comparison as close as possible, all the vehicle components except the engine were kept the same, and all the main operating points were maintained to correspond to the same brake power. They found that the new two-stroke engine could possess the advantages of the diesel in terms of fuel efficiency, while maintaining the compactness and cost effectiveness of the best SI engines.