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Numerical investigation of twin swirl application in diesel engine combustion

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ABSTRACT

Unlike conventional Diesel engine Combustion Chambers (CC) which have single swirl, MR-Process CC has twin swirl that promotes fuel air mixture formation by enabling ideal vaporization of fuel spray directed towards tangentially to piston walls. For the initial studies 2-valve (one intake manifold) engine CC geometry was modified aiming to create twin swirls from the initial single swirl and this limited version of MR-Process named as Quasi MR-Process. It is concluded in these studies that a 4-valve engine is needed for an ideal twin swirl formation. However, design and application of 4-valve engine head with two intake manifolds that satisfies ideal twin swirl conditions inside the CC is a challenging task. In addition, proposed unique MR-Process CC is not known before and there is no available experimental data for the optimum values of injection characteristics, air flow field and swirl conditions. Optimum intake manifold and MR-Process CC shape design and optimum spray injection angle determination will be an expensive and time-consuming task if only utilized from experimental studies. In this study numerical analysis of MR-Process CC were performed to investigate the feasibility of twin swirl initiation and the results are presented. This study aims to reveal effectiveness/potential of twin swirl application on Diesel engines utilizing closed cycle simulations. For this purpose, the existing swirl model in open source KIVA3V-R2 code was modified to create perfect initial twin swirls at the start of the compression stroke. Then different angular velocities of the initial swirls and injection directions of fuel sprays were applied to obtain optimum fuel air mixture that ensues to increase efficiency and decrease harmful exhaust emissions. The analyzed results showed that MR-Process has potential to obtain better fuel air mixture, hence reduce emission levels while increasing efficiency of Diesel engines. This study also presents a basis for further full-cycle investigations of MR-Process CC.

1. Introduction

Studies related to improving efficiency and reducing emission levels of ICEs are the prominent subjects of the research projects done on ICEs. In order to reduce harmful exhaust gas emissions and fuel consumption new fuel-air mixture formation strategies are proposed and tested by researchers. Among these investigations, airflow and fuel injection pressure are two essential subjects of air-fuel mixture formation. Regarding these issues, Diesel engines have showed a remarkable improvement by introducing Common Rail (CR) electronic fuel injection system to the market. Though CR systems are increasingly used in most of the Diesel engines after 2000, they have to be used with other after treatment systems such as Exhaust Gas Recirculation (EGR), Selective Catalytic Reduction (SCR) and Diesel Particulate Filters (DPF) to reduce emission levels below the limits which became more and more stringent [1]. On the other hand, using both LPG and Diesel fuel in the same engine has not been achieved yet and it is a subject under investigation. High compression ratios and lean fuel-air mixture conditions make conventional Diesel Engines inappropriate for gaseous fuels because of detonation.

Both the CR system itself with any other after treatment system is not preferred for off-road vehicles since they will not be cost-effective. To overcome this problem “MR-Process” CC was proposed by Mehdiyev [2]. MR-Process is a kind of stratified charge method for Spark Ignition (SI) Engines and the shape of CC also enables it to be used with Diesel fuel as well as with LPG and NG [3,4]. Enabling LPG, NG or Diesel fuel for the same CC can reduce the production cost for different type of engines and give easy modification option for user to add a new fuel system of the engine or alter it. By this way the engine equipped with MR-Process CC has advantage of using multi fuel systems.

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Nomenclature

CC	Combustion Chamber
CFD	Computational Fluid Dynamics
ICE	Internal Combustion Engine
CR	Common Rail
EGR	Exhaust Gas Recirculation
SCR	Selective Catalytic Reduction
DPF	Diesel Particulate Filters
LPG	Liquid Petrol Gas
SI	Spark Ignition
NG	Natural Gas
λ	Excess Air Ratio
SR	Swirl Ratio
DI	Direct Injection
IDI	InDirect Injection
ε	Compression Ratio
CNG	Compressed Natural Gas
RANS	Reynolds Averaged Navier Stokes
ALE	Arbitrary Lagrangian Eulerian
PaSR	Partially Stirred Reactor
RNG	Re-Normalization Group
KH-RT	Kelvin-Helmholtz and Rayleigh-Taylor
HACA	Hydrogen Abstraction Acetylene Addition
ω	Angular Velocity
n	Engine Speed
R	Cylinder Radius
B	Bessel Function
J	Bessel Function of the First Kind
$\boldsymbol{S_{\omega_p}}$	Swirl Profile
$\boldsymbol{V_{eff}}$	Effective Velocity
r	Distance to the Cylinder Axis
CA	Crank Angle
ATDC	After Top Dead Center
SOI	Start of Injection
CAD	Crank Angle Degree
RoHR	Rate of Heat Release
HR	Heat Release
IVC	Intake Valve Closing

Compared with the conventional combustion chambers, MR-Process CC presents flexible fuel choice and allows higher compression ratios for SI engines as well as diesel engines. Previous studies were mainly concentrated on the application of MR-Process in SI engine. The experiments of MR-Process CC which were conducted on test engines using LPG and NG showed promising results at high compression ratios (~16) without detonation, and using a lean ($\lambda \geq 1.3$) fuel-air mixture in all operation regimes of the engine. Also it complies with the emission standards while maintaining the high performance and efficiency of a tractor diesel engine. The achievements of using gaseous fuels in diesel conditions without detonation in previous studies [4] motivated us to search and optimize Diesel fuel injection conditions of MR-Process CC by using CFD techniques. By this way, we aimed to save high cost of complicated and expensive measurement techniques that are not available in our laboratory. In the former study, we investigated creating twin swirl motion and effects of air-fuel mixture formation on combustion for Quasi MR-Process CC which is applicable for 2-valve diesel engines [5]. In this continuing study, a twin swirl MR-Process CC was modeled to investigate the air fuel mixture conditions of diesel combustion for 4-valve diesel engines. Under different Swirl Ratio (SR) conditions and different spray injection orientations, CI combustion results were analyzed to determine the optimum initial settings to achieve the goal of improving fuel efficiency and reducing emissions.

2. Materials and methods

In a conventional ICE equipped with multi-hole injector, swirl intensity is expected to be as high as to enable spray droplets to cover the area between two adjacent fuel sprays. However, the swirl intensity should not exceed levels forcing two adjacent sprays to mix with each other. Also the swirl level should be consistent with the sweep angle between two adjacent sprays of a multi-hole injector nozzle (especially in large-bore DI diesel engines), in order to simultaneously reduce NO_x and particulate emissions. By using multi injector nozzle holes, relatively low swirl levels are sufficient to mix the fuel spray efficiently with the air. This is an advantage of the DI diesel engine over IDI (indirect injection) diesel engines which need high swirl intensity. Generation of high swirl intensity results in reduced volumetric efficiency of the intake system, resulting in decreased maximum power. For this reason, increasing nozzle number of injectors reduces the need of higher swirl intensity. Hence, it is considered unnecessary to generate high swirl levels with current injection systems used in large-bore DI diesel engines [6].

However in MR-2 CC which is proposed by Mehdiyev, the twin swirl motions which are created by special design of intake manifolds and CC geometry help fuel spray to spread over the piston wall. The basic properties of MR-2 CC are as follows,

a. It has two turbulent swirl rotating in opposite direction that is formed in “8” shaped CC in which two stage combustion mechanism of stratified mixture can be realized.
b. It has the ability to increase the compression ratio up to optimum level (ε = 14–17) for gaseous fuels without detonation.
c. It prevents extinguishing flame front in the cold walls of combustion chamber by drifting flame front with the help of swirl motion.

These properties make MR-process suitable for gaseous fuels like LPG and CNG as well as diesel fuel. By this way, low injection pressures can be used in engine and cost of very high-pressure injection system can be avoided. MR-2 CC realizes two stage combustion mechanisms in twin swirl turbulent flow conditions based on Bi-Modal CC theory and symbolically designated it as “MR-Process” [4]. In order to investigate effectiveness of higher compression ratios (ε = 17.5) on the MR-2 CC, a series of experiments were conducted in ITU with a specially designed single cylinder diesel engine (Bore/Stroke = 85/90 mm). A view of MR-2 CC piston of the diesel engine is shown in Fig. 1. This chamber is suitable for operation with diesel fuels as well as with LPG and NG.

With the help of two nozzle hole injector, approximately%95 of fuel is injected in low pressure (150–250 bar) tangentially to the air swirls on the CC wall, as in The M-combustion (“wall guided fuel” mixture) system of MAN [7], thus forming a micro-thin wall film layer on the

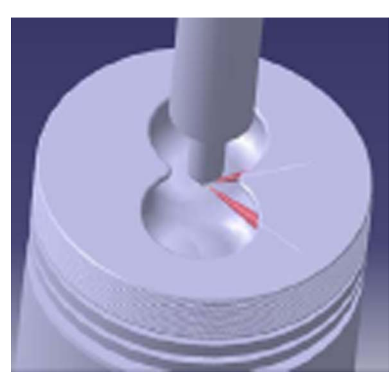

Fig. 1. MR-2 CC piston with two nozzle injection.