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Optimization of Hydrogen Direct injection engine to reduce NO_x emissions

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ABSTRACT: The proposed research work is based on the CFD simulations using ANSYS FLUENT software. In this work, injection timing is optimized (with constant levels of fuel injected), such that peak temperature inside the combustion chamber is low to prevent the pre-ignition and also reduce NO_x emissions.

KEYWORDS: PFI (Port Fuel Injection), DI (Direct Injection), CA (Crank Angle), TDC (Top Dead Center), CFD (Computational Fluid Dynamics), ϕ (Equivalence ratio).

1 INTRODUCTION

Due to the increasing rate of global warming due to gases like carbon dioxide, and the depletion of the conventional natural resources, there is a need of sustainable development and use of alternate sources of energy. In this regard, Hydrogen fuel is considered as a potential source of future energy because of its zero emissions of carbon dioxide and abundant supply in nature. It can be used as a conventional fuel in the IC engines without any major changes in the engine design itself.

External mixture formation (PFI) provides some benefits compared to internal mixture formation (DI) [1-4], higher engine efficiency, lower NO_x production, extended lean operation, lower cycle to cycle variation. These are the outcomes of higher mixture homogeneity due to longer mixing time for PFI and to the turbulence the mixture acquires passing through the intake valves. However, some recent studies show that an optimized DI system that allows proper mixture stratification around the spark plug improves efficiency, reduces cooling losses, extends lean operation, and reduces cycle to cycle variation [5-6].

However, there are some technical issues associated with it in its use in IC engines including chances of backfire at high loads, pre-ignition due to hot spots and the excessive NO_x emissions at high temperatures, as N2 reacts with O2 at temperatures greater than 1800K to form NO_x. Most modern fuel metering systems deliver fuel and air separately to the combustion chamber. Thus hydrogen can be added to the air mixture at a point where condition for pre-ignition are less favorable.

The high flame speed and wide flammability range of hydrogen mixtures allow very lean operation (stoichiometric ratio of hydrogen combustion is approximately 34:1) with important benefits on efficiency and NO_x control. NO_x production is very low for $\phi<0.45$ (the so called "mixture formation limit"), thus a quality based mixture control can be used as far as the load is compatible with this limit. At heavier loads, throttle stoichiometric operations becomes essential to enable the use of catalytic converter to reduce NO_x emissions[7]. It is worthwhile mentioning that a deoxidizing catalyst is very efficient in this application, because hydrogen that remains in the exhaust gas at $\phi=1$ is a highly efficient reducing agent. To avoid throttling and consequent pumping losses that reduce indicated efficiency, load control can be based on EGR (0-50%) addition to stoichiometric mixture, by recycling exhaust gas in a proportion depending upon power demand.

2 CFD PREDICTIONS

3D CFD simulations are a very powerful tool for the simulation of events occurring in IC engines that helps IC engine developers understand complex in cylinder events occurring in modern combustion systems. CFD allows getting deeper insight in mixture preparation process that is a key issue applicable in the case of hydrogen DI engines. All the H2-DI CFD studies in literature concern high pressure gaseous injection with high pressure ratios.

Our CFD study is based on ANSYS FLUENT 13.0, a CFD finite volume code involving chemically reacting turbulent flows in internal combustion engines. Turbulence is modeled using k-epsilon approach. A User defined function (UDF) file concerning the details of the initialization, injection timing and quantity of fuel injected was uploaded and compiled to get the necessary boundary conditions for the system. The computational grid has been shown below. Taking the advantage of engine symmetry, only a sector of combustion chamber was studied.

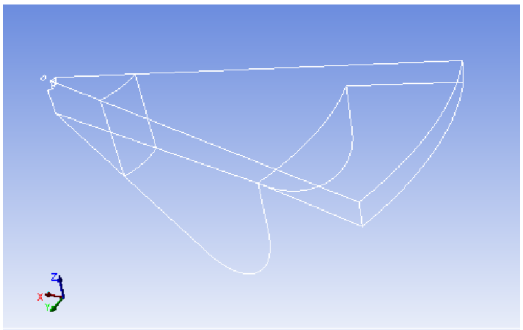

Figure 1: Sector of the combustion

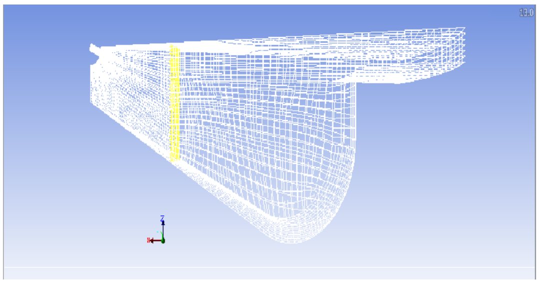

Figure 2: Mesh for the combustion chamber

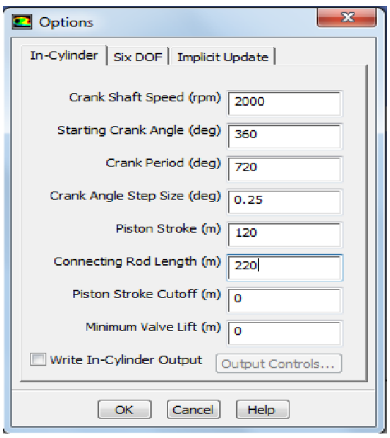

Figure 3: Incylinder options for Combustion Chamber

It should be noticed that hydrogen sonic velocity is greater than four times the sonic velocity of air. Therefore, in order to enhance calculation accuracy, small size cells were required in the region around the hydrogen valve where huge flow velocities occur. Hydrogen was injected in a single direct injection in the combustion chamber, and simulations were done at various crank angles to reduce the higher temperature pockets as much as possible, which subsequently reduces the NO_x emissions.

Analysis were performed at the both inlet and exhaust valve closed (during the compression stroke), in order to reduce the computational time required for analysis. Inlet valve closed also eliminates the chances of intake manifold backfiring due to the high combustion chamber temperature. The gauge pressure and temperature at the initial stage of analysis was taken to be 1898675Pa and 690K respectively. Higher initial temperature is required since the auto ignition temperature of hydrogen is high (773.15K). This can be attained by using a glow plug, heat generated by the glow plugs is directed into the cylinder, and serves to warm the engine block immediately surrounding the cylinder.

Injection was done at three different CA- 20^0, 27.5^0, 30^0 BTDC. The contour plots for the temperature distribution of the respective CA in the combustions chamber are shown below.

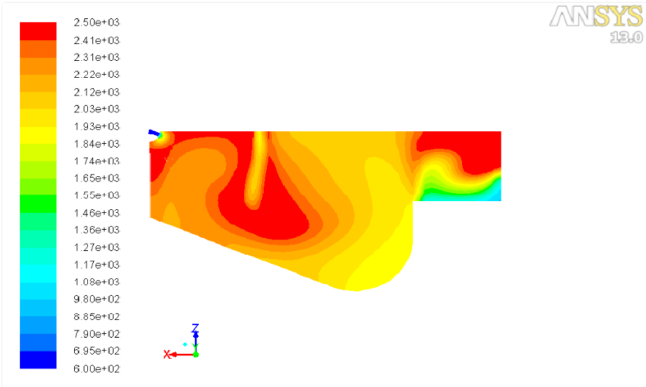

Figure 4: Temperature contour at 20 degrees below TDC.

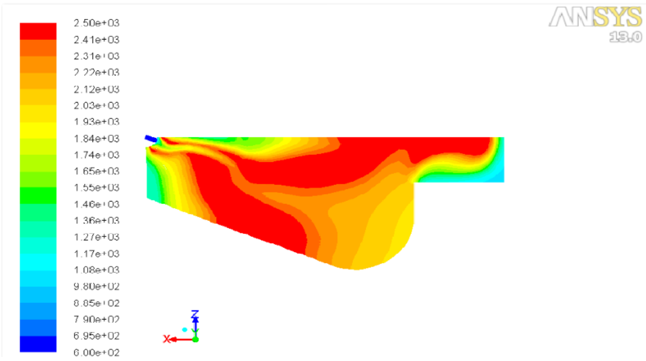

Figure 5: Temperature contour at 27.5 degrees below TDC

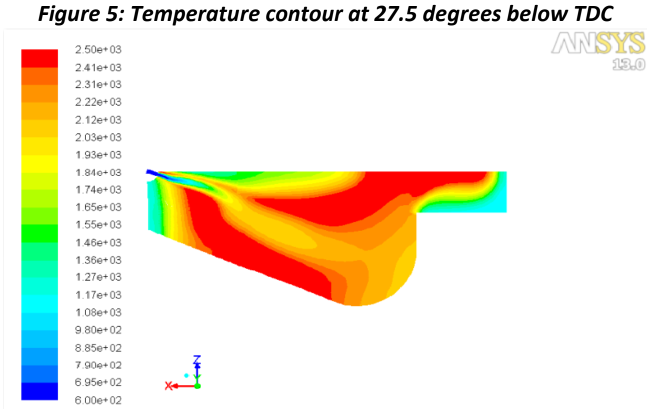

Figure 6: Temperature contour at 30 degrees below TDC

It can be inferred from the plots that the maximum temperature pockets (red plots corresponding to 2500K), and thus the NO_x emissions are relatively higher corresponding to 30^0BTDC and least in 20^0BTDC. The results can be justified because the more we give the time for mixture formation before combustion, the better the combustion takes place due to proper mixing and thus higher would be the peak temperature distribution. Also early injection may lead to pre-ignition phenomena at high loads. At the same time, for 20^0 below TDC, there would not be enough time for proper air-fuel mixing resulting in improper combustion that leaves a lot of unreacted hydrogen. Thus the optimal injection timing was found to be 27.5^0 below TDC.

The drawback of a single injection system is the auto-ignition cannot be optimized due to poor mixing rate of hydrogen-air, which leads to increased knocking tendencies.

3 Remarks and Conclusions:

The studied hydrogen injection system gives us the following benefits:

1. Advantage of the direct injection (high specific power and no backfiring).
2. Reduction of NO_x emissions by varying the injection timing.
3. Improved efficiency, decreased cooling losses, and extended lean operation.

Further improvement in the model can be performed using split injection of the hydrogen which involves injecting hydrogen partly in two intervals which will have the following benefits:

1. The first injection involves only a small amount of hydrogen injection in the combustion chamber that results in a homogenous air-fuel mixture formation. Because of this early initial injection, even at high loads, satisfactory mixture homogeneity is achieved at the ignition time.
2. The second injection involves injecting the remaining quantity of hydrogen in the combustion chamber. As the hydrogen is ignited as soon as it enters the combustion chamber, by controlling the amount of hydrogen injected in the second injection, we can control the combustion and thus control the peak temperatures.
3. Thus split injection will further reduce the NO_x level and the heat release rate.

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