Numerical and Experimental Simulation studies of Combustion in IDI Diesel Engine - A Review

Manjunath S
Dept. of Mechanical engineering
SMVITM, Bantakal – 574115
Manjunath.mech@sode-edu.in

Dr. Ramakrishna N Hegde
Prof & HOD of Dept of Aeronautical and
Automobile Engineering, SIT, Valchil – 574143
rkhegderk@gmail.com

Abstract— This article is a literature survey of combustion model and CFD codes used to investigate performance and emissions of IDI diesel engine. Many researchers have used the CFD code to model the fluid flow, turbulence, heat flow and pressure variation. Under simulated conditions, simulated results are compared with experimental results. Commercial CFD codes VECTIS, KIVA-3V, CONVERGE, FIRE, FLUENT are wide used by engineers due to their superior mesh generation interfaces. These studies reveal that CFD can be used as a tool for predicting the results and design new combustion chambers.

***Keywords* — CFD, *combustion, IDI, Swirl chamber*.**

I. Introduction

Fast depletion rate of petroleum products has inspired the researchers all over the world to improve efficiency of IC engines. Diesel engine is one of the prime movers for power generation and transportation. Experimentation on improving combustion efficiency and at the same time, reducing the emissions is a major challenge for investigators. Computational Fluid Dynamics (CFD) is one of the tools to help researcher to model the combustion and simulate same with experimental results. CFD also helps examiners to forecast the performance results and improve the design features of IC engines. Few researchers have conducted experiments with different approach to improve combustion, two stage injection, HCCI, CSCS, ethanol fumigation and gasoline fumigation.

II. CFD Modeling and simulation

For analysis, both pre-combustion chamber and main chamber are considered as open system. The first law of thermodynamics in differential form,

$$\frac{dQ_{n,1}}{dt} - p_1\frac{dV_1}{dt} + h_{2,1}\frac{dm_{2,1}}{dt} = \frac{dU_1}{dt} = m_1 c_{v,1}\frac{dT_1}{dt} + c_{v,1}T_1\frac{dm_1}{dt} \;....(1)$$

$$\frac{dQ_{n,2}}{dt} - h_{2,1}\frac{dm_{2,1}}{dt} = \frac{dU_2}{dt} = m_2 c_{v,2}\frac{dT_2}{dt} + c_{v,2}T_2\frac{dm_2}{dt} \;...(2)$$

Where the volume of the pre-combustion chamber V_2 is constant, U_1 & U_2 are gas sensible internal energy and $h_{2,1}$ are gas specific enthalpies.

For second law analysis, Availability balance equation is applied to main chamber and the pre-combustion chamber. For main chamber,

$$\frac{dA_m}{d\emptyset} = \frac{m_{im}b_{im} - m_{em}b_{em}}{6N} - \frac{dA_w}{d\emptyset} - \frac{dA_{mL}}{d\emptyset} + \frac{dA_{mf}}{d\emptyset} + \frac{m_{mp}b_{mp}}{6N} - \frac{dl_m}{d\emptyset} \;....(3)$$

For pre-combustion chamber,

$$\frac{dA_p}{d\emptyset} = \frac{dA_{pf}}{d\emptyset} - \frac{dA_{pL}}{d\emptyset} - \frac{m_{mp}b_{mp}}{6N} - \frac{dl_p}{d\emptyset} \;......(4)$$

For the study of combustion process, the model proposed by Whitehouse and way, is used separately for main chamber and the pre-combustion chamber. In this model the combustion process consists of two parts : preparation limited combustion rate

$$P = K_1 M_i^{1-x} M_u^x p_o^y$$

Reaction rate (kg of fuel per ^{o}CA)

$$R = \frac{K_2 p_o}{N\sqrt{T}} e^{-act/T}\int (P-R)\,d\emptyset$$

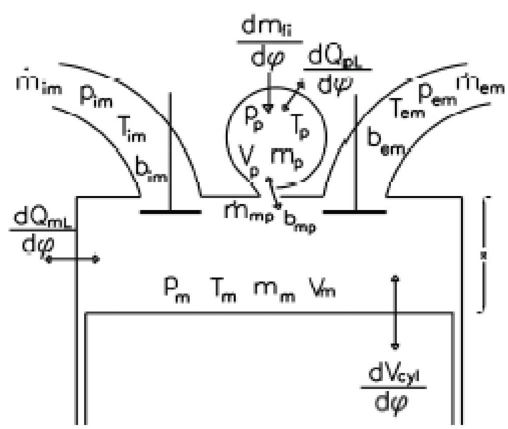

Figure 1. Schematic diagram of engine cylinder showing main and pre-combustion chamber basic thermodynamic properties.

C.D.Rakopoulos et al [1][2] has conducted an experiment to study the combustion and evaluate performance of engine operation under unsteady conditions. The influence of design and thermodynamic parameters on the performance of turbocharged diesel engine. Mass flow across the main chamber and pre-combustion chamber is as shown in figure 1. The results were analyzed for heat release in both the chambers, it reveals a interesting factor that heat release in PCC is independent of load, but heat release in main chamber increase with load.

In IDI engine, the disadvantage of higher fuel consumption rate restricts its further improvement. Liyan Feng et al [3] have carried out an investigation to decrease fuel consumption by designing a conical spray injector in swirl chamber. Also, a series of swirl chamber were designed and was matched with 3-D CFD model. Results show a improvement in fuel economy. Fuel economy can also improved by changing angle, shape and cross section area of the jet passage.

Gyeung Ho Choi et al [4] has carried out experiment, simulating with CFD model. It was concluded that passage hole areas and inclination angle of hole affects the combustion characteristics. For large hole passage, low NO_X formation was observed, it was concluded that because of deficiency of oxygen to combine with nitrogen for various oxide.

Combustion characteristics can be improved by new designed swirl chamber having better turbulence leading to better mixing of diesel with air. Wenhua Yuan [5] has made analysis of cylindrical flat bottom swirl chamber by simulation model. Better mixing of diesel oil with air is revealed by results. Using FLUENT dynamic mesh technique, author proposes new swirl chamber structure. Different fuel like natural gas and biodiesels can also used in IDI engines. Qing Ping Zheng et al.[6] has conducted an experiment to study combustion characteristics of natural gas in CI engine. With detailed kinetic mechanism of FIRE CFD code, multidimensional simulation is used to analyze combustion. Results reveal that combustion and emission are significantly affected by engine parameters like inlet temperature, fuel composition and injection time.

Other methods to improve engine performance are by exergy analysis and split injection, also ensuring low heat rejection and low emission formation. Samad Jafarmadar et al.[7][8][9] has carried out investigations on single cylinder Lister 8.1 IDI diesel engine. CFD modeling (as shown in figure 2) and emission formation was studied by comparing numerical results with experimental results and it shows good agreement. Experimental results of HRR for different loads at constant speed shows that heat loss in low heat engine decreases.

A different strategy to improve combustion efficiency of highly diluted air-fuel mixture is HCCI approach. Amin Yousefi et al [10] have utilized this method and have made comparison study between DI engine and IDI engine with low equivalence ratio (Φ<0.3). With the help of AVL-CHEMKIN CFD model, at different equivalence ratio, comparison between HRR, mean effective pressure and emission was done. Results indicate that with modified chamber of HCCI engine, decrease in average combustion temperature was observed and sequentially HRR and pressure rise rate. CO and HC emissions are less with modified chamber. But, NOX emissions are high because of higher temperature at centre of combustion chamber.

TABLE I
SUMMARY OF PERFORMANCE AND EMISSIONS OF IDI ENGINE

Reference	Engine type	Emissions
Qing Ping Zheng et al.[6]	Single cylinder engine with separate chamber	NO ▼
Amin Yousefi [10]	Single cylinder with swirl chamber	CO ▼ HC ▼
Kouji Iwazaki [11]	Single cylinder with two stage injection	CO ▼ NO ▼
Can Cinar [12]	Turbo charged diesel engine with CO_2 intake	NO ▼ CO ▼
Ozer Can [13]	Multi-cylinder turbocharged water cooled engine with ethanol addition	CO ▼ SO_2 ▼ NO ▼
Zehra Sahin [14]	Multi-cylinder turbocharged engine with gasoline fumigation	NO ▼

III. COMBUSTION, EMISSIONS AND PERFORMANCE

Kouji Iwazai et al [11] have adapted a different strategy of two stage injection to improve combustion and fuel economy.

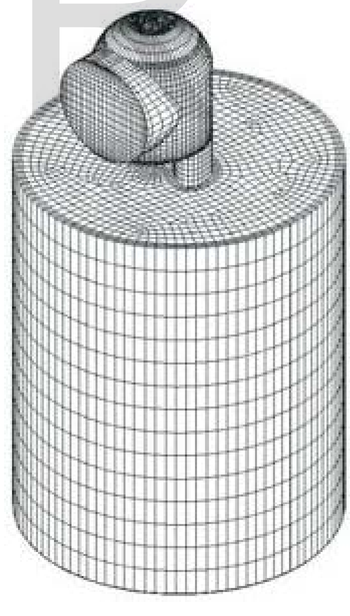

Figure. 2 Mesh of the Lister 8.1 IDI diesel engine

Early injection in DI engine may lead to higher emissions. But, since fuel is injected in separate chamber, it reduces the HC emissions. Results show that there is 20% improvement in fuel consumption. NO_X and smoke emissions were also reduced.

Another way to reduce NO_X formation is to dilute the inlet air by inert gas like CO_2. Can Cinar st al [12] have used same method to investigate NO_X formation in multicylinder IDI engine. Results show that NO_X formation has reduced 50% with CO_2, but, SFC increases proportionately and CO emission increased 8.5 times.

Ozer Can et al [13] have examined the consequences of using ethanol-diesel emulsion in multi-cylinder IDI engine. About 10% and 15% in volume of ethanol addition was done and injection pressure was varied. CO and SO_2 emissions were reduced, but, NO_X formation has increased by 12.5%. Zehra Sahin [14] has studied the combustion behavior by gasoline fumigation method. A simple carburetor was used to increase gasoline fumigation percentage by volume. NO_X emissions were lower and BSFC was less for all engine speed. But at higher gasoline fumigation of 10-12% decreases the effective power of engine at all speeds.

M.Y.E.Selim et al [15] have calculated the effect of using water/diesel emulsion in IDI engine. Experiments were carried out by comparing pure diesel with different Water/diesel emulsion. HFF was measured at critical areas using thermocouples, it was found that at 8% emulsion ratio, metal temperature of injector tip was low and author authenticates the reliability in service for diesel engines running on water/diesel emulsion. Adnan Parlak et al [16] have conducted a different experiment of optimizing irreversible dual cycle. comparison of derived optimum pressure ratio and cut-off ratio with experimental values were done. At 34CA, optimum performance was reached. Also, increase in BTE and decrease in SFC were observed.

Ali sanli et al [17] have assessed the performance of IDI engine by studying heat transfer characteristics. From experimental results it was concluded that increase in engine load at constant speed increases peak heat fluxes and heat transfer coefficients over the combustion chamber wall surfaces. Also, heat transfer depends on the engine speed and load. K.Prasada Rao et al [18] have conducted an experiment to evaluate combustion pressure using HRR and engine vibration correlation. A comparison of performance of diesel with biodiesel blend (mahua methyl ester) was made. It was observed that 3% blend showed a better performance in combustion pressure development and vibration on the cylinder head was uniform.

IV. EXERGY ANALYSIS AND EGR

Under transient and steady conditions, C.D.Rakopoulos et al [19] have carried out second law analysis in both chambers - precombustion chamber and main chamber of turbocharged IDI engine. Inference form results are increase in prechamber volume leads to destruction of total availability. Swirl chamber performs better when compared to pre-combustion chamber. Samad Jafarmadar [20][21][22][23] has carried out an experiment to analyze exergy for four different EGR mass fractions. CFD code is used for different EGR mass fractions. Results show that increase in EGR mass fraction decreases the peak pressure and cumulative exergy by 20%.

Usman Asad et al [24] have conducted an experiment to estimate accurate value of EGR for steady and transient conditions of engine operation. Equation is developed to calculate gas concentration in intake charge and in-cylinder excess-air ratio. The effectiveness of EGR at low loads is less because the recycled engine exhaust contains significant amount of fresh air in the intake.

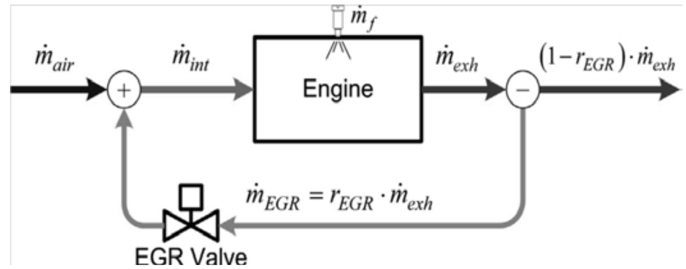

Figure 3 EGR on mass basis

$$r_{EGR} = \frac{m_{EGR}}{m_{air} + m_f + m_{EGR}}$$

r_{EGR} is the mass fraction of the recirculated exhaust gas.

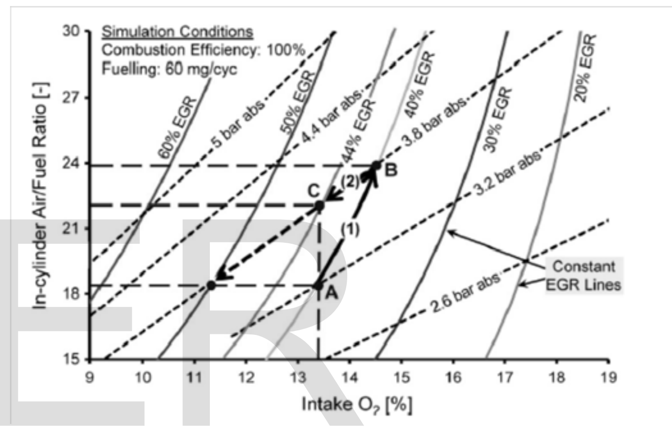

Figure 3 Air/fuel ratio and EGR relationship

From the graph, three points A,B and C represents different combustion mixture. Diffusion controlled combustion phase at point A is associated with high soot emissions. Higher oxygen availability at point B with less EGR effectiveness. At point C, lean combustion with longer ignition delay resulting in premixed burning.

M. Ghazikhani [25] has conducted an experimental study to investigate the effect of using Exhaust Gas Recirculation (EGR) on various exergy term so fan IDI diesel engine cylinder, Also the effectiveness of total in-cylinder irreversibility on Brake Specific Fuel Consumption (BSFC) in a diesel engine is investigated. An exergy analysis is conducted on the engine cylinder which provides all the availability terms by which the evaluation of in-cylinder irreversibilities is possible. The availability terms including heat transfer, inlet and exhaust gases and work output are presented during the engine operation at different load and speeds. To clarify the effect of using EGR in each case, EGR is introduced to the cylinder at various ratios during the tests. Finally, the dependence of total in-cylinder irreversibility and engine BSFC at particular engine operating conditions is introduced and the variations are compared. The results show that using EGR mostly increases the total in-cylinder irreversibility mainly due to extension of the flame region which reduces maximum combustion temperature. Also, the results revealed that the variations of the total in-cylinder irreversibility and engine BSFC follow the same trend especially at high load conditions.

M. Ghazikhani [26] has designed a heat exchanger for cooling exhaust gas and conducted an experiment to investigate the effect of Exhaust Gas Recirculation (EGR) temperature on destruction of the fuel's availability due to combustion processes in IDI diesel engine cylinder. An exergy analysis was conducted on the engine cylinder which provides all the availability terms by which the evaluation of in-cylinder irreversibilities is possible. The availability terms including heat transfer, inlet and exhaust gases and work output are presented during the engine operation at different load and speeds. To clarify the effect of using EGR in each case, EGR is introduced to the cylinder at various ratios and temperature during the tests. The results show about 60 to 70 % of fuel's availability is destroyed by irreversibilities. Also, the results reveal that the increase of EGR temperature leads to reduce of combustion irreversibility. On the other hand the increase of EGR temperature leads to heat and availability are dissipated of the wall and exhaust gas. So depending on the engine operation at different loads and speeds, the increase of EGR temperature could be lead to a positive or negative effect on the engine performance

Hari Shankar sivadas [27] has examined the effects of exhaust gas recirculation (EGR) on the exergy destroyed due to combustion in a simple constant pressure combustion system. Both cooled and adiabatic cases of EGR were studied. Higher 'cooled EGR' fractions lead to higher exergy destruction for reactant temperatures less than 2000 K. For the base case, the percentage of the reactant exergy destroyed for 0, 20, and 40% EGR at 300 K was found to be 28, 32, and 36%, respectively. Neglecting the chemical exergy in the products, the equivalence ratio and reactant temperature that corresponded to the lowest exergy destruction varied from 0.9 to 1.0 and 800–1300 K, respectively, depending on the EGR fraction. The fraction of the reactant exergy destroyed increased with increase in the molecular mass of the fuel for the alkanes examined. The exergy destroyed due to combustion was the least for acetylene and the highest for the alcohols. The trends stayed the same for the different EGR fractions for the eight fuels that were analyzed. For the 'adiabatic EGR' case, the percentage destruction of exergy decreased with increase in the EGR fraction with a 40% 'adiabatic EGR' fraction corresponding to a destruction of exergy of 14%.

V. CONCLUSION

The application of CFD methods to reciprocating engine models is influenced by computational mesh generation and efficiency of solver. It requires compressible /expandable meshes and movable domain boundaries. The study aims at investigating combustion characteristics, fluid flow, pressure rise, exergy and heat release rate in swirl chamber and pre-combustion chamber by using CFD codes. For simulating diesel combustion, turbulent characteristics model finds wide application.

To meet the NO_X targets, utilization of EGR and high intake pressure across the range of load serves the purpose. But, high EGR rate tends to deviate engine performance and reduces exergy. Therefore, for transient engine operation, an accurate estimation of EGR is very necessary.

NOMENCLATURE

BTE	BRAKE THERMAL EFFICIENCY
CO	CARBON MONOXIDE
CA	CRANK ANGLE
EGR	EXHAUST GAS RECIRCULATION
HCCI	HOMOGENEOUS CHARGE COMPRESSION IGNITION
HRR	HEAT RELEASE RATE
HC	HYDROCARBON
IDI	INDIRECT INJECTION
K	REDUCED ACTIVATED ENERGY
NO_X	OXIDES OF NITROGEN
M	MASS, KG
P	PRESSURE
SO_2	SULPHUR DIOXIDE
SFC	SPECIFIC FUEL CONSUMPTION
Φ	EQUIVALENCE RATIO

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