Numerical and Experimental Investigation on CNG Fueled HCCI Engine with EGR

Dr. P. M. Diaz[1], N. Austin[2], Dr. K. Maniysundar[3] and M. Julie Emerald Jiju[4]

[1]Professor, Ponjesly College of Engineering, Tamilnadu, India
[2]Research Scholar,Sathyabama University, Tamilnadu, India
[3]Principal, Ponjesly College of Engineering, Tamilnadu, India
[4]Professor, CSI Institute of Technology, Tamilnadu, India
pauldiaz71@gmail.com

Abstract: Numerical investigations are studied for the homogeneous-charge compression-ignition for CNG fuelled engine with EGR. The Homogeneous Charge Compression Ignition (HCCI) engines fuel oxidation chemistry determines the auto-ignition timing, heat release rate, reaction intermediates products, combustion duration and the ultimate products of combustion. Compressed Natural gas is promising alternative fuel to meet strict engine emission regulations in most of countries. In CNG-fueled HCCI engines the activation energy required for auto-ignition must be obtained by extreme levels of air fuel mixture heating and compression to auto-ignition conditions. This leads inherently to a high rate of heat release and, in consequence, the air fuel mixture highly diluted with EGR to avoid heavy knocking. The limited calculation capacities, experimental investigation cost and the shortened time from development to product need the Numerical simulation of the complex chemical and physical processes. Multi zone modeling is used to simulate CNG fuelled HCCI engine concept validated with experimental results collected from literature review. At all load range the effect of increasing EGR leading to longer burn duration was confirmed. This is in good agreement with experimental validation, and showed increases in figures. The mid load 2 condition showed a slightly more complex trend with a general trend of decreasing PM and NOx emissions with increasing EGR but local minima for both pollutants between 10 and 25% EGR.
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1. Introduction

Over the last few years, a consensus has developed as to the nature of HCCI combustion. It is now generally agreed that HCCI combustion is dominated by local chemical-kinetic reaction rates[1], with no requirement for flame propagation. This notion has been supported by spectroscopic data indicating that the order of radical formation in HCCI combustion corresponds to self-ignition rather than flame propagation [2,3]. Recent analytical developments also support the view that HCCI combustion is dominated by chemical kinetics, and an analysis methodology based on this premise has had considerable success in predicting HCCI combustion and emissions[4]. If a truly homogeneous mixture exists at the time of combustion, turbulence has little direct effect on HCCI combustion, but it may have an indirect effect by altering the temperature distribution and the boundary layer thickness within the cylinder. Small temperature differences inside the cylinder have a considerable effect on combustion because chemical kinetics is very sensitive to temperature. As a result, heat transfer and mixing are important in forming the condition of the charge prior to ignition. However, they play a secondary role during the HCCI combustion process itself because HCCI combustion is very rapid.

A wide used approach is the treatment of the combustion chamber as a perfectly stirred reactor with variable volume and heat losses[5-9]. This approach is very useful if a valuation of suitability is performed and only the trends are essential[5-9]. Chen et al.[6] performed an investigation of internal EGR. He showed that using internal hot EGR leads to an earlier combustion. Fiveland et al. investigated in[8] the influence of initial temperature, initial pressure of mixture, natural gas composition, heat transfer model, equivalence ratio and compression ratio on ignition behavior of an HCCI engine. As expected, an increase of initial temperature leaded to an earlier ignition. Similar was the behavior while increasing the inlet pressure keeping the equivalence ratio and the inlet temperature constant. Adding to methane hydrocarbons of higher order – such as ethane and propane - in a range which is absolutely possible in natural occurrence, the ignition delay could be shortened up to half a millisecond. In[9] the computational investigation of[8] was extended and was compared with experiments. Both, experiments and simulation, showed again that adding higher order alkanes leaded to an earlier ignition. For 100% methane simulation and experiments agreed reasonable. But using gas mixture the difference between simulation and experiments was increased.

Because in reality the combustion chamber is not homogeneous, models have been improved using various zones, which can have stochastic [19,20] initial conditions or the use of models which divide the combustion chamber into an adiabatic core, a boundary layer and a crevice volume [21,22]. Depending on the model assumption the zones experience no interaction[19], volumetric work between the boundaries or mass and energy exchange due to stochastic collision[20]. In[21, 22] there is mass exchange between the crevice zone,the boundary layer and the adiabatic core zone,respectively. Bikas[23] developed a reduced kinetic mechanism and investigated the HCCI combustion process under different conditions with a single zone model. He used a representative interactive flamelet (RIF) model to capture for spatial inhomogenities and compared the results with the obtained by the 0D-model for one operating condition. The authors propose two promising ways to simulate HCCI combustion processes. The first model is a classical multi zone model with stochastic initialization of the lambda and the temperature distribution and is physically only recommendable to simulate HCCI combustion process with port injection. The second model, allows for spatial and temporal inhomogeneities by calculating the complete high pressure cycle with 3DCFD. To solve the chemistry source term only the mixture fraction and its variance is transported and detailed chemistry is solved in the mixture fraction space. The models accounts for combustion turbulence interaction by conditional moment closure. This model has been used in more fundamental research such as spray combustion by Mastorakos et al.[24], Wright et al. [25] and Weisser et al [26].

Because EGR serves two purposes in HCCI engines, adding thermal energy to the uncompressed mixture and acting as an energy sink to slow oxidation kinetics, it is widely used for extending the HCCI operating range. Since the earliest studies by Onishi *et al.* (1979)[18], Noguchi *et al.* (1979), Najt and Foster (1983), and Thring (1989)[2], at least some level of EGR has been utilized in nearly all HCCI experiments. The goal of this work is to determine the influence of using EGR to control SOC on the emissions from an CNG fueled HCCI engine. Data are presented on combustion behavior, gas phase emissions, and particulate phase emissions and a relationship between EGR, combustion behavior, and emissions is established. The simulations results have been validated with the data collected from literature review[27].

2 NUMERICAL MODELING OF THE ENGINE

Present work is carried out using a single cylinder HCCI engine fitted with a hemispherical considered for the analysis. Some important engine details considered for the analyses are given in Table 1. Figure 1 shows engine model used for simulation.

Table 1 Engine Specifications

Bore	8.00 cm
Stroke	11.0 cm
Connecting rod length	23.2 cm
Piston bowl configuration	Hemispherical and toroidal bowls.
CR	19.8
Engine speed	1500 rpm
Fuel	CNG
Exhaust Valve Open	43° bBDC
Exhaust Valve Close	6° aTDC
Inlet Valve Open	8°aTDC
Inlet Valve Close	36° aBDC
Wall temperature(K)	460K

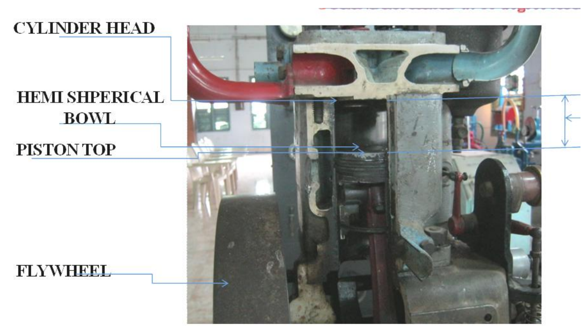

Figure 1 Engine Model

3. Result and Discussion

Figure 2 shows the peak cylinder pressure as a function of combustion timing. For this operating point the pressure curve matches very well with the experiment. The trend shows for CNG fuel are consistent in that the peak pressure is relatively flat at peak of heat release near TDC and then decreases as the peak of heat release occurs later in the cycle. The peak pressure increases with decreasing temperature due to the higher volumetric efficiency at lower intake temperature. Figures 3 and Figure 4 are a plot of brakes specific emissions against EGR. This operating condition shows somewhat different emissions behavior from the lighter load conditions. Both CO and HC emissions peak at 10% EGR and then fall, but CO rises again after 25% EGR while HC continues to fall. The heat release figure 3 shows that peak in-cylinder temperature initially falls between 0 and 10% EGR but then increases. On the other hand, lambda and exhaust oxygen decrease steadily as EGR increases. The opposing effects of in-cylinder oxygen and temperature may explain the observed trend of CO but the opposite trends in CO and HC at the highest EGR rates suggests that HC oxidation may be more temperature dependent that CO oxidation.

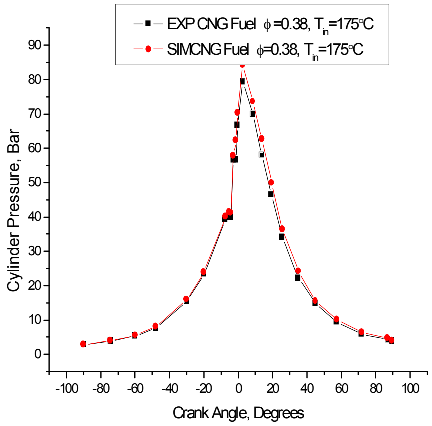

Figure 2. Peak Cylinder Pressure with respect to crank angle at equivalent ratio of 0.38 and inlet temperature of 175° C in both experimental and simulation study

The trends in NOx and PM emissions shown in Figure 4 are somewhat more complex than for the light load cases. Both show a local minimum between 10 and 25% EGR followed by an increase and then a slow decrease. The trends in peak in-cylinder temperature and peak HRR rate are also complex with a general increase in temperature with EGR but with a dip in temperature a 10% EGR while HRR, like PM and NOx, falls, rises, and then fall again as EGR increases. Although the relationship between incylinder temperatures and PM mass is not obvious, a clear relationship between HRR and PM mass is apparent. Increased HRR caused total PM mass to trend upwards. Uncertainty exists in both computational and experimental results. The uncertainty can exist in the form of bias and precision errors. With careful calibration, the bias error can be minimized.

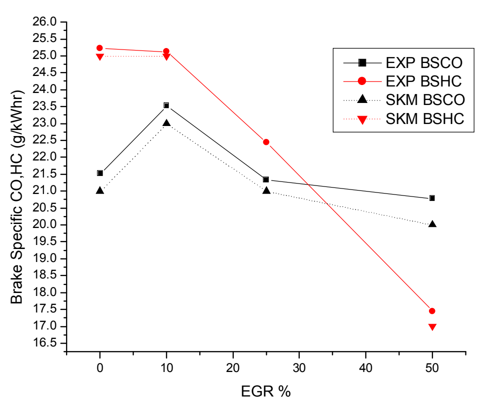

Figure 3. BSCO & BSHC versus EGR at three load condition in both experimental and simulation study.

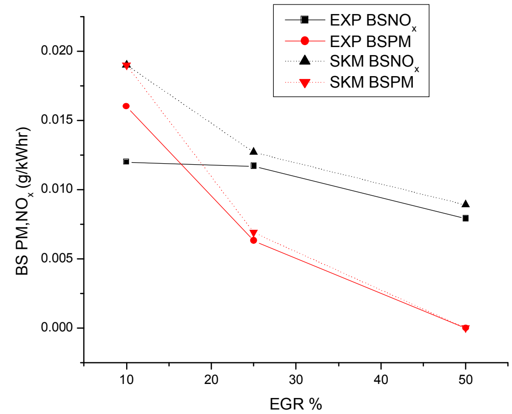

Figure 4. BSPM & $BSNO_x$ versus EGR at three load condition in both experimental and simulation study.

4. Conclusion

The effects of EGR on an CNG fueled HCCI engine were studied at constant speed. Data were collected on performance, in-cylinder behavior, and emissions. The effects of increasing EGR leading to longer burn duration were confirmed. This is in good agreement with numerical simulation findings. In this study, increases in EGR led to decreases in both NOx and total PM mass and number emissions. The influence of EGR on combustion behavior was as expected, extending burn duration, limiting rates of pressure rise, and minimizing peak rates of heat release. Cooler combustion led to small reductions in NO_X as EGR rates were increased. In general, increased rates of EGR led to lower PM number and mass concentrations and smaller particle diameters. These reductions are thought to be due to the lower peak rates of heat release leading to less heat transfer to cylinder walls and reductions in the rates of evaporation of oil films from in-cylinder surfaces.

Corresponding Author:
Dr. P. M. Diaz
Department of Mechanical Engineering
Alampaarai, Vettunnimadam p.o,
Nagercoil, Tamilnadu, India-629003.
Cell No: 09443558554
Tel No: 914651-279160
E-mail: pauldiaz71@gmail.com

References

1. Najt, P. M. and Foster, D. E. 'Compression-Ignited Homogeneous Charge Combustion,' SAE paper 830264, 1983.
2. Noguchi, M., Tanaka, Y., Tanaka, T., and Takeuchi,Y. 'A Study on Gasoline Engine Combustion by Observation of Intermediate Reactive Products During Combustion' SAE paper 790840, 1979.

3. Iida, N. 'Alternative Fuels and Homogeneous Charge Compression Ignition Combustion Technology' SAE paper 972071, 1997.
4. Aceves, S. M., Flowers, D. L., Westbrook, C. K., Smith, J. R., Pitz, W., Dibble, R., Christensen, M.,and Johansson, B.'A Multi-Zone Model for Prediction of HCCI Combustion and Emissions' SAE paper no. 2000-01-0327, 2000.
5. Aichlmayr H.T., D.B.Kittelson, and M. R.Zachariah,'Micro-HCCI Combustion: Experimental Characterization and Development of a Detailed Chemical Kinetic Model with Coupled Piston Motion' Combustion and Flame 135(3) pp. 227-248, 2003.
6. Chen, R., Milovanovic N. 'A computational study into the effect of exhaust gas recycling on homogeneous charge compression ignition combustion in internal combustion engines fuelled with methane' International Journal of Thermal Sciences 41 (2002) 805–813, 2002.
7. Aichlmayr, H. T., D. B. Kittelson, and M. R.Zachariah. 'Miniature Free-Piston Homogeneous Charge Compression Ignition Engine-Compressor Concept Part II: Modeling HCCI Combustion in Small-Scales with Detailed Homogeneous Gas Phase Chemical Kinetics", Chemical Engineering Science 57(19) pp. 4173-4186, 2002.
8. Fiveland S. B., Assanis D. 'A Four Stroke Homogenous Charge Compression Ignition Engine Simulation for Combustion and Performance Studies' SAE paper 2000-01-0332, 2000.
9. Fiveland, S.B., Agama, R., Christensen, M.,Johansson, B., Hiltner, J., Mauss, F.,Assanisand, D.N.'Experimental and Simulated Results Detailing the Sensitivity of Natural Gas HCCI Engines to Fuel Composition", SAE 2001-01-3609, 2001.
10. Zoran S. F., Chang, J., Guralp, O. A., Assanis, D. N., Kuo, T.W., Najt, P.M., Rask,R.B., 'New Heat Transfer Correlation for an HCCI Engine Derived From Measurements of Instantaneous Surface Heat Flux", SAE 2004-01-2996, 2004.
11. Mastorakos, E., Wright, Y.M. 'imulations of Turbulent Spray Auto-ignition with Elliptic Conditional Moment Closure' Proceedings of the European Combustion Meeting, 2003.
12. Wright, Y.M., de Paola, G., Boulouchos, K.,Mastorakos, E.'Simulations of spray autoignition and flame establishment with twodimensional CMC', Submitted for publication in Combustion and Flame, 2005.
13. Bilger, R. W. (1993). 'Conditional moment closure for turbulent reacting flows', Phys. Fluids A 5, 436-444.[14] Klimenko, A.Y. & Bilger, R.W. (1999)"Conditional Moment Closure for turbulent combustion". Prog. Energy Combust. Sci.25, 595-687.
15. Li, H., Miller, D.L. and Cernansky, N.P. (1996):'Development of Reduced Kinetic Model for Prediction of Preignition Reactivity and Autoignition of Primary Reference Fuels', SAE Paper No. 960498.
16. Krieger, R.B., and Borman, G.L., 'The Computation of Apparent Heat Release for the Internal Combustion Engine' Proceedings of the Ninth International Symposium on Combustion, pp. 1069 – 1082, The Combustion Institute, 1962.
17. Krieger, R.B., and Borman, G.L., 'The Computation of Apparent Heat Release for the Internal Combustion Engine' Proceedings of the Ninth International Symposium on Combustion, pp. 1069 – 1082, The Combustion Institute, 1962.
18. S. Onishi, S. H. Jo, K. Shoda, P. D. Jo, S. Kato, 'Active thermo-atmosphere combustion (ATAC) a new combustion process for internal combustion engines' SAE Paper 790501.
19. Kraft M., Maigaard P., Mauss F., Christensen M., Johansson B. 'Investigation of Combustion Emissions in a Homogeneous Charge Compression Ignition Engine: Measurements and a New Computational Model', Proc. Comb. Inst.,28, 1195. 2000.
20. Maiwald, O., Schießl, R., Maas, U. 'Investigations using laser diagnostics and detailed numerical modelling of the ignition in an HCCI engine' 6. Internationales Symposium für Verbrennungstechnik, Baden-Baden, 2004.
21. Rao, S., Fiveland, S.B., and Rutland, C.J., 2003. 'A computationally efficient method for the solution of methane – air chemical kinetics with application to HCCI combustion' SAE 2003-01-1093, 2003.
22. Fiveland, S.B, Assanis, D. N. 'Development and Validation of a Quasi-Dimensional Model for HCCI Engine Performance and Emissions Studies Under Turbocharged Conditions ' SAE 2002-01-1757, 2002.
23. Amano, T., Morimoto, S. and Kawabata, Y. 'Modeling of the Effect of Air/Fuel Ratio and Temperature Distribution on HCCI Engines', SAE Paper 2001-01-1024, 2001.
24. Mastorakos, E., Wright, Y.M.'Simulations of Turbulent Spray Auto-ignition with Elliptic Conditional Moment Closure' Proceedings of the European Combustion Meeting, 2003.
25. Wright, Y.M., de Paola, G., Boulouchos, K., Mastorakos, E.'Simulations of spray autoignition and flame establishment with twodimensional CMC", Submitted for publication in Combustion and Flame, 2005.
26. Weisser, G., Schulz, R., Wright, Y.M., Boulouchos, K.'Progress in Computational Fluid Dynamics (CFD) - Applications for Large Diesel Engine Development', Paper No. 211, CIMAC Congress 2004, Kyoto.
27. Jan-Ola Olsson, Per Tunestål, Bengt Johansson, Scott Fiveland, Rey Agama, Martin Willi and Dennis Assanis (2002). 'Compression Ratio Influence on Maximum Load of a Natural Gas Fueled HCCI Engine.' SAE, 2002-02P-147.

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