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Institute of Thermal Technology

PhD dissertation

Experimental and numerical investigation of combustion process of conventional and alternative fuels in Internal Combustion Engine

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Abstract

The results of research into conventional and alternative fuel combustion within the Internal Combustion Engine (ICE) are presented in this work. Emphasis in this work was placed on the experimental and numerical investigation of engine performance and emissions, as well as in case of numerical study, on the reliability of the numerical model. The study was also enriched with a mathematical model based on the laws of thermodynamics supplemented by empirical models. The main goal of the dissertation was to investigate the combustion process, formation of harmful compounds and to compare the performance curves for methane and biogas fuel using experimental and numerical techniques.

The initial stage was to modernize and develop the *in-house* test stand to meet the latest standards of research. Therefore, the engine was equipped with liquid and gaseous fuel preparation and injection system, cooling system, rotational speed control system, engine control system and, last but not least, up-to-date various measurement systems coupled with the National Instruments (NI) LabVIEW *in-house* application for data collection. The experimental investigations were conducted for methane and biogas fuels including five different oxygen excess ratios and three start of spark timings. Therefore, an extensive database was built to compare the results and validate mathematical and numerical models. Furthermore, the quantitative and qualitative comparisons applying both methane and biogas fuels were presented in terms of pressure, temperature, Heat Release Rate (HRR), Mass Fraction Burned (MFB), volumetric efficiency, Indicated Mean Effective Pressure (IMEP), indicated thermal efficiency and emission analysis. The results obtained from experimental investigations showed overall lower power output from biogas; however, it was due to lower volumetric efficiency and heating value. The indicated thermal efficiency showed higher values for biogas for stoichiometric conditions and $\lambda = 1.05$ case. On the other hand, methane showed a rising trend with higher λ suggesting that lean combustion is more appropriate for pure methane in terms of efficiency. The comparison of pollutant emission for the highest efficiency cases showed that the CO and HC levels are similar for both fuels. However, the NOx values are significantly lower in case of biogas fuel. The main cause for such phenomena is the diluent effect that significantly lowers the in-cylinder combustion temperature in case of biogas. Therefore, the high content of carbon dioxide influences the combustion in a way similar to the recirculation of exhaust gas (EGR). Therefore, the removal of EGR equipment would simplify the construction of ICE. Moreover, the recirculation process considerably lowers the volumetric efficiency of the engine, which has a negative impact on efficiency and power output. On the other hand, the significantly slower combustion of biogas leads to higher HC emission for lean conditions ($\lambda = 1.2$ case) in comparison to methane. The combustion time of fuel-air mixture in the cylinder is too long, which causes combustion during expansion stroke. Therefore, biogas presents a narrower operation window in comparison to methane fuel.

The next stage of research was devoted to the development of a mathematical model

in order to assess the accuracy, applicability and usefulness of existing mathematical models. The model was based on the first and second law of thermodynamics with additional empirical models used for the burnout of fuel, heat transfer through the walls and estimation of mass trapped inside the cylinder. The main problem encountered during the development of the model was the selection of the empirical models that would accurately predict all processes under consideration. Hence, a group of models designed for spark ignition engines was investigated and the most accurate were used in further research. The results showed mediocre agreement in terms of pressure prediction accuracy. On the other hand, the general tendencies were preserved. Hence, such approach may be used for initial and generic analysis. The main advantage of such an approach is the robustness of a system, as the calculation time is measured in seconds.

Finally, numerical simulations were performed for all investigated cases. The work includes two different approaches in terms of well-established Ansys Fluent and recently introduced Ansys Forte. The former utilizes the Finite Volume Method (FVM) and C-equation model for combustion that is widely used in various applications. The latter was developed especially for ICE and utilizes a new approach in terms of Immersed Boundary Method with Arbitrary Lagrangian-Eulerian method (IBM-ALE method) that significantly simplifies the process of valve and piston movement within the mesh. Moreover, a G-equation model with detailed kinetics was utilized for the simulation of a combustion process and pollutant formation. The additional advantage of IBM-ALE is a significant reduction of computational time due to the possibility to use a more coarse mesh. The preliminary results showed that the Ansys Forte predicts the in-cylinder phenomena more accurately in comparison to the Ansys Fluent; hence, the first solver was used for further investigations. The conducted numerical simulations helped to understand the mechanisms behind the experimental results. Initially, a 2D model was tested coupled with various combustion models. The results showed that only a premixed model in terms of the C-equation was capable of predicting the combustion inside the cylinder. Therefore, a fully 3D model in Ansys Fluent was developed, but its results were unsatisfactory. The main disadvantage was lack of information concerning the emissions. Furthermore, the in-cylinder pressure during compression stroke was overpredicted, the ignition and flame development phase occurred early in comparison to experimental data. On the other hand, the Ansys Forte results showed good agreement during compression. The pressure during combustion was higher in comparison to experimental data; however, the results were significantly improved by additional blow-by application and careful selection of combustion model parameters. Hence, an accurate 3D model of ICE was developed in Ansys Forte and validated using experimental data for stoichiometric conditions and Start of Spark (SOS) 35 CAD before Top Dead Center (BTDC). During the validation process, a set of combustion parameters were adjusted to fit the experimental results. Next, the calculations for the remaining cases were conducted using the preserved parameters from the validation case. The aim was to investigate the sensitivity of the model to various operating conditions (i.e. oxygen excess ratio and spark timing). Additionally, the underlying cause of nitrogen oxides and carbon monoxide formation during combustion inside ICE was researched. Therefore, the Ansys Chemkin solver is included in the Ansys Forte numerical process for which the reduced mechanism GRI-MECH 3.0 was utilized to simulate the chemical reactions occurring inside the chamber. The results of a series of calculations for various conditions were compared with experimental findings. Moreover, the visualization of the NOx and CO formation process as well as the flame front propagation was presented on a cross section through the cylinder. The conducted simulations showed a very good agreement with experimental data for validated cases. The investigations of reliability for various operating conditions led to the conclusion that the combustion model in terms of G-equation is mostly influenced by the fuel composition and laminar flame speed tables. However, for selected fuel the model is only sensitive to larger oxygen excess ratios. The λ=1.2 and λ=1.1 cases for biogas showed significant discrepancies of the pressure trace and thus to obtain feasible results, the model parameters were adjusted accordingly. The reason for that is the calculation of laminar flame speed for which validation was not performed and discrepancies with literature results were observed for a higher oxygen excess ratio. Furthermore, the ignition model showed dependency on the ignition timing. The flame front propagation showed that the initial flame development phase is strongly influenced by the fluid flow inside the cylinder. The biogas case showed an impaired early flame phase which led to longer combustion, lower efficiency, power output, repeatability and in some cases higher HC and CO emissions as a result of combustion during the exhaust stroke. The investigation of pollutant formation presented interesting results. The CO formation occurs instantly with the flame front as a result of methane oxidation, while the NOx formation is delayed. However, the highest content of pollutants is located in the vicinity of the spark plug. Therefore, lowering the temperature at the ignition location is crucial in order to reduce emission.

In conclusion, the biogas fuel showed advantages over the methane fuel mostly in terms of emission reduction. Moreover, the investigation of the combustion process showed general scope for further improvement, mostly in terms of flame development phase for biogas fuel. The biogas fuel derived from anaerobic digestion proved to be a valid alternative for fossil fuels, especially for stationary ICE.