HEAT TRANSFER IN HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINES

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Introduction

The rising concentration of greenhouse gases in the atmosphere and diminishing oil supplies have led to a stringent emission legislation, which new internal combustion engines have to comply with. For passenger cars and light commercial vehicles, the legislation in Europe [1] restricts tail-pipe emissions of carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC) and particulate matter (PM). In the near future carbon dioxide (CO_2) emissions will also be limited [2]. Currently two types of internal combustion engines exist: spark ignition (SI) engines and compression ignition (CI) engines. Port fuel injected SI engines have a homogeneously mixed stoichiometric air-fuel mixture, which enables low PM emissions and with the use of a three way catalyst also low NO_x emissions. Because the mixture has to be stoichiometric, the load is controlled by a throttle valve in the inlet manifold that regulates the air flow. The throttle losses associated with this load control strategy, cause a low part-load efficiency and, hence, high specific CO_2 emissions. In CI engines the fuel is injected directly into the combustion chamber and it auto-ignites upon mixing with the air during the injection. The mixture is globally lean and the load is controlled by varying the amount of injected fuel. Due to the absence of a throttle valve and the high compression ratio used, the peak and part-load efficiency is higher compared to SI engines. However, during the combustion, local fuel-rich zones can occur that cause high PM emissions. The formed PM can be oxidized if the temperature is high enough, but this leads to higher NO_x emissions. This trade-off, combined with the expensive after-treatment for lean mixtures, gives the CI engine poor emission performance. A new type of internal combustion engine is being developed which combines the high efficiency of CI engines with the low emissions of SI engines, the homogeneous charge compression ignition (HCCI) engine.

HCCI combustion

In an HCCI engine, a lean mixture is injected in such a way that a homogeneous fuel-air mixture is obtained in the combustion chamber. The injection can take place in the inlet manifold or directly in the combustion chamber. The combustion occurs when the fuel auto-ignites due to the temperature rise during the compression stroke. No PM is formed because the mixture is homogeneous and no NO_x is formed because the mixture is lean and the combustion temperature remains below the formation temperature of NO_x (1600°C). The part-load efficiency is high because the load is controlled by regulating the equivalence ratio of the lean mixture.

The main drawback of the HCCI engine is the lack of control over the start of the combustion. In order to obtain maximum efficiency, the peak pressure due to combustion must occur closely after the piston has passed the top dead centre. If the combustion occurs too early, the compression work increases and a higher peak pressures may cause engine damage. If the combustion occurs too late, the expansion work decreases. Unlike SI and CI engines, the start of the combustion cannot be directly controlled because it is governed by the start of the auto-ignition reaction. The auto-ignition process is affected by several factors e.g. the type of fuel, the temperature and the equivalence ratio of the mixture, the compression ratio, the amount of recirculated exhaust gases and the heat transfer to the cylinder walls. By changing one of these factors, it is possible to indirectly change the start of the combustion. The engine mapping that specifies the engine's settings must take into account these factors, in order to obtain maximum efficiency at each operating point.

Another drawback of the HCCI engine is the limited operating range in which a stable combustion occurs. At very low loads, the auto-ignition reaction may not take place, because not enough energy is available to start the reaction. At very high loads, when lots of fuel is being injected, the rapid combustion leads to a high peak pressure that may cause engine damage. An appropriate fuel must be chosen to obtain an acceptable operating range.

A lot of research has been conducted to overcome these drawbacks and various solutions have been proposed e.g.: inlet air preheating, variable compression ratio, variable valve timing, exhaust gas recirculation, using multiple fuels, advanced injection strategies, hybrid SI/HCCI and CI/HCCI systems,… Currently, these solutions are mainly being investigated using an experimental approach. This is however very time-consuming due to the large amount of possible combinations of fuels and engine settings. Consequently, a simulation tool could significantly reduce the development time of HCCI engines.

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Heat transfer

In simulation software the heat transfer to the cylinder walls needs to be calculated at every time step to solve the equations of mass and energy and to determine the in-cylinder temperature. Because the autoignition reaction is a thermally controlled process, an accurate heat transfer model is essential to obtain correct simulation results. However, current HCCI simulation tools use heat transfer models developed for SI and CI engines, e.g. the models proposed by Annand [3] and Woschni [4]. This approach has been found to be inadequate for both the HCCI combustion [5] and alternative fuels [6]. Woschni's model, for example, contains a term that accounts for the heat transfer due to the propagating flame front in an SI engine. Because no propagating flame front is present during HCCI combustion, the model overestimates the heat transfer during combustion. Researchers [7] have proposed modifications to Woschni's model, that take into account the absence of a propagating flame front by changing the term's coefficient based on experimental data. However, this approach requires a different coefficient for each engine [5], which significantly reduces the applicability of the model. A new heat transfer model needs to be developed that accounts for the specific processes during HCCI combustion.

Hence, PhD research has started at Ghent University with the following goals: constructing a heat transfer model based on heat flux measurements on an HCCI engine and investigating the possibility of using heat flux as an input for the engine control unit. The latter should allow controlling the start of combustion with a feedback loop based on a signal from an inexpensive heat flux sensor mounted in the combustion chamber.

Conclusions

The HCCI engine is a promising technology that allows both a high efficiency and low emissions. The lack of control over the start of combustion and the limited operating range are the main challenges that need to be overcome before the HCCI engine can replace the SI and CI engine. Various techniques have been proposed to overcome these drawbacks. The development time can be reduced if simulation software is used to validate these techniques. This requires a heat transfer model developed specifically for HCCI engines.

Acknowledgements

The work presented in this paper has been made possible thanks to a Starting Grant from the Special Research Fund (BOF) of Ghent University.

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