MODELLING THE HEAT TRANSFER OF HCCI ENGINES

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Introduction

The rising concentration of greenhouse gases in the atmosphere and increasingly stringent emission legislation has renewed the interest in internal combustion engines operating according to alternative combustion principles, such as homogeneous charge compression ignition (HCCI) [1, 2]. Contrary to traditional spark- and compression ignition engines, HCCI engines can achieve both a high thermal efficiency and near-zero emissions of NOx and soot. These advantageous properties are achieved by having a lean premixed fuel-air mixture auto-ignite in the combustion chamber due to the temperature rise during the compression stroke. No soot is formed because fuel-rich zones are avoided and no NOx is produced because the temperature during combustion remains below its formation temperature. A high thermal efficiency is obtained by using a lean air-fuel mixture and by controlling the load by adjusting the equivalence ratio instead of using a throttle valve.

The main drawbacks of HCCI engines are the lack of control over the start of the combustion and the limited operating range in which a stable combustion occurs. Engine simulation software can help to find techniques to overcome these drawbacks and speed up the development of HCCI engines for commercial use.

Heat transfer

An important model used in the engine simulation software is the heat transfer model, which predicts the heat transfer from the combustion gases to the combustion chamber walls. The heat transfer needs to be calculated every time step to solve the equations of mass and energy, but it also has a direct effect on the combustion. The combustion is determined by chemical kinetics, making it is very sensitive to the mixture temperature. For this reason, the heat transfer affects important combustion properties such as the start of combustion and the burn duration.

In current simulation software heat transfer models are used that were developed for spark- and compression ignition engines, e.g. the models proposed by Annand [3] and Woschni [4]. However, these models do not take into account the specific nature of HCCI combustion. Chang et al. [5] and Hensel et al. [6] have tried to modify these models to resolve this, but their modified models have not been validated by others.

The goal of the current work is to evaluate the heat transfer models of Annand and Woschni for HCCI operation as well as the modified models of Chang et al. and Hensel et al. This is done by comparing the predicted heat flux to the measured heat flux in a CFR-engine converted to HCCI operation. Based on this evaluation an approach is suggested to better model the heat transfer of an HCCI engine.

Methodology

The engine used in this research is a Waukesha CFR engine. This is a standardized, single cylinder, four stroke engine. It operates at a constant speed and has an adjustable compression ratio. HCCI operation is obtained by pre-heating the inlet air and using n-heptane as a fuel. The heat flux is measured with a Vatell HFM-7 thermopile sensor, which is mounted in the cylinder head.

The heat transfer models are evaluated in a wide range of engine operating conditions. First, the operating range of the engine is determined. With this information, and using Design of Experiments techniques [7], the necessary engine operating conditions are identified that allow a full characterization of the engine as a function of its settings. The varied engine settings are the compression ratio, mass fuel rate, inlet air temperature and engine speed. An example of this approach is presented in Fig. 1, where an experimental surface of the maximum of the heat flux is shown as a function of the compression ratio and mass fuel rate.

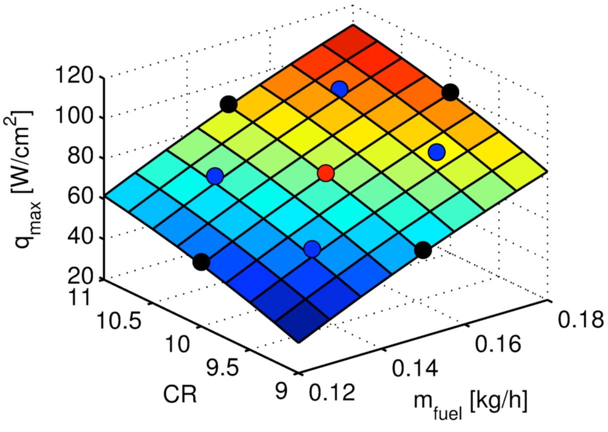

Figure 1: Maximum heat flux as a function of compression ratio and mass fuel rate

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The models are first evaluated using the model coefficients proposed by each author. Next, it is verified whether adjusting the model scaling coefficients, makes it possible to match the predicted heat flux to the experimental heat flux in one operating point. With these calibrated scaling coefficients, the predictive ability of the models is evaluated, by comparing them to the measured heat flux in other operating points. The maximum of the heat flux and the total amount of heat released are discussed.

Results

None of the models is able to accurately predict the heat flux when the model coefficients proposed by each author are used. The models from Chang et al. and Hensel et al. underestimate the heat flux during the entire cycle. Annand's model underestimates the heat flux during the compression and combustion, but overestimates it during the expansion stroke. Woschni's model underestimates the heat flux during the compression and overestimates it during the combustion and expansion. The shape of the heat flux trace predicted by the models of Chang et al. and Woschni does not agree with the measured heat flux trace. This is because these models overestimate the effect of the combustion on the heat flux. They have a term in their models that is proportional to the pressure rise caused by the combustion. For this reason, these models are not investigated further.

Next, the models are calibrated to match the maximum value of the measured heat flux. It was found that Hensel et al.'s model then overestimates the heat flux during the entire cycle whereas Annand's model is able to accurately predict the complete heat flux trace. Finally, the models are applied to other operating conditions using the calibrated coefficients. They proved to be able to predict the trend in peak heat flux when the compression ratio, mass fuel rate or inlet air temperature are changed. Annand's model tracks the changes best. This is because it takes into account more gas properties compared to Hensel et al's model. However, if the engine speed is varied, none of the models are able to predict the heat flux adequately. This indicates that the characteristic velocity used in these models is not suitable.

Conclusions

It can be concluded that the current heat transfer models cannot be used with their standard coefficients. The model coefficients should be calibrated to the engine. Once calibrated, the models of Annand and Hensel et al. are able to capture the trends in peak heat flux, when varying the operating conditions. However, the models are not able to accurately predict the entire heat flux trace. This is most noticeable when the engine speed is varied.

Hence, in order to accurately model the heat transfer in an HCCI engine, the following should be considered:

- The pressure rise due to combustion should not be explicitly added.
- The instantaneous gas properties should be incorporated directly.
- The mean piston speed is not sufficient to predict the effect of the engine speed.

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References

[1] Onishi, S., Jo, S.H, Shoda, K., Jo, P.D. et al., Active thermoatmosphere combustion (ATAC) - A new combustion process for internal combustion engines, SAE Technical Paper 790501 (1979).

[2] Najt, P.M. and Foster, D.E., Compression-ignited homogeneous charge combustion, SAE Technical Paper 830264 (1983).

[3] Annand, W., Heat transfer in the cylinders of reciprocating internal combustion engines, Proc Instn Mech Engrs 177 (36) (1963) 973:996.

[4] Woschni, G., A universally applicable equation for the instantaneous heat transfer coefficient in the internal combustion engine, SAE paper 670931 (1967).

[5] Chang, J., Guralp, O., Filipi, Z., Assanis, D., New heat transfer correlation for an HCCI engine derived from measurements of instantaneous surface heat flux, SAE paper 2004-01-2996 (2004).

[6] Hensel, S., Sarikoc, F., Schumann, F. Kubach, H. et al., Investigations on the Heat Transfer in HCCI Gasoline Engines, SAE Technical Paper 2009-01-1804 (2009).

[7] Berger, P., Experimental Design with Applications in Management, Engineering, and the Sciences, Duxbury, Belmont, USA (2002).