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COMPARATIVE ANALYSIS OF HEAT TRANSFER COEFFICIENTS APPLIED TO SPARK IGNITION COMBUSTION ENGINES

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Abstract. *In the present work a comparative analysis of different correlations was performed to calculate the convection coefficient applied to the heat exchange between the working fluid and the internal walls of the combustion chamber of a spark ignition engine. This analysis was conducted through computational modeling, implemented in a two-zone combustion model. The rate of energy release is obtained through Wiebe functions. The calibration of the model was performed by means of experimental data obtained from a single cylinder test engine. The results showed that, except for Sitkei's correlation, all of the others reach a good level of precision. Also, it could be seen that Woschini's correlations had the highest degree of precision when determining the heat transfer between the working fluid and the walls.*

Keywords: *convection coefficient, two-zone modeling, combustion*

1. INTRODUCTION

Among the many different methodologies used on the development of internal combustion engines, stands out the computational modeling. Simulation tools allow for quicker and less expensive studies to be performed, making it possible to optimize real life systems much sooner in project life. Also, simulations can help on further understandings of the physics involved in the process. Finally, this approach permits a reduced quantity of empirical tests during the design and validation of new engines. (Guilbert, 2005)

On the other hand, the heat transfer occurring inside the combustion chamber is particularly important in the analysis and modeling of combustion engines, once they account for nearly 40% of the energy inside the system. Also, keeping the combustion chamber under acceptable levels of temperature is key to obtain high levels of engine reliability. (Heywood, 1988)

When considering the simulation of the heat transfer inside the combustion chamber, one key factor to be taken into account is the correlation used to calculate the convective heat transfer coefficient. Many different correlations were proposed along the years with the objective of determine the heat transfer coefficient with the highest level of precision. For example: Woschni's, Hohenberg's, Eichelberg's, Annand's, Sitkei's. On the other hand, these correlations were developed empirically, and may not be fit for all applications. (Ollivier, 2006)

Considering the above, the present work investigated the influence of different convective coefficient correlations in a zero-dimensional two-zone model, calibrated through experimental data obtained in a spark ignition engine.

2. METHODOLOGY

To achieve the final objective, this work was performed as a sequence of previous works of some of the authors. In the previous works of Och (2014), a simulation model was conceived in order to predict the thermodynamic state of the working fluid inside the combustion chamber during the complete cycle. This simulation model was calibrated through empirical data obtained from a real life spark ignition engine. Then, in the present work, different results were obtained from the simulation model by changing the correlation for convective heat transfer coefficient. The results were then compared to reach the conclusions.

2.1 Simulation model

The simulation model presented was developed in previous works of the authors, and simulates different parts of the engine cycle, including the processes that occur in the intake and exhaust ducts. Since the present work is focused on the processes that occur inside the combustion chamber, this part of the model will be detailed bellow.

The modeling methods applied to the processes inside the combustion chamber may be classified in three different types, according to the complexity of the model and computational effort: i/ zero-dimensional (or thermodynamic); ii/ quasi-dimensional; iii/ multi-dimensional (or CFD – Computation Fluid Dynamics). (Pianovski Jr., 2002)

Although much simpler than CFD models or quasi-dimensional models, the thermodynamic models present a high level of precision. This approach is the most appropriate when looking for a global analysis of the processes. The CFD models, although much more precise, require significant amount of computing effort even when working with simplified equations for complex phenomena – such as the combustion chemical reaction. For this reason, the zero-dimensional or quasi-dimensional models are the most used approaches for combustion process simulation. (ALLA et al., 2001)

The zero-dimensional approach may be applied in single-zone models (mostly on compression ignition engine simulations) or dual-zone model (more common in spark ignition engine simulations). This type of modeling considers the volume inside the combustion chamber as having two distinct zones: burned zone and unburned zone. (Ma et al., 2008)

The mixture of gases is considered as a homogeneous fluid occupying the full volume of the combustion chamber. This is true when the engine operates in high speeds. With this hypothesis, it is possible to neglect the pressure and temperature gradients. Also, fuel atomization and vaporization process, and ignition delay may be neglected. (Och, 2014)

During the compression, expansion and exhaustion processes the composition of the fluid does not change. During the intake process, the composition changes due to the fuel injection. All these processes can be modeled as single-zone.

On the other hand, during combustion process the fluid is modeled as a dual-zone where the flame thickness is neglected. Also, both burned and unburned gases are considered as a mixture of ideal gases. During this phase, the gases composition of the unburned zone is constant. The burned fraction is given by the Wiebe function. (Och, 2014)

2.2 Experimental setup

In order to calibrate the simulation model, real life data was needed. In previous works, an experimental setup was made in the laboratory of CORIA (*COmplexe de Recherche Interprofessionnel em Aérothermochimie*), based in the city of Rouen, in France.

The setup consisted in a single cylinder, spark ignition, direct injection engine (model AVL5482). The engine walls are made of quartz, allowing to see the combustion process occurring in real time. The engine was linked to a DC motor dynamometer for starting. The general characteristics of the engine can be found in table 1.

Table 1. AVL5482 engine – general characteristics.

Manufacturer	AVL
Model	5482
Number of cylinders	1
Number of valves	4
Cylinder bore	82mm
Stroke	86mm
Connecting rod length	144mm
Engine displacement	0.454 L
Compression ratio	8.5

The piston is cooled by compressed air applied at its bottom. In addition, the bench has a lubrication and cooling system, which maintains the oil temperature constant at 90°C. It also provides the correct cooling of the engine. Both the oil and the coolant are pumped by the bench apparatus, so the engine itself does not need to provide power to drive the lubrication and cooling systems. The coolant temperature is measured at both the inlet and the outlet of the engine.

2.3 Heat exchange parameter correlations

The heat exchange in internal combustion engines is extremely complex, once the phenomena are transitory, tridimensional, and may suffer rapid oscillations in pressure and temperature inside the combustion chamber. Also, the piston movement makes the control volume even more complex. (Rakopoulos, 2004)

This complexity makes it difficult to evaluate the heat exchange rate in the first law analysis. Since the model used in the present work considers that the thermodynamic properties are uniform inside the combustion chamber, it is only possible to evaluate the heat exchange globally.

The solution to this is the use of empirical correlations found on references. Those correlation allow for the estimation of a global convection coefficient for the heat exchange occurring inside the combustion chamber. They are based not only on fluid properties, but also on the geometry of the engine. Also, it is considered that the boundary layer for heat exchange and the heat capacity may be neglected. This means that there is no gradient of any properties around the boundaries of the system.

Annand (1963), based on many different experimental data, stated that the convection coefficient may be calculated by Eq. (1):

$$h_g = a \times \frac{k_g}{B} Re^{0.7} + b \frac{(T_g^4 - T_w^4)}{(T_g - T_w)}$$ (1)

In Eq. (1), hg is the heat exchange coefficient, a and b are constants, k_g is the thermal conductivity of the gas, B is the cylinder bore, T_g is the temperature of the gas and T_w is the temperature of the cylinder walls.

From Eq. (1) it is possible to see that Annand's correlation considers not only forced convection but also radiation heat exchange. Also, Rakopoulos et al. (2004) concluded that the temperature variation of the cylinder walls are around 1% of the variation of temperature of the gases during the combustion process. Hence, it is possible to consider that the wall temperature is uniform and constant. The Reynolds number in Eq. (1) is based on mean piston velocity:

$$Re = \frac{\rho \times \overline{V_p} \times B}{\mu}$$ (2)

In Eq. (2), Re is the Reynolds number, ρ is the specific weight, $\overline{V_p}$ is the mean piston velocity and μ is the fluid dynamic viscosity.

The dynamic viscosity on Eq. (2) can be calculated by another empirical equation developed by Annand (1963):

$$\mu = 4.57 \times 10^{-7} \times T_g^{-0.645}$$ (3)

In Eq. (1), the constants a and b are coefficients used to adjust the equation to empirical data. This is needed due to the many different types of applications (engine geometries and operating range).

Woschini (1967) also worked on many experimental data for heat pumps and compressed ignition engines, and concluded that the convection coefficient may be calculated by:

$$h_g = 890 \times \frac{P^{0.8} W^{0.8}}{B^{0.2} T^{0.53}}$$ (4)

In Eq. (4), P and T are the cylinder pressure and temperature, and W is the characteristic velocity given by:

$$W = C_1 \times w_p + \frac{C_2 (V_h \times T_1)}{P_1 V_1} \times (P - P_o)_g$$ (5)

In Eq. (5), the constants C_1 and C_2 were determined empirically by Woschini, and may change according to the process that is being considered. The values for C_1 and C_2 are given on Table 2.

Table 2. C_1 and C_2 coefficients for Woschini's correlation.

Phase	C_1 [-]	C_2 [m/s K]
Intake	6.18	0
Exhaust	6.18	0
Compression	2.28	0
Combustion	2.28	3.24×10^{-3}
Expansion	2.28	3.24×10^{-3}

The Woschini's correlation is the most commonly used, as can be seen in the works of Lounici et al. (2011). On the other hand, Hohenberg (1979) noted that the Woschni's correlation overestimates the heat transfer coefficient during combustion process, and underestimates it during the compression process. Also, Hohenberg reported that Woschini's correlation use may be of great difficulty in some cases. The observations led Hohenberg to propose his own modified version of Woschini's correlation:

$$h_g = C_1 \times C_u^{-0.06} \times P^{0.8} \times T^{-0.4} \times (C_2 + \overline{V_p})^{0.8}$$ (6)

In Eq. (6) the values for $C_1 = 130$ and $C_2 = 1.4$ are constants given by empirical data obtained by Hohenberg. Another correlation for heat transfer coefficient is the one given by Eichelberg (1939).

$$h_g = 0.00767 \times w_p^{0.003} \times \sqrt{(P \times T)}$$ (7)

Eichelberg's correlation is based in the assumption of natural convection, and so the more modern expressions have been favored. Yet, it seems that Eq. (7) can still bea good approximation for heat transfer coefficient, as recently applied in the work of Grondin (2004).

Another correlation from the same family as Woschni and Hohenberg, is the one proposed by Sitkei et al. (1972). It can be expressed by:

$$h_g = 2.36 \times 10^4 (1 + b) \times \frac{\left[(P \times \overline{V_p})^{0.7} \times A^{0.3} \right]}{[T^{0.2} \times (4V)^{0.3}]} \tag{8}$$

In Eq. (8), b can vary from 0 to 0.35.

In order to understand the effects of heat transfer correlation on calculated engine performance, two engine parameters were analyzed: pressure and temperature inside the cylinder. This choice was made for many reasons. First, both parameters are among the main output of the simulation model used on this work. Also, pressure and temperature can be used to calculate many other performance parameters of the engine. Finally, it is known that the knocking phenomenon can reduce performance due to risk of destruction of the engine, and in this case both pressure and temperature can be a good indicator of knocking occurrence during combustion process.

The many correlations listed previously were then applied to the simulation model. The results were generated and compared in graphic form.

3. RESULTS AND CONCLUSIONS

In Figure 1 is possible do see the influence of the heat transfer correlation on the maximum pressure of the cycle. It can be seen that the maximum pressure can vary from a range of almost 5 bar depending on the correlation. The highest maximum pressure occurred in the Sitkei's correlation, while the lowest value was generated using Woschini's correlation.
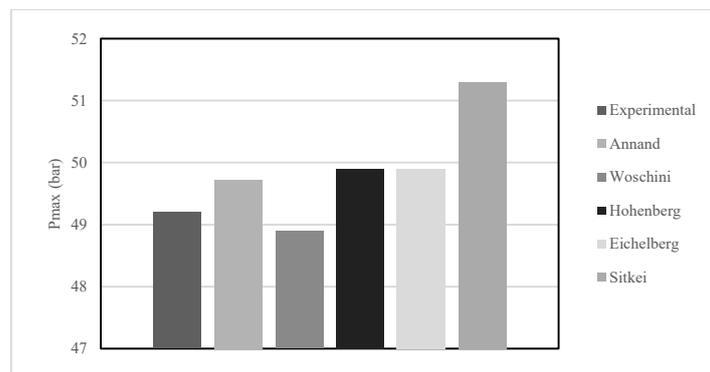

Figure 1 – Maximum pressure variation according to correlation

On Figure 2 it is possible to compare the maximum temperature inside the cylinder, calculated with the different heat transfer correlations. The difference between most correlations was about 50K, except for Sitkei's correlation in which the difference reaches almost 100K.
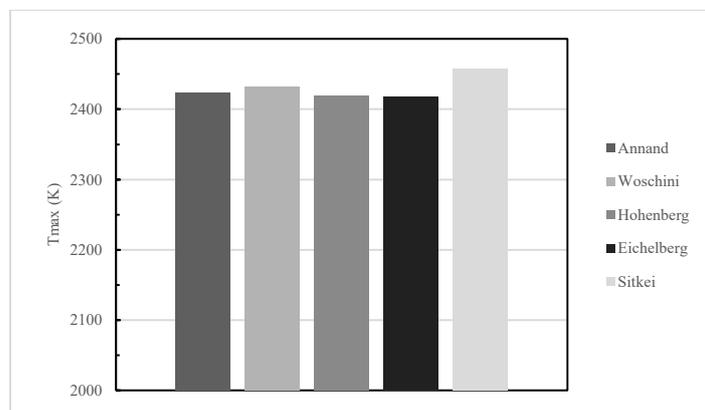

Figure 2 – Maximum temperature variation according to correlation

In Figure 3, the cylinder pressure comparison between the many correlations is given. It is possible to see that all correlations resulted in a pressure profile very near the experimental data. On the other hand, as the pressure values arise, the correlations may differ substantially from each other.
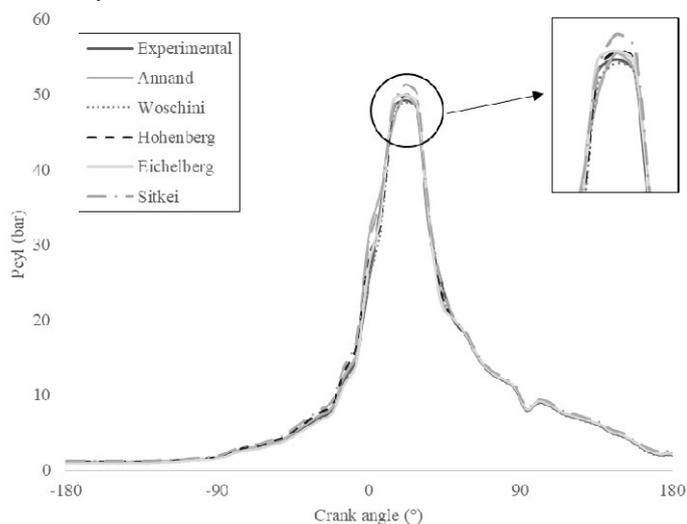

Figure 3 – Pressure comparison for the different correlations

From the results exposed, many conclusions can be taken. For example, it is possible to see that the Woschini's correlation can underestimate the heat transfer coefficient during combustion process. Yet, the global effect on the cycle is negligible. It is also the correlation that matches more closely the results obtained experimentally. On the other hand, the Hohenberg's correlation showed the same level of precision from the Eichelberg's correlation. This result was not expected, since Hohenberg's correlation was developed as an improvement on Woschini's. Yet, it shows that Eichelberg's correlation is still a good match, even considering natural convection. Annand's takes into account the radiation terms, and was a better match than Hohenberg's. Yet, since the difference between Annand's and Hohenberg's results are minimum, it may be concluded that the radiation can be neglected in the combustion process. Finally, for Sitkei's correlation, the engine performance is highly overestimated, and the accuracy is not acceptable.

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