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Modelling of In-Cylinder Convective Heat Transfer Losses to the Combustion Chamber Wall of Compression-Ignition Engine

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Abstract—**Modelling of heat transfer losses to the engine wall of diesel engine involves the employment of heat transfer correlations in quasi one-dimensional thermodynamic simulation. In this study, four common existing heat transfer correlations - Woshni, Sitkei & Ramaniah, Hohenberg and Assanis - are utilised in a quasi one-dimensional thermodynamic simulation. Results are compared with experimental data from existing literature. The results indicate that Woshni's correlation shows the best results as it includes a parameter that characterize the bore size of combustion chamber, while others exclude it. Attempt has been made to improve Woschni's correlation by altering value of constants and power values in the velocity and temperature variables, in order to reduce the error from the experimental results. This finding reveals the current heat transfer correlations have inadequate representation of gas flow characteristics in the correlation especially in the near wall region, where velocity and thermal boundary layer occurs.**

Keywords-convective heat transfer, correlation, modelling, compression- ignition engine.

I. Introduction

Heat losses in diesel engine is attributed to a lot of components such as combustion chamber, intake and exhaust system, coolant system and lubrication system. Inside the combustion chamber, where the process of fuel injection, auto-ignition and production of emission species occurs in fraction of miliseconds, makes it the focus of most researchers in investigating heat transfer in diesel engine. The characteristics of heat transfer in diesel engine are unsteady (varies from zero to as high as 10 MWm^{-2}) and varies with time, position and material properties of combustion chamber wall [1].

Thermodynamic simulation of diesel engine has progressed rapidly over the last forty years. Difficult and costly data that usually measured by experimental technique can be obtained through computer simulation. The simulation process offers varieties of design configurations during initial engine development stages through system parametric optimization and sensitivity analysis [2].

The earliest heat transfer correlation dated back in 1939 was introduced by Eichelberg [3]. That led to other global zero-dimensional correlations, taking into consideration numerous physical processes involving convection, radiation, wall heat flux etc. [4,5].

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Over the years, the most widely used correlations are Woshcni and Annand correlation, due to their non-complex nature and relatively consistence. However, these correlations seem to be effective on a limited range of operating condition and engine specifications.

This modelling study attempts to investigate selected heat transfer correlations using quasi one-dimensional thermodynamic simulation software for their accuracy and inherent characteristics. A new modified correlations was proposed based on observation of the modelling results of the selected correlations.

II. Literature review

A. *Heat Transfer Correlation*

The fluid conditions can be correlated to the process of heat transfer using nondimensional parameters such as the Nusselt and Reynolds number. Nusselt number, *Nu* represents the ratio of convection to the conduction heat transfer over the same temperature difference. This correlation is as follow:

$$Nu = \frac{hL}{k} \quad (1)$$

where h = heat transfer coefficient, L = length scale such as the cylinder bore and k = working fluid thermal conductivity. The rate of heat transfer coefficient, h varies with the position in the cylinder and is time-dependent.

In this study, four heat transfer correlations are selected for quasi one-dimensional thermodynamic simulation. These are Woschni, Sitket and Ramaniah., Hohenberg and Assanis. All of them considers gas velocity, pressure and temperature in their equations. Only Woschni and Assanis have additional parameters that characterize engine geometry: bore and height of combustion chamber, respectively. The correlations of Woschni, Sitket and Ramaniah., Hohenberg and Assanis are as follow:

Woschni Correlation [6]:

$$h_g = 3.26p^{0.8}U^{0.8}b^{-0.2}T^{-0.55} \quad (1)$$

Sitkei and Ramaniah Correlation [7]:

$$h_g = 130V^{-0.06}p^{0.8}T^{-0.4}(U+1.4)^{0.8} \quad (2)$$

Hohenberg Correlation [8]:

$$h_g = 130V^{-0.08}p^{0.8}T^{-0.4}(U+1.4)^{0.8} \quad (3)$$

Assanis Correlation [9]:

$$h_g = 3.26L^{-0.2}p^{0.8}T^{-0.73}U^{0.8} \quad (4)$$

where h_g = heat transfer coefficient, p = pressure, U = gas velocity, b = cylinder bore, L = height of combustion chamber, T = working fluid temperature and V = Instantaneous cylinder volume.

III. Diesel engine

In this study, quasi one-dimensional thermodynamic modelling of diesel engine is performed using GT-Power software using the inputs parameter based from Rakopolous [10]. The input parameters of the diesel engine to the GT-Power software are shown in TABLE I.

TABLE I. DIESEL ENGINE SPECIFICATION [8]

Parameter	Value
Bore	85.73 mm
Stroke	82.55 mm
Connecting rod length	148.59 mm
Compression ratio	18.1
Number of cylinder	1
Type of fuel injection	Direct
Aspiration	Natural
Injector nozzle opening pressure	190 bar
Static injection timing	280°CA before TDC
Weight	83 kg
Fuel consumption (continuous power, 100% load at 1500rpm)	1.1 liter/hr
Cylinder capacity	477 cc

IV. Results and discussion

Simulations using GT-Power software was run based on engine configuration and experimental configuration from Rakopolous [10] where the operating conditions are measured at 1500 RPM for 20%, 40% and 60% of maximum engine load.

A. Pressure Diagram

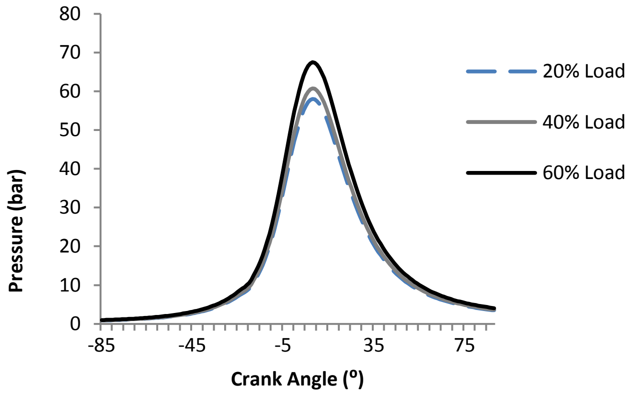

Figure 1. Simulation results of pressure diagram of varying loads

Fig. 1 shows the simulation results of pressure diagram produced by the thermodynamic simulation of the diesel engine of 20%, 40% and 60% load. The results in Fig.1 are then compared with points data from Rakopolous [10]. The comparison indicates that the model set up using the GT-power software provides good match with the measured data by Rakopolous [10]. The simulated maximum pressure obtained are 58.01 bar, 60.75 and 67.5 bar for 20%, 40% and 60% load respectively while the measured maximum pressure values are 58.0 bar, 60.75 bar and 67.5 bar respectively, which indicates of 0.02% error between the simulated and the measured data.

B. Heat Transfer Coefficient

Fig. 2 to Fig. 4 shows the heat transfer coefficient values obtained using the four heat transfer correlations and the measured data [10]. The four heat transfer correlations were based on parameters resulted from the simulation using GT-power software. The results show varying degree of closeness to the measured data, where correlation of Woschni seems to be the closest and correlation of Hohenberg displayed the furthest. The differences of each correlation can be shown in the Table 2. The percentage error here is produced based on the percentage difference of values between instantaneous heat transfer coefficient results using GT power simulations and the experimental data [8] for the range of -20◦CA to 20◦CA.

It can be seen here that the result of heat transfer correlations show that engine bore size – that is not part of the parameters in all correlations except for Woschni – is a crucial parameter in heat transfer of diesel engine. Although Assanis correlation includes the length of combustion chamber as part of the parameter, but this is not, as the error indicate, the geometrical importance in heat transfer of the engine. This might be due to greater heat transfer area exposure per engine cycle in the engine head and pison, rather than on the cylindrical wall of the engine.

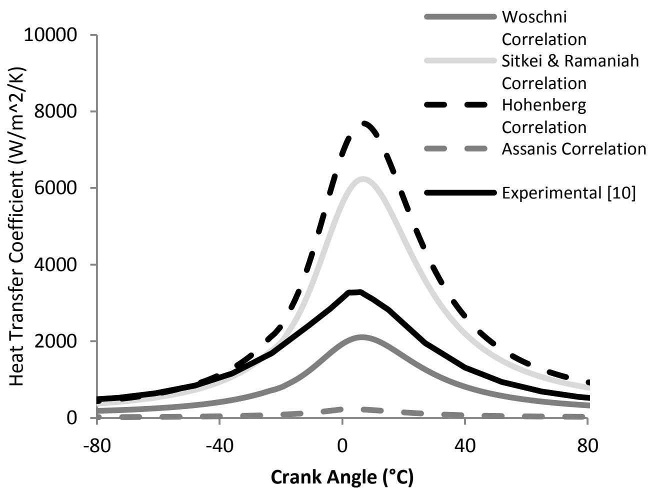

Figure 2. Heat transfer coefficient versus crank angle for engine loads of 20%

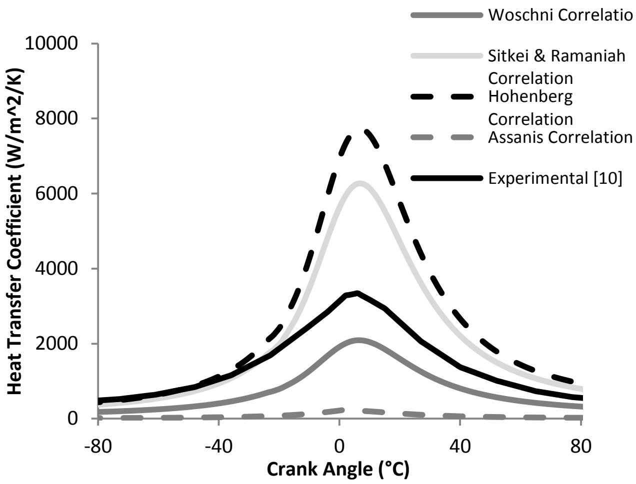

Figure 3. Heat transfer coefficient versus crank angle for engine loads of 40%

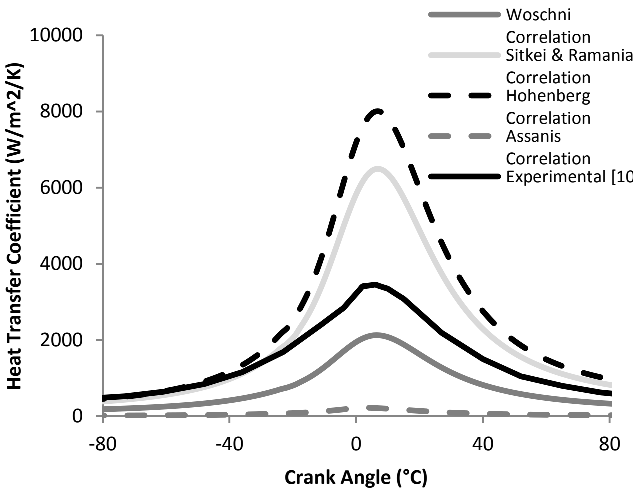

Figure 4. Heat transfer coefficient versus crank angle for engine loads of 60%

TABLE II. PERCENTAGE DIFFERENCE OF CORRELATIONS TO THE EXPERIMENTAL RESULT

Engine Load	Woschni (%)	Sitkei & Ramaniah (%)	Hohenberg (%)	Assanis (%)
20%	41.6	66.1	104.0	94.0
40%	42.8	64.6	102.1	94.2
60%	43.3	66.0	103.9	94.4

C. *Modified Heat Transfer Coefficient*

Attempt has been made to improve the heat transfer simulation by modifying the heat transfer correlation. The approach of this aim is based on parametric studies of Woshni's correlation involving common variables: pressure, characteristic velocity and gas temperature. Woshni's correlation was chosen as the base equation due to it as the best correlations from previous simulations. The change on the heat transfer coefficient results is observed when varying the parameters with the objective to establish the optimum setting for the parameters to reduce the error from the experimental result.

For the modified model, the coefficient is reduced to 3.2 from the original 3.26. Besides that, the power of the gas velocity is reduced from 0.8 to 0.7 while the power of the temperature is increase from -0.55 to -0.45. By doing so, the modified convective heat transfer model can better represent the heat loss as compared to the measured data. The new modified heat transfer correlation proposed is as follows:

$$h = 3.26p^{0.8}U^{0.7}b^{-0.2}T^{-0.45} \tag{5}$$

TABLE III represents the percentage error of modified heat transfer equations to the experimental results. Though only slight arbitrary adjustment to the power raised on the parameters performed, results show vast improvement in comparison with result TABLE II.

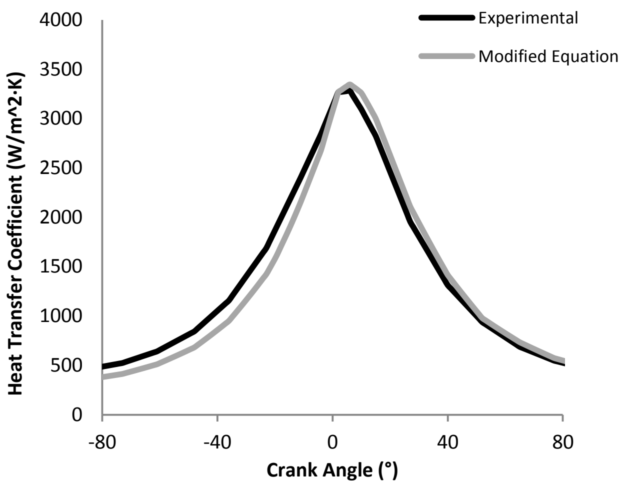

Figure 5. Heat transfer coefficient versus crank angle for engine loads of 20%

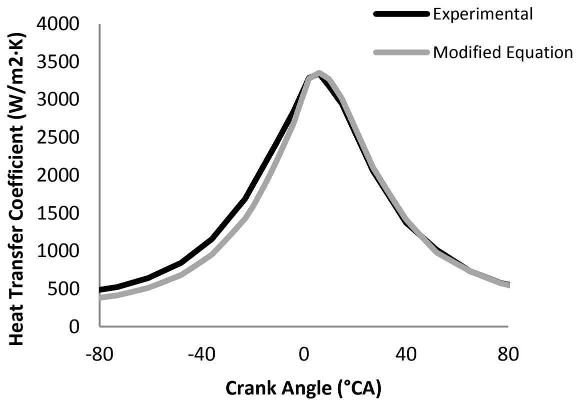

Figure 6. Heat transfer coefficient versus crank angle for engine loads of 40%

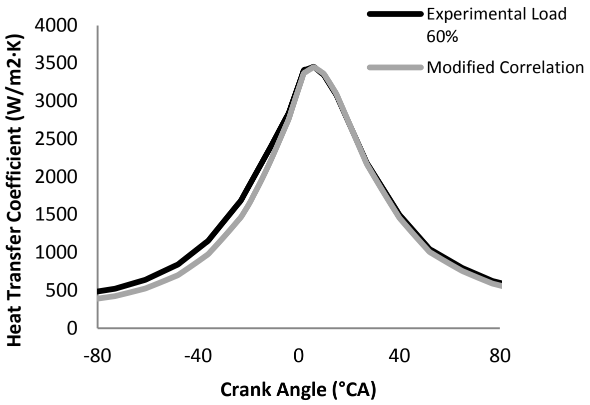

Figure 7. Heat transfer coefficient versus crank angle for engine loads of 60%

TABLE III. PERCENTAGE DIFFERENCE OF NEW MODIFIED CORRELATION TO THE EXPERIMENTAL RESULT

Engine Load (%)	Error (%)
20%	6.86
40%	5.57
60%	3.78

V. Conclusion

Based on the simulations of one-dimensional thermodynamic simulation using GT-power software using the common existing heat transfer correlation used – Woshni, Sitkei & Ramaniah, Hohenberg and Assanis - Woshni's correlation produced the least error from the experimental data. This alludes to the importance of engine bore as significant parameters for modelling of heat transfer from diesel engine as engine bore characterizes the size of surface area of the cylinder head and piston surface area.

The modified Woshni's correlation has improved the one-dimensional thermodynamic simulation result significantly through arbitrary alteration of power raised in the gas velocity and temperature. This finding reveals the inadequate representation of gas flow characteristics in the correlation especially in the near wall region, where velocity and thermal boundary layer occurs. This deficiency could be addressed by having suitable velocity and temperature profiles in the near wall region.

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References

[1] G. Borman and K. Nishiwaki, "Internal combustion engine heat transfer," Progress in Energy and Combustion Science, vol. 13, pp. 1–46, August 1987.

[2] C. A. Finol and K. Robinson, "Thermal modelling of modern engines: a review of empirical correlations to estimate the in-cylinder heat transfer coefficient," Proceedings of the Institution of Mechanical Engineers, Part D:J. of Automotive Engineering, vol. 220, pp. 1765-1781, December 2006.

[3] G. Eichelberg, "Some new investigations on old combustion-engine problems" Engineering, London. vol 148, 1939.****

[4] K. Boulouchos and R. Isch, "Modeling of heat transfer during combustion:a quasi-dimensional approach with emphasis on large low-speed diesel engines," International Symposium COMODIA, vol. 90, pp. 321-328, 1990.

[5] A.Chow and M.L. Wysznski,"Thermodynamic modelling of complete engine systems - a review," Proceedings in Istitution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 213, No. 4, pp. 403-415, April 1999.

[6] G. Woschni, "A universally applicable equation for the instantaneous heat transfer coefficient in the internal combustion engine," SAE Paper 670931.

[7] G. Sitkei and Ramanaiah, "A rational approach for calculation of heat transfer in diesel engines," SAE Paper 720027.

[8] G.F. Hohenberg, "Advanced approaches for heat transfer calculation," SAE Paper 790825.

[9] H.S. Soyhan, H. Yasar, H. Walmsey and B. Head,"Evaluation of heat transfer correlation for HCCI engine modelling," Applied Thermal Engineering, vol. 29, 2-3, pp 541-549, February 2009.

[10] C.D. Rakopoulous, G.C. Mavropoulos, E.G. Giakoumis,"Experimental and theoretical study of short term response temperature transients in the cylinder walls of a diesel engine at various operating conditions," vol. 24, 5-6, pp. 679-702, April 2004.