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IN-CYLINDER HEAT TRANSFER MODELLING

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ABSTRACT
The goal of the paper is to discuss specific features of the in-cylinder heat transfer calculation based on widely used empirical formulas. The potential of in-house codes compared with commercially available software packages is presented. The principles of user models in the GT-SUITE environment are also explained. The results of calibrated models are briefly discussed.
KEYWORDS: HEAT TRANSFER COEFFICIENT, GT-SUITE, USER MODEL, FORTRAN, DIESEL, JOHN DEERE, WOSCHNI, HOHENBERG, EICHELBERG, ANNAND, SITKEI, RAMANAIAH, TAYLOR, TOONG

SHRNUTÍ
Cílem příspěvku je poukázat na problematiku výpočtu tepla odvedeného z válce na základě často používaných empirických vztahů. Dále je ukázán potenciál vlastních programů v porovnání s komerčně dostupným programovým vybavením. V článku jsou také osvětleny základy uživatelských modelů v prostředí GT-SUITE. Stručné výsledky kalibrovaných modelů jsou uvedeny v závěru.
KLÍČOVÁ SLOVA: SOUČINITEL PŘESTUPU TEPLA, GT-SUITE, UŽIVATELSKÝ MODEL, FORTRAN, DIESEL, JOHN DEERE, WOSCHNI, HOHENBERG, EICHELBERG, ANNAND, SITKEI, RAMANAIAH, TAYLOR, TOONG

1. INTRODUCTION
The goal of the contribution is to describe the specific features of in-cylinder heat transfer modelling and the feasibility of improving the accuracy of resulting models. The capability of the standard heat transfer models in GT-SUITE is limited due to model calibration constrains. It is possible to increase the capability of the simulation tool using the user model linked to the main solver of commercially available software. Modelling is therefore not restricted to standard tools and templates, but it is possible to develop software utilities with very specific features. The original correlation formulas are usually not accurate enough in the case of a specific combustion engine, so it is desirable to tune the coefficients of empirical formulas during the model calibration process. The presented in-house heat transfer model enables use of any correlation formula and the varying of all applied coefficients. The code is open and ready for further development. The correlation formulas currently available in the developed user model are briefly described below. The developed user model is able to cooperate with a standard cylinder wall temperature solver based on the finite element method (FEM).

2. HEAT TRANSFER MODELLING
The very popular and frequently used formula "Woschni GT" is an improved correlation based on the original Woschni relation without swirl. The Woschni GT is recommended by Gamma

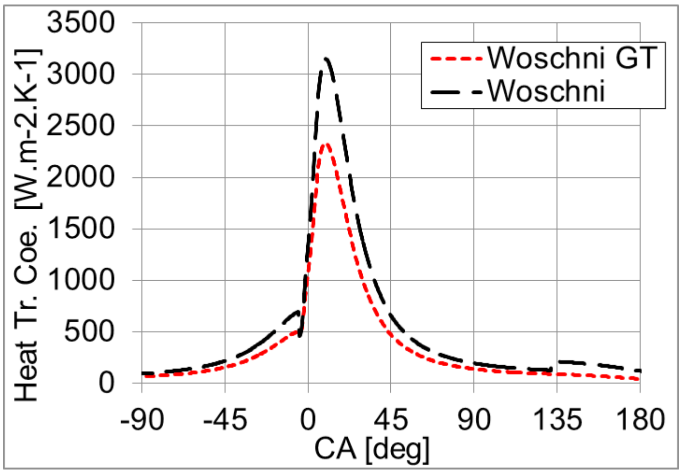

FIGURE 1: Heat transfer coefficients; Woschni GT adapted (red dashed line); Woschni adapted (black long dashed line); 900 RPM, full load, IMEP = 9.6 bar
OBRÁZEK 1: Součinitelé přestupu tepla; Woschni GT upravený vztah (červená čárkovaná čára); Woschni upravený vztah (černá dlouze čárkovaná čára); 900 RPM, plné zatížení motoru, IMEP = 9.6 bar

Technologies as the first choice at the beginning of the calibration process of the internal combustion engine model. The heat transfer coefficients calculated via the Woschni GT and Woschni formulas are in Figure 1. The user may influence the heat transfer coefficient course via two tuning parameters, i.e. a radiation and convection multiplier. The radiation multiplier is typically equal to one for diesel engines and zero for other engines. The radiation part of the total heat transfer rate, when the radiation multiplier equals one, is compared with the total heat transfer rates estimated by the Woschni GT and Woschni in Figure 2.

It is strongly recommended to hold only one value of the convection multiplier for the complete engine characteristic, but obtained results are quite unsatisfactory. The calibration of convection multiplier in relation to engine speed and load provides much better results. The achievement of the exact measured in-cylinder pressure course is, however, often impossible.

Woschni classic, Woschni swirl, Woschni – Huber and Hohenberg correlations are also available in the GT-SUITE environment.

In the case of the user model, when the in-house developed code is used, the user is able to adapt the model and algorithm to very specific purposes. The problems may consist of the number of calibration parameters and elaborateness of the mentioned approach.

The fundamental Woschni's correlation without swirl (1), (2) and (3) is described in detail in [2] and [3]. Coefficients C1 and C2 in the relation of in-cylinder gas velocity depend on the engine cycle phase (2). The user of the developed in-house code may tune all calibration coefficients A1-A8 arbitrarily.

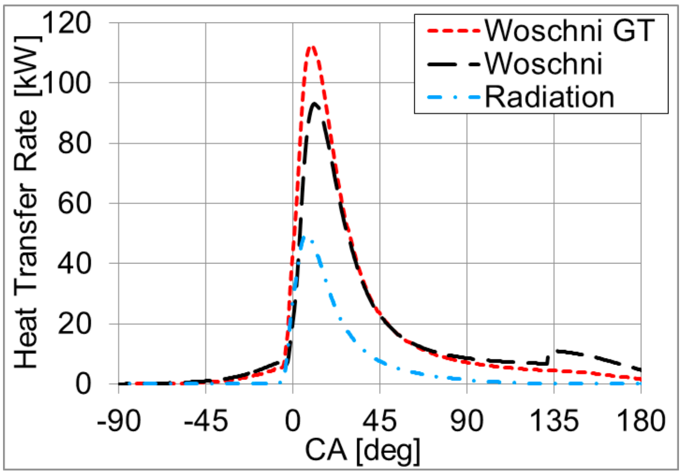

FIGURE 2: Heat transfer rate; Woschni GT adapted (red dashed line); Woschni adapted (black long dashed line); Radiation (blue dashed and dotted line); 900 RPM, full load, IMEP = 9.6 bar

OBRÁZEK 2: Tepelný tok chlazením; Woschni GT upravený vztah (červená čárkovaná čára); Woschni upravený vztah (černá dlouze čárkovaná čára); Radiační složka (modrá čerchovaná čára); 900 RPM, plné zatížení motoru, IMEP = 9.6 bar

$$h = 0.01297829376\, B^{-0.2}\, p^{\,0.8}\, T^{-0.53}\, w^{\,0.8} = \\ = A_1\, B^{\,A_2}\, p^{\,A_3}\, T^{\,A_4}\, w^{\,A_5} \tag{1}$$

$$w = C_1\, S_p + C_2\, \frac{V_d\, T_{ref}}{p_{ref}\, V_{ref}}\, (p - p_m) = \\ = A_6\, S_p + A_7\, \frac{V_d\, T_{ref}}{p_{ref}\, V_{ref}}\, (p - p_m) \tag{2}$$

$$p_m = p_{ref}\left(\frac{V_{ref}}{V}\right)^{\kappa} = p_{ref}\left(\frac{V_{ref}}{V}\right)^{A_8} \tag{3}$$

Gas exchange period: $C_1 = 6.18$; $C_2 = 0$; Compression period: $C_1 = 2.28$; $C_2 = 0$; Combustion and expansion period: $C_1 = 2.28$; $C_2 = 3.24 \cdot 10^{-3}$

The effect of the swirl is included in the second Woschni formula (4), (5), (6), (7) and (8). See [2], [4] and [5]. The intensity of the swirl is described by rotational speed of the paddle wheel (7) and (8) obtained by measurement on a flowbench.

$$h = 0.01297829376\, B^{-0.2}\, p^{\,0.8}\, T^{-0.53}\, w^{\,0.8} = \\ = A_{11}\, B^{\,A_{12}}\, p^{\,A_{13}}\, T^{\,A_{14}}\, w^{\,A_{15}} \tag{4}$$

$$w = C_1\, S_p + C_2\, \frac{V_d\, T_{ref}}{p_{ref}\, V_{ref}}\, (p - p_m) = \\ = C_1\, S_p + A_{19}\, \frac{V_d\, T_{ref}}{p_{ref}\, V_{ref}}\, (p - p_m) \tag{5}$$

$$p_m = p_{ref}\left(\frac{V_{ref}}{V}\right)^{A_{20}} \tag{6}$$

$$\text{Gas exchange period: } C_1 = 6.18 + 0.417\, B\, \pi\, n_p\, \frac{1}{S_p} = \\ = A_{16} + A_{17}\, B\, \pi\, A_{18}\, \frac{1}{S_p} \tag{7}$$

$$\text{Rest of cycle: } C_1 = 2.28 + 0.308\, B\, \pi\, n_p\, \frac{1}{S_p} \tag{8}$$

Gas exchange period: $C_2 = 0$; Compression period: $C_2 = 0$; Combustion and expansion period: $C_2 = 3.24 \cdot 10^{-3}$

The relation developed by Hohenberg stated in (9) and [8]:

$$h = 0.013\, V^{-0.06}\, p^{\,0.8}\, T^{-0.4}\, (S_p + 1.4)^{0.8} = \\ = A_{23}\, V^{\,A_{24}}\, p^{\,A_{25}}\, T^{\,A_{26}}\, (S_p + A_{27})^{A_{28}} \tag{9}$$

Eichelbergs' correlation is an often used formula, partly due to its simplicity (10) and [7].

$$h = 7.799 \,.\, 10^{-3}\; S_p^{\frac{1}{3}}\; p^{0.5}\, T^{0.5} =$$

$$= A_{31}\; S_p^{A_{32}}\; p^{A_{33}}\, T^{A_{34}} \tag{10}$$

The effect of in-cylinder radiation on the heat transfer coefficient, which is significant for diesel engines, is described in Annand's equation directly (11) and (12), see also [9] and [10]. The radiation multiplier is different for SI and CI engines and also differs depending on engine cycle period.

$$h = a\,\frac{k_G}{B}\,Re^b + c\,\sigma\,\frac{T_G^4 - T_W^4}{T_G - T_W} =$$

$$= A_{38}\,\frac{A_{39}}{B}\,Re^{A_{40}} + A_{41}\,\sigma\,\frac{T_G^4 - T_W^4}{T_G - T_W} \tag{11}$$

$$Re = \frac{\rho\, S_p\, B}{\mu} = \frac{\rho\, S_p\, B}{A_{37}} \tag{12}$$

Combustion and expansion period: (CI engine: c = 0.576; SI engine: c = 0.075); Rest of cycle: c = 0

The influence of radiation is also described in the equation of Sitkei – Ramanaiah (13), (14) and [11]. The mentioned correlation is determined primarily for diesel engines.

$$h = 0.01455\,(1+b)\,\frac{p^{0.7}\, S_p^{0.7}\, A^{0.3}}{T_G^{0.2}\,(4\,V)^{0.3}} + \varepsilon\,\sigma\,\frac{T_G^4 - T_W^4}{T_G - T_W} \tag{13}$$

$$h = A_{44}\,\frac{p^{A_{45}}\, S_p^{A_{46}}\, A^{A_{47}}}{T_G^{A_{48}}\,(A_{49}\,V)^{A_{50}}} + A_{51}\,\sigma\,\frac{T_G^4 - T_W^4}{T_G - T_W} \tag{14}$$

DI direct injection (b = 0 - 0.03); piston chamber (b = 0.05 - 0.1); swirl (b = 0.15 - 0.25); prechamber (b = 0.25 - 0.35)

The formula developed by Taylor – Toong stated in (15), (16) and [12]:

$$h = 0.35\,\frac{k_G}{B}\,Re^{0.75} = A_{55}\,\frac{A_{56}}{B}\,Re^{A_{57}} \tag{15}$$

$$Re = \frac{\rho\, S_p\, B}{\mu} = \frac{\rho\, S_p\, B}{A_{54}} \tag{16}$$

Several standard templates in GT-SUITE support the utilization of the model developed by a user. The basic user model template is defined as a part of a parent template with a particular setup. The code has to be developed in Fortran or C++. It is also needful to create a subroutine, which is unavoidable for communication between utilities, user templates and communication boxes. The user model (Fortran code) is able to communicate with the main model (e.g. internal combustion engine) via communication boxes. Some variables are accessible directly via the main solver. GT-SUITE software allows utilization of several user models concurrently. The heat transfer correlations mentioned above are available in the current version of the developed user model linked to GT-SUITE.

The actual engine cycle phase is described in the model by cycle flag, see Figure 3. The course of the heat release fraction is updated from cycle to cycle and the end of combustion (engine cycle flag = 3) is defined by the user via selectable variable "heat release fraction" in the setup (e.g. 0.99 in Figure 3). The described function is independent of actual heat release course or mixture composition (lean/rich). The engine cylinders in the model are entirely independent (e.g. geometry, valve timing of relevant cylinder, volumetric efficiency, heat release etc.). The user model automatically detects the number of cylinders, firing order, local crank angle of the cylinder, number of species, mass for each species in zone etc. The presented model can operate with one or two temperature zones based on the used combustion model. In the case of two zones, the model calculates heat transfer coefficients for burned and unburned zones concurrently. The model also cooperates with the finite element (FEM) cylinder wall temperature solver including cylinder liner, piston, head, valves and valve guides. The FEM wall temperature model has to be calibrated independently as usual.

The coefficients in the correlation formula can vary in dependence on engine cycle phase, according to cycle flag, or

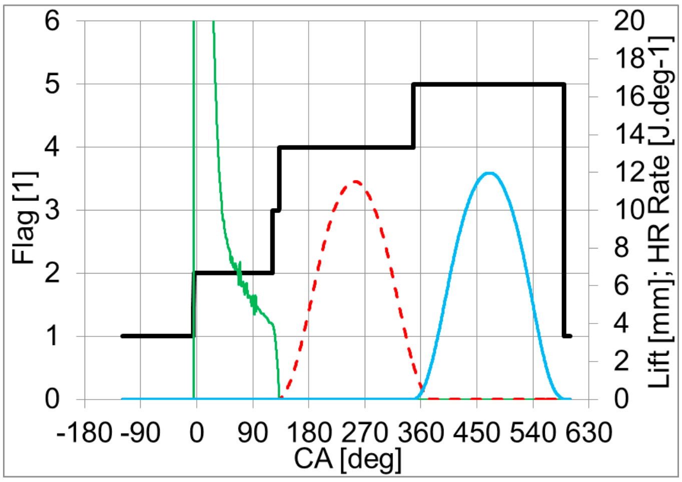

FIGURE 3: Engine cycle flag (black) – 1) intake valve closing – combustion; 2) combustion; 3) end of combustion – exhaust valve opening; 4) exhaust valve opening – exhaust valve closing; 5) intake valve opening – intake valve closing; Exhaust valve lift (red dashed line); Intake valve lift (blue); Heat Release Rate (green)

OBRÁZEK 3: Fáze oběhu (černá) – 1) zavření sacího ventilu – hoření; 2) hoření; 3) konec hoření – otevření výfukového ventilu; 4) otevření výfukového venitlu – zavření výfukového ventilu; 5) otevření sacího ventilu – zavření sacího ventilu; Zdvih výfukového ventilu (červená čárkovaná čára); Zdvih sacího ventilu (modrá); Vývin tepla (zelená) with respect to local crank angle of the cylinder, see examples in Figure 4. The aim is to improve the accuracy of the empirical formula by tuning the applied coefficients for the specific case. The next step could be creation of new formula suitable for special purposes. It is no problem to extend the current in-house code of the presented user model.

3. RESULTS

The single cylinder model of the internal combustion engine was developed in the GT-SUITE environment for the simulation purposes. The model is suitable for the three pressure analysis of the experimental data. Experimental data, measured on the experimental six cylinder diesel engine (Table 1), were used in the model calibration process. The goal is to show the behaviour of the developed user model. The comparison of the results predicted by the model, which utilized the user model of the in-cylinder heat transfer, with the experiments is a side effect only. The indicated pressures at intake port inlet, in cylinder and at exhaust port outlet are required for the three pressure analysis. Further inputs for the model are engine geometry, temperatures, brake torque, fuel flow etc. The temperatures of the engine parts are not available from the measurement.
The discussion of the simulation results starts with the heat transfer coefficients predicted by the correlation formulas in original forms are shown in Figure 5 and Figure 6. The difference between formulas, thus the predicted heat transfer coefficients are clearly visible. The accuracy level of results obtained using the original equations is not sufficient for the current purposes. It is needful to derive a correlation tailored to the specific combustion engine.
The aim of the calibration was to create a model capable of predicting engine parameters comparable to the experiments. For the achievement of the same in-cylinder pressure, thus the indicated mean effective pressure, it was necessary to adapt the heat transfer correlations. The main coefficient of each equation, used in the relevant simulation was tuned. The main coefficient is the multiplier of the whole equation (e.g. A1 in Woschni formula, A11, A23 etc.).
It is of course possible to change any introduced calibration coefficient. It is recommended to try several different classical formulas, choose one with the best tendency and then calibrate it in dependence on the engine speed and load. The approach has been tested during the comprehensive three pressure analyses in the GT-SUITE environment.

Label	John Deere 6068 Diesel
Type	compression ignition
Fuel	diesel oil
Cylinders	6 in-line
Bore [mm]	106.426
Stroke [mm]	127
Displacement [dm3]	6.779

TABLE 1: Parameters of the experimental combustion engine
TABULKA 1: Parametry experimentálního spalovacího motoru

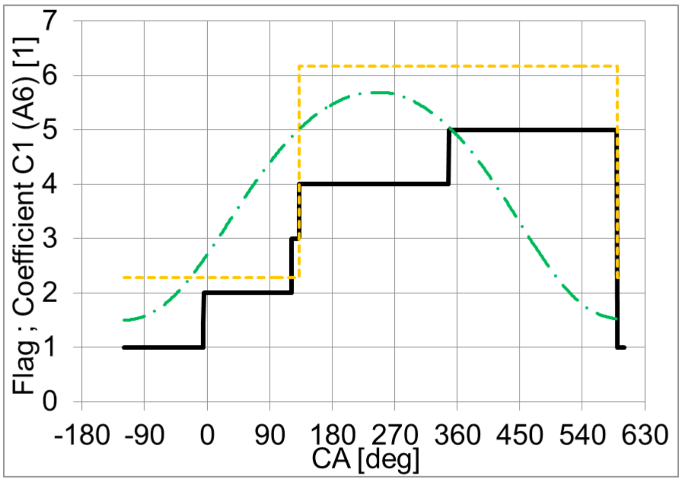

FIGURE 4: Coefficient A6 (C1) as a variable in the user model setup (or linked to GT-S case setup) (orange dotted line); Example of user defined arbitrary course of coefficient vs. crank angle (green dash-dot line); Engine cycle flag (by user model code)
OBRÁZEK 4: Součinitel A6 (C1) jako proměnná v nastavení uživatelského modelu (lze případně svázat s nastavením výpočtu v GT-S) (oranžová čárkovaná čára); Příklad uživatelsky definovaného libovolného průběhu součinitele v závislosti na úhlu klikové hřídele (zelená čerchovaná čára); Fáze oběhu (generováno uživatelským modelem)

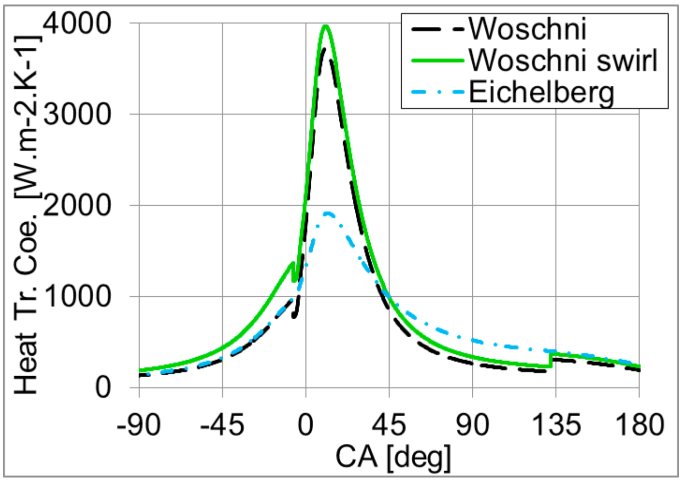

FIGURE 5: Heat transfer coefficients – original correlation formulas; Woschni original (black dashed line); Woschni swirl original (green line); Eichelberg original (blue dashed and dotted line); 1200 RPM, full load, IMEP = 13 bar
OBRÁZEK 5: Součinitelé přestupu tepla – korelace v originálním tvaru; Woschni original (černá čárkovaná); Woschni swirl original (zelená); Eichelberg original (modrá čerchovaná); 1200 RPM, plné zatížení motoru, IMEP = 13 bar

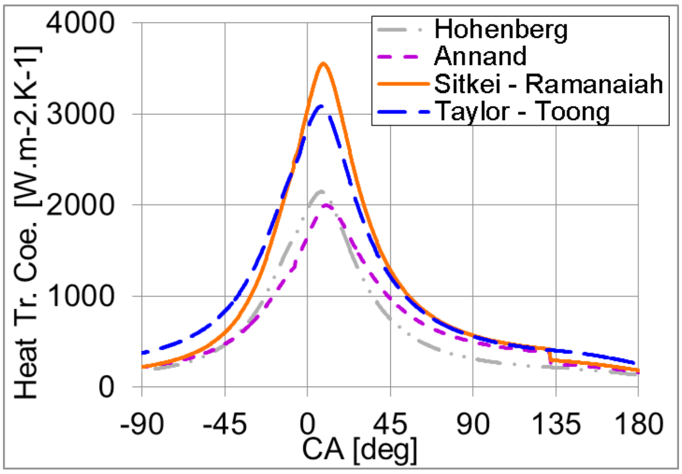

FIGURE 6: Heat transfer coefficients – original correlation formulas; Hohenberg original (grey dashed and dotted line); Annand original (purple dashed line); Sitkei – Ramanaiah original (orange line); Taylor – Toong original (blue long dashed line); 1200 RPM, full load, IMEP = 13 bar

OBRÁZEK 6: Součinitelé přestupu tepla – korelace v originálním tvaru; Hohenberg original (šedá čerchovaná); Annand original (fialová čárkovaná); Sitkei – Ramanaiah original (oranžová); Taylor – Toong original (modrá dlouze čárkovaná); 1200 RPM, plné zatížení motoru, IMEP = 13 bar

The comparison of heat transfer coefficient courses calculated via original or adapted formulas is shown in Figure 7. Figure 7 shows the three pressure analysis results of original (uncalibrated) and adapted (calibrated) heat transfer correlation equations. The differences are obvious and confirmed in the following pictures. The original and adapted main coefficients are presented in Figure 8.

The indicated mean effective pressure predicted by the simulations compared to experimental data is shown in Figure 9. The engine model based on the original Woschni and Eichelberg formulas is not able to reproduce the measured values.

The indicated efficiency of the experimental engine is presented in Figure 10. The results of indicated efficiency are consistent with the indicated mean effective pressures in Figure 9. The results calculated by the model with adapted heat transfer correlations formulas are comparable to the experimental data.

The engine model with in-cylinder heat transfer user model tailored to the specific combustion engine also reproduces the maximum pressure in cylinder very well as presented in Figure 11.

The adapted Eichelberg equation predicts higher values of the in-cylinder heat transfer at full engine load than the Woschni adapted relation – Figure 12. The calculated percentage of useful exhaust energy in Figure 13 is consistent with the tendency of the presented heat transfer.

The simulation of the whole combustion engine, not just the single cylinder model for the purposes of three pressure analysis, has to be performed to answer the question of which formula is better for the current combustion engine. The balance between the in-cylinder heat transfer and useful exhaust energy is important for the estimation of turbine power, i.e. the overall energy balance of the turbocharged internal combustion engine. The differences between the adapted

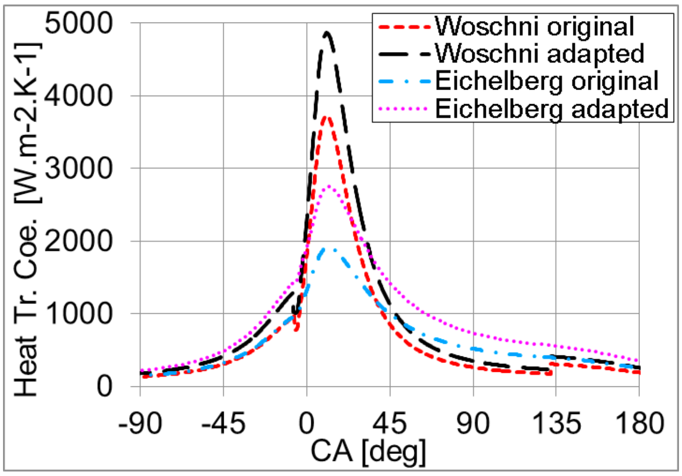

FIGURE 7: Heat transfer coefficients – original and adapted correlation formulas; Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line); 1200 RPM, full load, IMEP = 13 bar

OBRÁZEK 7: Součinitelé přestupu tepla – korelace v originálním a upraveném tvaru; Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná); 1200 RPM, plné zatížení motoru, IMEP = 13 bar

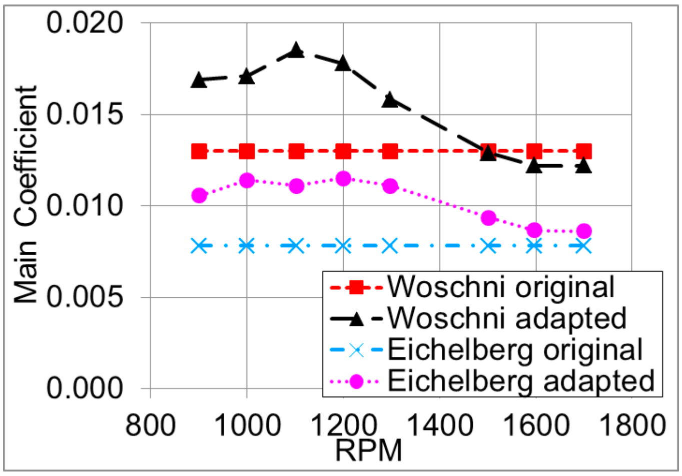

FIGURE 8: Main coefficients (A1 – Woschni; A31 – Eichelberg) – original and adapted; Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)

OBRÁZEK 8: Hlavní koeficienty (A1 – Woschni; A31 – Eichelberg) – originální a upravené; Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

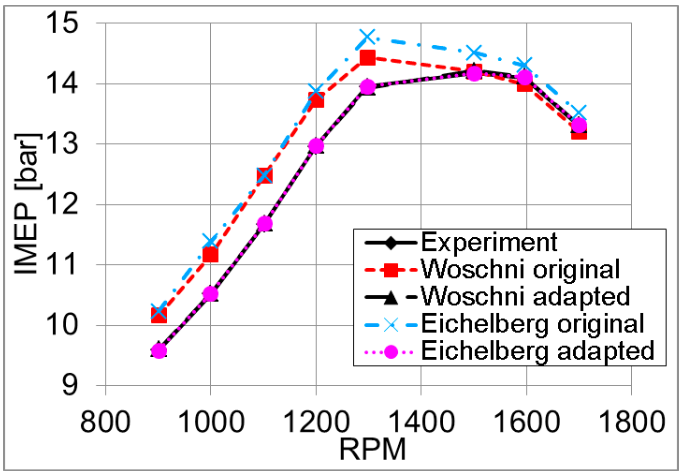

FIGURE 9: Indicated mean effective pressure – original and adapted correlation formulas; Experiment (black); Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 9: Střední efektivní tlak – korelace v originálním a upraveném tvaru; Experiment (černá); Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

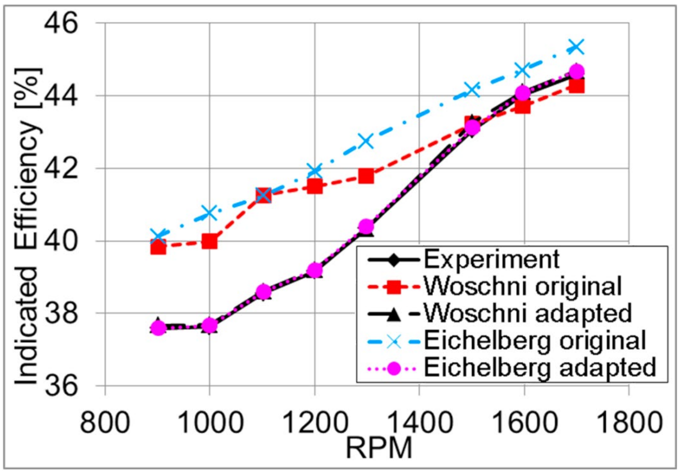

FIGURE 10: Indicated efficiency – original and adapted correlation formulas; Experiment (black); Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 10: Indikovaná účinnost – korelace v originálním a upraveném tvaru; Experiment (černá); Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

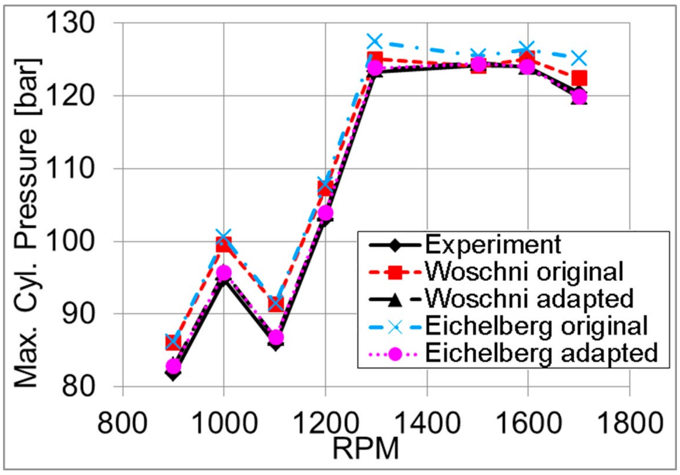

FIGURE 11: Maximum in-cylinder pressure – original and adapted correlation formulas; Experiment (black); Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 11: Maximální tlak ve válci – korelace v originálním a upraveném tvaru; Experiment (černá); Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

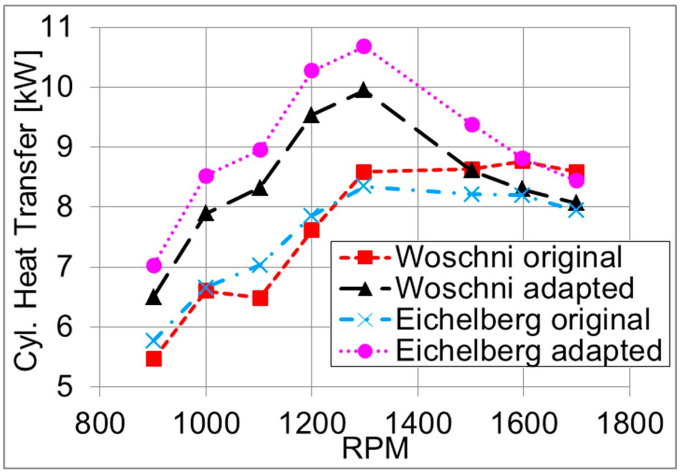

FIGURE 12: In-cylinder heat transfer (1 cylinder) – original and adapted correlation formulas; Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 12: Odvod tepla chlazením (jeden válec) – korelace v originálním a upraveném tvaru; Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

formulas results show – at least – uncertainties in obtaining correct heat transfer figures. The results will be analyzed and published in the future.

The important feature of the presented model is the interaction between the heat transfer model and the FEM model of wall temperatures. The FEM solver includes the cylinder liner, piston, head, valves and valve guides. The wall temperature model has to be calibrated independently, but the calibration options are limited [16]. The cylinder temperature zones modelled in GT-SUITE are drawn in Figure 14.

The temperatures of particular parts calculated by the FEM solver are presented in following pictures. It has to be stressed that the engine part temperatures are not available from the experiments. The aim is to show the trends of the predicted zone temperatures. The cylinder wall temperatures are slightly higher in the case of the Eichelberg adapted

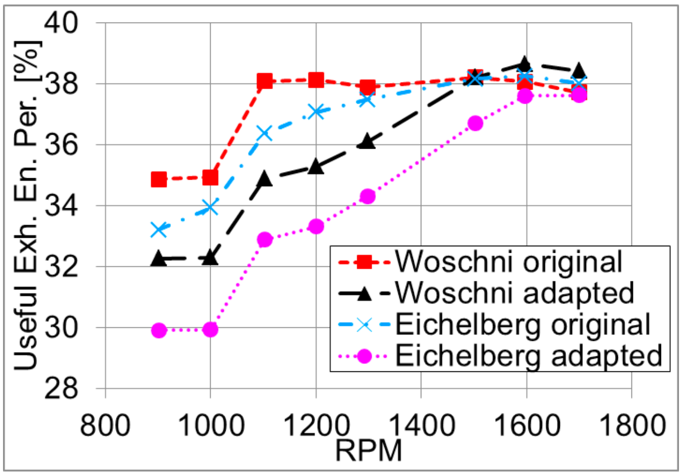

FIGURE 13: Percentage of useful exhaust energy – original and adapted correlation formulas; Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 13: Podíl využitelné energie výfukových plynů – korelace v originálním a upraveném tvaru; Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

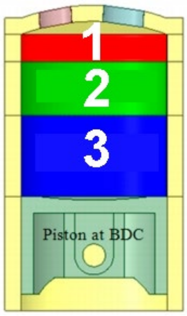

FIGURE 14: Cylinder temperature zones, see [16]
OBRÁZEK 14: Teplotní zóny válce, viz [16]

formula compared to Woschni – Figure 15, Figure 16 and Figure 17. The differences are, nevertheless, within the range of measurement errors.

The temperatures of the cylinder head (Figure 18) and piston (Figure 19) are slightly lower for the Eichelberg adapted formula in comparison with the adapted Woschni relation. Finally, the brake specific fuel consumption calculated by the models compared to the experimental data is given in Figure 20.

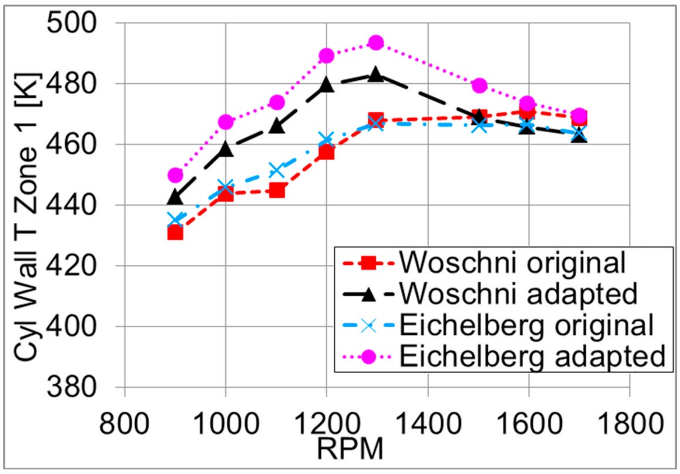

FIGURE 15: Temperature of cylinder wall (zone 1) – original and adapted correlation formulas; Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 15: Teplota stěny válce (zóna 1) – korelace v originálním a upraveném tvaru; Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

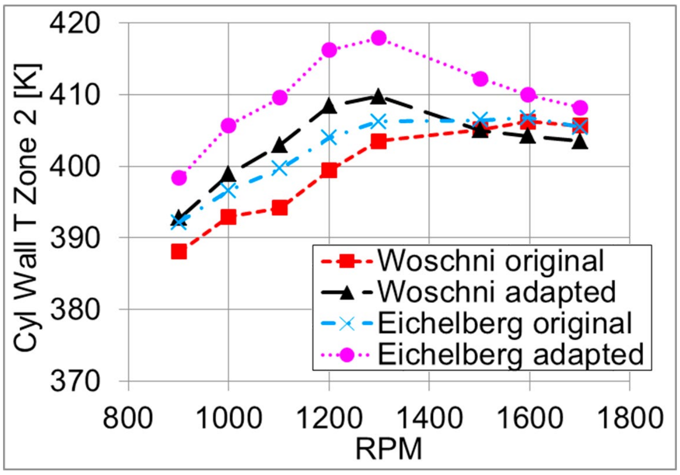

FIGURE 16: Temperature of cylinder wall (zone 2) – original and adapted correlation formulas; Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 16: Teplota stěny válce (zóna 2) – korelace v originálním a upraveném tvaru; Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

4. CONCLUSION

The frequently used empirical formulas are not usually accurate enough, and therefore the level of accuracy and the predictive capability of the whole engine model are not sufficient. It is necessary to adjust classical formula to a unique application in order to achieve the desired course of the in-cylinder heat transfer coefficient and consequently proper heat transfer rate. The user model enables the creation of in-house heat transfer correlations and calibration of all coefficients during the calibration process (three pressure analysis or measured cylinder pressure analysis in GT-SUITE). It is feasible to calibrate not only the amount of transferred heat, but also to tune the heat transfer coefficient course to achieve the required cylinder pressure. The presented user model increases the number of usable empirical formulas, the ability of the heat transfer model

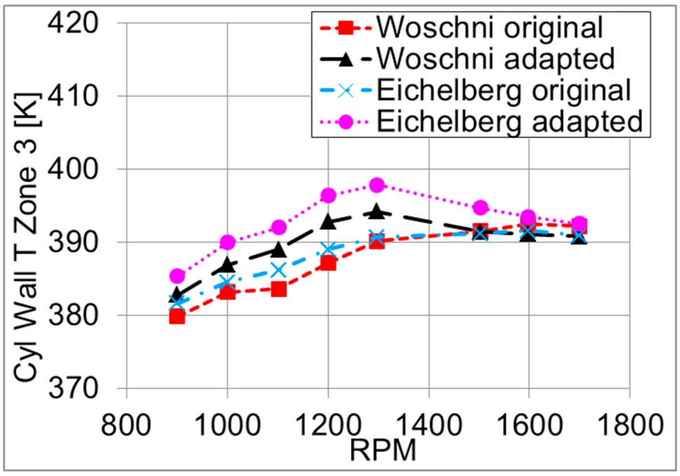

FIGURE 17: Temperature of cylinder wall (zone 3) – original and adapted correlation formulas; Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 17: Teplota stěny válce (zóna 3) – korelace v originálním a upraveném tvaru; Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

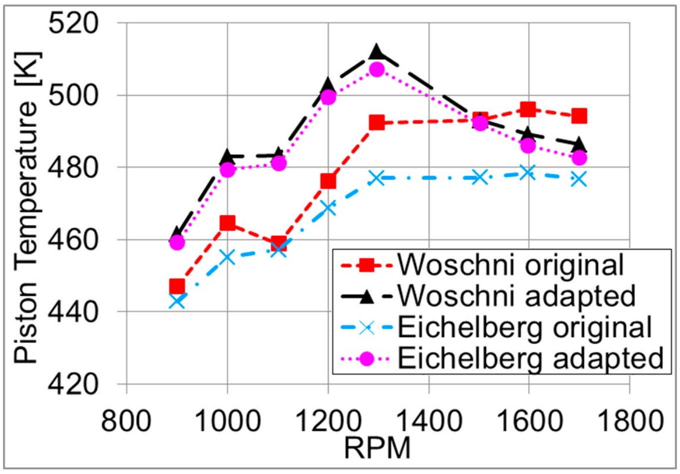

FIGURE 19: Piston temperature – original and adapted correlation formulas; Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 19: Teplota pístu – korelace v originálním a upraveném tvaru; Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

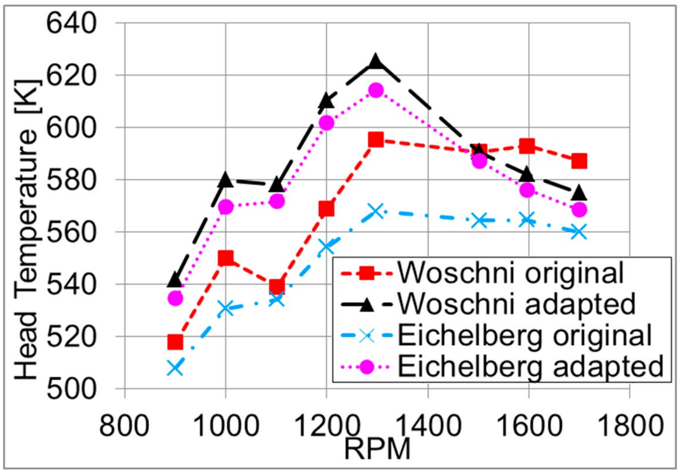

FIGURE 18: Cylinder head temperature – original and adapted correlation formulas; Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 18: Teplota hlavy válce – korelace v originálním a upraveném tvaru; Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

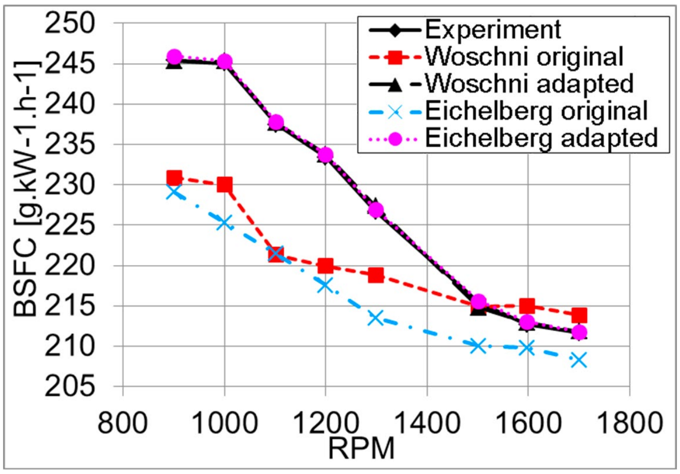

FIGURE 20: Brake specific fuel consumption – original and adapted correlation formulas; Experiment (black); Woschni original (red dashed line); Woschni adapted (black long dashed line); Eichelberg original (blue dashed and dotted line); Eichelberg adapted (pink dotted line)
OBRÁZEK 20: Měrná spotřeba paliva – korelace v originálním a upraveném tvaru; Experiment (černá); Woschni original (červená čárkovaná); Woschni upravený (černá dlouze čárkovaná); Eichelberg original (modrá čerchovaná); Eichelberg upravený (růžová tečkovaná)

to achieve required values and the level of accuracy of the whole model of the internal combustion engine. The general structure of the user model is the same for every template in the GT-SUITE environment, which allows development of an in-house algorithm for specific purposes. The mentioned approach is generally demanding, time consuming and the number of calibration parameters also increases. The potential of extension codes consists of the solution of very specific problems which are not solvable using standard commercial software templates. The main benefit of in-house code in combination with commercial software rests in the ability to solve a special problem and utilize all coupled models and main solver capability for basic problems at the same time.

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LIST OF NOTATIONS AND ABBREVIATIONS

a, b, c	coefficients
A [m^2]	instantaneous surface area (piston, head, liner)
A_{1-n}	coefficients
B [m]	cylinder bore
C_{1-n}	coefficients (Woschni correlations)
h [$Wm^{-2}K^{-1}$]	instantaneous heat transfer coefficient
k_G [$Wm^{-1}K^{-1}$]	thermal conductivity
n_p [s^{-1}]	rotational speed of the paddle wheel (swirl measurement)
p [Pa]	instantaneous in-cylinder pressure
p_m [Pa]	instantaneous motored in-cylinder pressure
Re [1]	Reynolds number
ref	reference values (after intake valve closing)
S_p [ms^{-1}]	mean piston speed
T [K]	instantaneous averaged in-cylinder temperature
T_G [K]	instantaneous averaged in-cylinder temperature
T_W [K]	cylinder wall temperature
V [m^3]	instantaneous cylinder volume (displaced + clearance)
V_d [m^3]	displaced (swept) cylinder volume – constant
w [ms^{-1}]	instantaneous averaged in-cylinder gas velocity
ε [1]	flame emissivity
κ [1]	specific heat ratio
μ [Pa. s]	dynamic viscosity
ρ [kg m^{-3}]	instantaneous in-cylinder gas density
$\sigma = 5.67 \cdot 10^{-8}$ [$Wm^{-2}K^{-4}$]	Stefan Boltzmann constant

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