UTILIZATION OF MULTI-ZONE MODEL RESULTS IN SI ENGINE MODELING

ZDENĚK ŽÁK, JIŘÍ HVĚZDA, MILOSLAV EMRICH, JAN MACEK, LIBOR ČERVENKA

Czech Technical University, Vehicle Centre of Sustainable Mobility, Technická 4, 16607 Praha 6

E-mail: zdenek.zak@fs.cvut.cz, jiri.hvezda@fs.cvut.cz, miloslav.emrich@fs.cvut.cz, jan.macek@fs.cvut.cz, libor.cervenka@fs.cvut.cz

SHRNUTÍ

Příspěvek se zabývá využitím výsledků vícezónových modelů v simulacích oběhů čtyřtákních zážehových motorů. Popsány jsou základní principy vícezónových modelů. Inverzní forma modelu byla využita k získání požadovaných výstupů, založených na dostupných geometrických a experimentálních datech. V příspěvku je nastíněn potenciál vícezónových modelů propojených s parametrickým generátorem geometrie spalovacího prostoru. Výsledky simulací oběhů zážehového motoru získané pomocí detailního 1-D modelu, který využívá výsledky zónových modelů, jsou porovnávány s experimentálními daty.

KLÍČOVÁ SLOVA: VÍCEZÓNOVÝ MODEL, INVERZNÍ FORMA, PREDIKTIVNÍ FORMA, GEOGEN, PARAMETRICKÝ GENERÁTOR GEOMETRICKÝCH CHARAKTERISTIK, GEOMETRIE SPALOVACÍHO PROSTORU, ZÁŽEHOVÝ MOTOR, MODELOVÁNÍ, 1-D MODEL, GT-POWER

ABSTRACT

The paper deals with the utilization of multi-zone model results in the thermodynamic cycle modeling of a four-stroke spark ignition engine. The principles of a basic multi-zone model are described. The inverse form of the model has been used to obtain the required outputs based on available geometrical and experimental data. The potential of a multi-zone model in conjunction with the generator of combustion chamber geometry is discussed. The SI engine 1-D model, which uses the multi-zone model outputs, is described in detail. A comparison of the engine cycle simulation results with the experimental data concludes this paper.

KEYWORDS: MULTI-ZONE MODEL, INVERSE FORM, PREDICTIVE FORM, GEOGEN, PARAMETRIC GENERATOR OF GEOMETRICAL CHARACTERISTICS, COMBUSTION CHAMBER GEOMETRY, SPARK IGNITION ENGINE, MODELING, 1-D MODEL, GT-POWER

1. INTRODUCTION

The goals of the contribution are to briefly describe the features of multi-zone models of combustion and heat transfer processes in spark ignition engines along with a generator of geometrical characteristics, and to present the first results of various simulation tools. The outputs of a multi-zone model were used in the higher level simulation of a reciprocating internal combustion engine cycle. The connection of various models with different profundity and comprehensiveness can be helpful in cases where required input data are missing. The multi-zone model of combustion and heat transfer in conjunction with the generator of geometrical characteristics could be useful, in particular, at the early stage of the internal combustion engine development process, when the simulation results are based only on models of virtual engines. This paper presents a comparison of simulation results with the data measured on the real combustion engine. The results of the inverse and predictive form of the multi-zone model and the

results of complex engine simulation in GT-Power, which utilizes the multi-zone model outputs, are discussed in the following paragraphs. The basic parameters of the spark ignition gasoline engine tested on the dynamometer are given in Table 1.

Bore [mm]	76.5
Stroke [mm]	86.9
Displacement [dm ³]	1.198
Configuration	3-cylinder in-line
Compression ratio	10.3
Fuel	gasoline
Number of valves per cylinder	2

TABLE 1: Basic parameters of the spark ignition four-stroke engine

TABULKA 2: Základní parametry zážehového čtyřtákního motoru

2. EXPERIMENT AND SIMULATION

2.1 EXPERIMENTAL RESULTS

The mentioned combustion engine has in the past been comprehensively tested at the Josef Božek Research Centre [7], [8]. The engine has been run on common unleaded gasoline Super 95. The measured steady state operating points cover the complete engine characteristics. The values of brake mean effective pressure, air excess (λ) and friction mean effective pressure are given in Figure 1 and Figure 2. The substantial experimental results including measured cylinder pressure were used in the calibration process of the models. The real shape of the combustion chamber of the tested engine is taken as an input parameter for the inverse form of the multi-zone model.

2.2 MULTI-ZONE MODEL

A zone model is a relatively simple method of modeling of the thermodynamic processes in an internal combustion engine. The model consists of a geometrical estimation of the flame surface along with the rate of heat release [10]. The combustion chamber is divided into n zones in the case of a multi-zone model. The zones can touch each other or a border. Mass or heat can be exchanged between zones or between the zone and the surroundings of a combustion chamber. The equation system is based on the conservation of mass and energy and the state equation. The total volume of a combustion chamber, which is a function of piston position, is equal to the sum of the individual zone volumes.

The combustion chamber is divided into the three zones by the flame front borders with a spherical surface in the case of a three-zone model. Zone 1 consists of the fresh fuel-air mixture

and residual gases from previous engine cycle given by residual gases coefficient. Zone 2 consists of components from zone 1 and products of the combustion process in the current zone. Zone 3 contains only the products of combustion. The pressure in the cylinder is identical for all zones. The temperature of each zone is different. The mixture of ideal gases is considered in all zones.

The mass changes of components are based on various principles. The mass transfer across zones is described by turbulent entrainment. This mechanism provides the transfer of a mixture into the flame front and the products of combustion out of the flame zone. The ideal oxidation of a fuel occurs in the flame zone. The chemical equilibrium establishment takes place in cases of afterburning processes in the flame front and combustion products zone. The mass flow rates across the zones depend on the turbulent flame velocity, which is corrected by the turbulent coefficient.

The chemical transformation of fuel-air mixture into the products of combustion is formed by combination of many chemical reactions with various reaction rates. The current multi-zone model utilizes the advanced method for determination of chemical composition changes for complicated chemical systems. The procedure is based on the combination of the kinetic scheme and the method of chemical equilibrium. The computation begins with the kinetic scheme. The problematic reactions with too high reaction rate values are excluded and calculated by the method of chemical equilibrium [3], [4].

The geometrical characteristics define volumes, borders and heat transfer surfaces. These characteristics are defined by

FIGURE 1: Brake mean effective pressure and values of air excess (λ) of all measured working points

OBRÁZEK 1: Střední efektivní tlak a hodnoty přebytků vzduchu (λ) všech měřených pracovních bodů

FIGURE 2: Friction mean effective pressure of all measured working points

OBRÁZEK 2: Ztrátový tlak všech měřených pracovních bodů

FIGURE 3: Example of zone propagation

A: crank angle -10 deg, burned fuel fraction 0.05
 B: crank angle 0 deg, burned fuel fraction 0.30
 C: crank angle 10 deg, burned fuel fraction 0.70
 D: crank angle 20 deg, burned fuel fraction 0.95

OBRÁZEK 3: Příklad šíření zóny

A: úhel natočení klikové hřídele -10 stupňů, podíl spáleného paliva 0.05
 B: úhel natočení klikové hřídele 0 stupňů, podíl spáleného paliva 0.30
 C: úhel natočení klikové hřídele 10 stupňů, podíl spáleného paliva 0.70
 D: úhel natočení klikové hřídele 20 stupňů, podíl spáleného paliva 0.95

the dependence between a geometric element and the three independent variables, crank angle, and forward and backward spherical border surfaces. The total volume of a combustion chamber, volume of each zone, area of border a surface between zones, areas of heat transfer between a zone and inlet valve, exhaust valve, piston, cylinder head and cylinder liner, which is divided into eight areas, are taken into account in the mentioned multi-zone models.

The desired outputs of both forms of the zone model are the plots of the burned fuel fraction and the heat release fraction. The burned fuel fraction is defined as a subtraction of initial fuel mass and sum of fuel masses in all zones divided by the initial mass of fuel. The heat release fraction is defined as a sequential production of heat, normalized by the maximum heat gain

FIGURE 5: Cylinder pressure vs. crank angle; measured pressure (black), output of inverse form of zone model (blue), BMEP=8.5 bar, 3500 RPM

OBRÁZEK 5: Závislost tlaku ve válci na úhlu natočení klikové hřídele, naměřený tlak (černá), výsledek inverzní formy zónového modelu (modrá), BMEP=8.5 bar, 3500 RPM

FIGURE 4: Shape of the combustion chamber, real geometry of measured engine

OBRÁZEK 4: Provedení spalovacího prostoru, reálná geometrie měřeného motoru

according to the initial mass of fuel and its tabulated lower calorific value. The burned fuel fraction plots are utilized by the GT-Power model.

The robustness of the zone model lies in the simple physical description of the flame propagation in the combustion chamber. An example of a zone propagation is given in Figure 3. The experimental data, results of the inverse multi-zone model with the real geometry and the results of the predictive form of the model using the virtual combustion chamber geometry are compared on the following pages.

2.3 INVERSE FORM OF ZONE MODEL

The inverse form of the multi-zone model has been used to obtain the dependence of burned fuel fraction on crank angle. The real geometry of a combustion chamber of the measured engine has been used (Figure 4). The aim of the inverse form of the multi-zone model is to achieve the same cylinder pressure trace as in the case of the measured cylinder pressure during experiments. The pressure traces can be seen in Figure 5. The result depends on the value of the turbulent coefficient,

FIGURE 6: Burned fuel fraction vs. crank angle, result of inverse form of zone model, BMEP=8.5 bar, 3500 RPM

OBRÁZEK 6: Závislost podílu spáleného paliva na úhlu natočení klikové hřídele, výsledek inverzní formy zónového modelu, BMEP=8.5 bar, 3500 RPM

FIGURE 7: Options of present GeoGen version, selected combination of cylinder head type H3 and piston type P2
OBRÁZEK 7: Varianty současné evoluce GeoGen, označena vybraná kombinace hlavy válce (typ H3) a pístu (typ P2)

which influences the turbulent flame velocity. The turbulent flame velocity affects the fresh mixture transfer into the flame front and consequently the heat release. The correct turbulent coefficient values have been determined by the iterative procedure [6]. The measured cylinder pressure has been used for calibration of the multi-zone model by the inverse form of the code. The model uses the measured cylinder pressure before ignition and the temperature of the cylinder filling calculates via the state equation. The proper turbulent coefficient, for the best agreement of pressure traces, has been determined for all engine operating points. The turbulent coefficient values of each operating point

from the inverse model were used for simulation of the predictive model. The traces of the burned fuel fraction of all engine working points serve as input data for the GT-Power simulation. The dependence of burned fuel fraction on crank angle of the specific operating point is shown in Figure 6.

2.4 GEOGEN - GENERATOR OF GEOMETRICAL CHARACTERISTICS

The GeoGen is the parametric generator of geometrical characteristics of the combustion chamber. The GeoGen in conjunction with the predictive form of the multi-zone model may be helpful for estimation of promising variants at the beginning of a project. The available types of cylinder heads and pistons of the current generator are shown in Figure 7. The ability of the GeoGen to create the relevant combustion chamber geometry has been tested on the example of the mentioned spark ignition engine. The requirements on the model were: bore and clearance volume consistent with the real measured engine, two valves per cylinder and a simple piston shape. The combination of cylinder head type H3 and piston type P2 was selected and the geometrical characteristics were generated for this combination. The shape of the virtual combustion chamber is shown in Figure 8.

FIGURE 8: Shape of the combustion chamber, geometry generated by GeoGen, cylinder head H3 + piston P2
OBRÁZEK 8: Tvar spalovacího prostoru, geometrie generována pomocí GeoGen, hlava válců H3 + píst P2

2.5 PREDICTIVE FORM OF ZONE MODEL

The predictive form of the multi-zone model may be a worthwhile simulation tool at the early stage of an internal combustion engine development. The contribution of the model lies in the preliminary layout of the combustion chamber, spark plug position, prediction of the rate of heat release and perhaps even the knock resistance of the engine. The predictive zone model may become an alternative simulation method for the high-pressure part of the engine cycle. The connection of the model with higher level simulation, such as GT-Power [2], is worth considering.

The initial conditions and required tuning parameters of the predictive three-zone model were assumed from the inverse form of the model. The most important tuning parameter was the turbulent coefficient. The predictive form of the multi-zone model uses the virtual combustion chamber shape generated by GeoGen (Figure 8). The comparison of the cylinder pressure traces (measured pressure – black, output of inverse model – blue and output of predictive model – purple) is shown in Figure 9. The burned fuel fractions are displayed in Figure 10.

2.6 ENGINE MODEL

The detailed model of the measured 3-cylinder spark ignition gasoline engine was built in GT-Power and calibrated using the experimental data and the results of the inverse and predictive forms of the multi-zone model. The GT-Power simulation utilizes the traces of the burned fuel fraction generated by the zone model as an input data for the user model of combustion. The model uses the fuel with the lower

heating value 41.8 MJ/kg. The values of air excess (λ) in all models were the same as measured in experiments. The important geometrical data and layout of the essential engine parts were obtained by the measurement of the real engine and inserted into the mathematical model. The valve lifts, flow discharge coefficients and the layout of the combustion chamber were available. The model of mechanical losses uses the values of friction mean effective pressure, evaluated during the experiments, directly without any extrapolation or interpolation of the data. The pressure upstream of a catalytic converter model has been calibrated to provide reasonable accordance with the experimental values. The finite element model was applied for calculation of the combustion chamber temperatures. The combustion model includes the crank angles of the combustion beginning of each engine operating point and the corresponding dependences of the burned fuel fraction on crank angle. All available data are entered directly into the solver. Two versions of the model have been built. The first version is based on the results of the inverse form of the multi-zone model, which uses the real geometry of the combustion chamber and experimental data. The second version utilizes the results of the combustion process of the predictive model based on the geometrical characteristics generated by GeoGen. The measured values, results of the GT-Power simulation with the traces of burned fuel fraction from the inverse model and from the predictive model are compared in the pictures. The comparison of the brake mean effective pressures of all operating points is shown in Figure 11, the measured values (black), the simulation with the data from the inverse model (red) and the simulation

FIGURE 9: Cylinder pressure vs. crank angle; measured pressure (black), output of inverse form of zone model (blue), result of predictive form of zone model (purple), BMEP=8.5 bar, 3500 RPM

OBRAZĚK 9: Závislost tlaku ve válci na úhlu natočení klikové hřídele, naměřený tlak (černá), výsledek inverzní formy zónového modelu (modrá), výsledek prediktivní formy zónového modelu (fialová), BMEP=8.5 bar, 3500 RPM

FIGURE 10: Burned fuel fraction vs. crank angle; results of inverse (blue) and predictive (purple) forms of zone model, BMEP=8.5 bar, 3500 RPM

OBRAZĚK 10: Závislost podílu spáleného paliva na úhlu natočení klikové hřídele, výsledky inverzního (modrá) a prediktivního modelu (fialová), BMEP=8.5 bar, 3500 RPM

FIGURE 11: Brake mean effective pressure of all operating points; measured values (black), results of GT-Power simulation with data from inverse form of zone model (red), results of GT-Power simulation with data from predictive form of zone model (green)

OBRÁZEK 11: Střední efektivní tlak všech pracovních bodů, naměřené hodnoty (černá), výsledky simulace v GT-Power s daty získanými pomocí inverzní formy zónového modelu (červená), výsledky simulace v GT-Power s daty z prediktivního zónového modelu (zelená)

FIGURE 12: Brake specific fuel consumption of all operating points; measured values (black), results of GT-Power simulation with data from inverse form of zone model (red), results of GT-Power simulation with data from predictive form of zone model (green)

OBRÁZEK 12: Měrná spotřeba paliva všech pracovních bodů, naměřené hodnoty (černá), výsledky simulací v GT-Power s daty z inverzního modelu (červená), výsledky simulací v GT-Power s daty získanými pomocí prediktivního zónového modelu (zelená)

FIGURE 14: Trace of heat release fraction vs. crank angle; results of predictive form of zone model (purple), inverse form of zone model (blue), GT-Power simulation with data from predictive form of zone model (green), GT-Power simulation with data from inverse form of zone model (red), BMEP=8.5 bar, 3500 RPM

OBRÁZEK 14: Průběh vývinu tepla v závislosti na úhlu natočení klikové hřídele, výsledky prediktivního zónového modelu (fialová), inverzního zónového modelu (modrá), GT-Power simulace s využitím dat z prediktivní formy (zelená), GT-Power simulace s daty z inverzní formy zónového modelu (červená), BMEP=8.5 bar, 3500 RPM

FIGURE 15: Trace of cylinder pressure vs. crank angle; measured pressure (black), result of GT-Power simulation with data from predictive form of zone model (green), result of GT-Power simulation with data from inverse form of zone model (red), BMEP=8.5 bar, 3500 RPM

OBRÁZEK 15: Průběh tlaku ve válci v závislosti na úhlu natočení klikové hřídele, naměřený tlak (černá), výsledek simulace v GT-Power s daty z prediktivního modelu (zelená), výsledek simulace v GT-Power s daty z inverzní formy zónového modelu (červená), BMEP=8.5 bar, 3500 RPM

FIGURE 13: Maximum cylinder pressure of all operating points; measured values (black), results of GT-Power simulation with data from inverse form of zone model (red), results of GT-Power simulation with data from predictive form of zone model (green)

OBRÁZEK 13: Maximální tlak oběhu všech pracovních bodů, naměřené hodnoty (černá), výsledky simulací v GT-Power s daty z inverzního zónového modelu (červená), výsledky simulací v GT-Power s daty z prediktivního zónového modelu (zelená)

FIGURE 16: p-V diagram; measured trace (black), result of GT-Power simulation with data from predictive form of zone model (green), result of GT-Power simulation with data from inverse form of zone model (red), BMEP=8.5 bar, 3500 RPM

OBRÁZEK 16: p-V diagram, naměřený průběh (černá), výsledek simulace v GT-Power s daty z prediktivního modelu (zelená), výsledek simulace v GT-Power s daty z inverzní formy zónového modelu (červená), BMEP=8.5 bar, 3500 RPM

with the data from the predictive model (green). The brake specific fuel consumption values are given in Figure 12 and the maximum pressures of the engine cycle are given in Figure 13. The difference in values of maximum cylinder pressure at the two highest load and speed points is caused by the in-cylinder heat transfer model. The applied Woschni heat transfer model is not totally suitable in the case of the natural aspirated spark ignition engines. Simulation with the Eichelberg formula will be performed in the future.

The heat release fraction traces are compared in Figure 14. There are plotted the outputs of the inverse zone model (blue), the predictive zone model (purple), the simulation based on the inverse form (red) and the simulation based on the predictive form (green). The cylinder pressure traces are shown in Figure 15 and the corresponding p-V diagram is displayed in Figure 16.

3. CONCLUSION

The goals of the paper were to present the main features of multi-zone models of combustion and heat transfer processes in spark ignition engines and to show the results of various simulation tools compared with the experimental data.

The inverse form of the multi-zone model is suitable for model calibration, which utilizes the measured cylinder pressure and the real geometry of a combustion chamber of the tested engine. The GeoGen is the parametric generator of geometrical characteristics of an arbitrary combustion chamber. The ability of the predictive model in conjunction with the GeoGen has been tested and verified on the example of the mentioned real combustion engine. The predictive zone model is based on the generated virtual geometrical characteristics and the calibration coefficients from the inverse form of the model. Both versions of the zone model have been used to determine the dependence of burned fuel fraction on crank angle of all operating points of the engine. The results of the inverse and predictive forms of the multi-zone model and GT-Power detailed simulations, which utilize the zone model outputs – the traces of burned fuel fractions, were compared with the experimental data.

The predictive form of the multi-zone model along with the generator of geometrical characteristics – GeoGen may be a worthwhile simulation tool, in particular at the early stage of an internal combustion engine development. The contribution of the model consists in the preliminary layout of the combustion chamber, spark plug position, prediction of the rate of heat release and perhaps even the knock resistance of the engine. The zone model potential is also in the prediction of emissions production by virtue of information about the local

temperature distribution and utilization of the kinetic scheme combined with the method of chemical equilibrium. The predictive zone model may become an alternative simulation method for the high-pressure part of the engine cycle. The future development of the zone model will focus on the improvement of the combination of the kinetic scheme and the method of chemical equilibrium and on the research of the knocking prediction. It is necessary to test the ability of the predictive model and GeoGen on several different combustion engines. Further steps for the development of this method are the modeling of in-cylinder heat transfer using the Eichelberg formula and the direct connection of the zone model with the higher level simulation.

ACKNOWLEDGEMENT

The work has been supported by the Centralized Development Project CSM 100 – TALENT of Ministry of Education, Youth and Sports, Czech Republic (MŠMT CSM 100 – TALENT). This research has been realized using the support of EU Regional Development Fund in OP R&D for Innovations (OP VaVpl) and Ministry for Education, Czech Republic, project # CZ.1.05/2.1.00/03.0125 Acquisition of Technology for Vehicle Center of Sustainable Mobility and the support of Technological Agency, Czech Republic, programme Centres of Competence, project # TE01020020 Josef Božek Competence Centre for Automotive Industry. All the support is gratefully acknowledged.

REFERENCES

- [1] HEYWOOD, J. B. (1988). [Internal Combustion Engine Fundamentals](#). McGraw-Hill series in mechanical engineering, printed in USA. McGraw-Hill. ISBN 0-07-028637-X.
- [2] GT-POWER (2009). User's manual and Tutorial GT-Suite version 7.0, Gamma Technologies Inc.
- [3] HVĚZDA, J. (2011) [Multi-Zone Models of Combustion and Heat Transfer Processes in SI Engines](#). SAE Paper 2011-37-0024.
- [4] HVĚZDA, J. (2011). Species Chemical Transformation Description using Combination of Chemical Kinetics and Chemical Equilibrium. In: KOKA 2011. Žilina. University of Žilina. 2011.
- [5] HVĚZDA, J. (2009). Multi-Zone Models of Combustion and Heat Transfer Processes in SI Engines. [Journal of Mecca](#), number 02 2009, volume VI.
- [6] HVĚZDA, J. (2010). Inverse Form of Multi-Zone Model of Combustion and Heat Transfer Processes in SI Engines. [Journal of Mecca](#), number 02 2010, volume VIII.
- [7] EMRICH, M., FUENTE, D., RUDOLF, M. (2010). Measurement of Friction in Internal Combustion Engine. In: KOKA 2010. Liberec. Technical University of Liberec.
- [8] MACEK, J., FUENTE, D., EMRICH, M. (2010). Friction Measurements of Internal Combustion Engines and Comparison with Semi-empirical Code. In: KOKA 2010. Liberec. Technical University of Liberec.
- [9] POULOS, S., HEYWOOD, J. (1983). [The Effect of Chamber Geometry on Spark-Ignition Engine Combustion](#). SAE Technical Paper 830334. 1983, doi:10.4271/830334.
- [10] MACEK, J., STEINER, T. (1995). Advanced Multizone Multidimensional Models of Engine Thermoaerodynamics. 21th CIMAC Congress 1995, Interlaken 1995.