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Genetic-fuzzy model of diesel engine working cycle

M. KEKEZ* and L. RADZISZEWSKI

Faculty of Mechatronics and Machine Building, Kielce University of Technology,
7 Tysiąclecia Państwa Polskiego Ave., 25-314 Kielce, Poland

Abstract. This paper concerns measurement and modeling of cylinder pressure in diesel engines. The aim of this paper is to build the empirical-analytical model of engine working cycle. The experiments on engine test bench were conducted. The new genetic-fuzzy system GFSm was proposed. By means of GFSm, the engine working cycle model was built. This model allows simulation of cylinder pressure for each allowable crankshaft speed, and loads and also for several biofuels. The model can be used to evaluate the quality of working cycles of piston engine with an accuracy required in practical technical applications.

Key words: diesel engines, modeling, fuzzy systems, genetic algorithms, biofuels.

1. Introduction

The control system of internal combustion engine should allow checking and manipulating the fuel supply process and combustion of the fuel during every working cycle of the engine. In order to achieve this, the measurement of cylinder pressure must be performed. Having known pressure curve, we can calculate a series of important values such as: mean indicated pressure, indicated power, start point of ignition, relative air/fuel ratio.

Experimental tests can be partially replaced by appropriate models that describe engine work. Empirical models (based on the first law of thermodynamics [1]) as well as Computational Fluid Dynamics models [2] are well known. Expert systems, artificial neural networks, genetic algorithms [3], fuzzy logic [4] and neuro-fuzzy networks [5] in such technical applications are still relatively rarely used. They can easily represent nonlinear systems and they have ability to self-train as well. Moreover, they can be applied in various controllers.

Most publications about engine modeling with the use of artificial intelligence methods concern the control of engine work [6] and exhaust gas emission [7, 8]. Spray penetration in the diesel engine, depending on fuel pressure and density, was also modeled, by means of the neuro-fuzzy system [9]. The review of literature shows that existing engine work models, both numerical and analytical, have some limitations which make it difficult to use them in practice.

The aim of the paper is to develop a genetic-fuzzy system for modeling of diesel engine operation. The results of experimental research were used to build the empirical-analytical model of engine working cycle.

2. Test stand

Experimental research was made on a test stand which consisted of: the diesel engine Perkins AD3.152UR, water brake, and control panel. Pressure was measured by quartz piezoelectric transducers and injector needle lift was measured by

an inductive displacement sensor [10]. Measured values were recorded as a function of crankshaft rotation angle, in degrees (°CA). The value of rotation angle was recorded by a rotary pulse transducer and a system of marking and synchronization of crankshaft position.

The necessary measurements of cylinder pressure curves were made on the test bench. The engine operated in external speed characteristic and load characteristic regimes, with the crankshaft speeds 1000, 1200, 1400, 1600, 1800 and 2000 rpm. The engine was fueled by diesel oil, and biofuels: methyl esters of rapeseed oil (FAME) and its blends. Cylinder pressure values were recorded every 1.4°CA (exactly 512 measurements for one working cycle of 4-stroke engine). At each measurement point, values of parameters were recorded, for 50 consecutive working cycles. Indicator diagrams, acquired in this way, were averaged thereafter.

3. Results of experimental research and modeling of pressure curves

Figures 1a and 1b show indicator diagrams of cylinder pressure, in the ranges of 180–540 and 340–390°CA, acquired for different rotational speeds. For the latter range, the differences between pressure curves for different rotational speeds are noticeable. Pressure starts to increase rapidly when it reaches 3.5 to 4 MPa, and when crankshaft rotation angle lies between 353° and 359°CA, but exact moment depends on rotational speed. When rotational speed of crankshaft increases, the maximum value of cylinder pressure decreases from 8.7 to 8 MPa, but the crankshaft angle, at which it appears, increases from 367 to 371°CA. Maximum value of the slope of the tangent to the pressure curve decreases from 1.17 to 0.65 MPa/°CA with the increase of rotational speed. Knowledge of first and second derivative of pressure curve with respect to crankshaft rotation angle allows determining the start of self-ignition, which was about 352°CA.

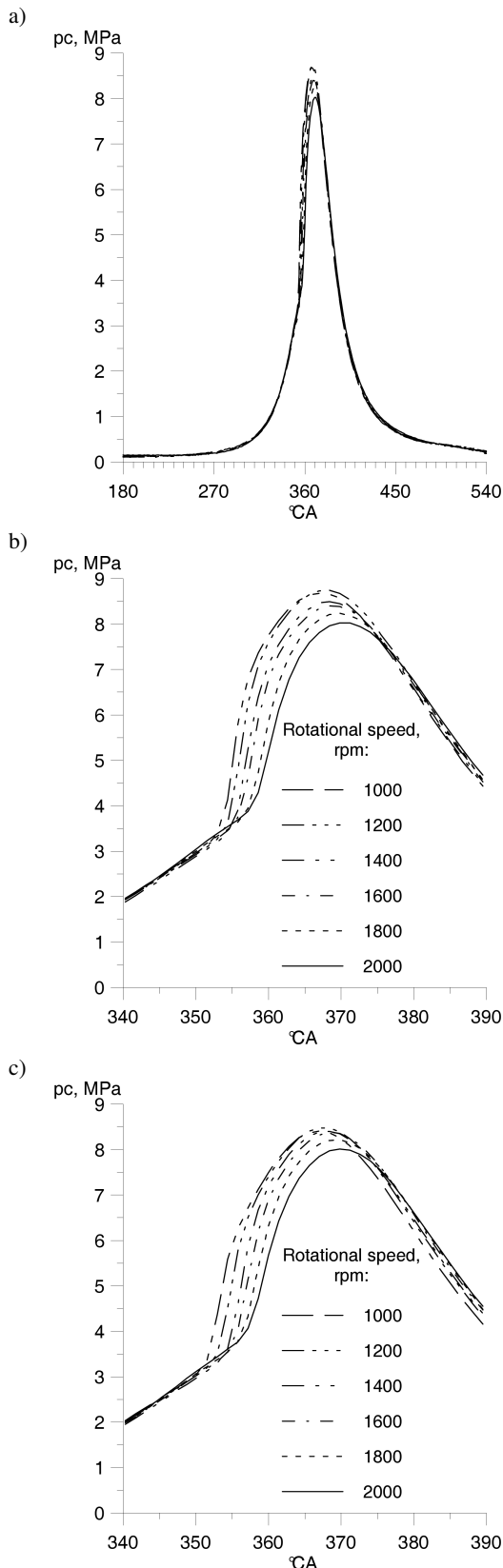*e-mail: m.kekez@tu.kielce.pl

a)

b)

c)

Fig. 1. Indication diagram of cylinder pressure in diesel engine in function of crankshaft rotation angle, for different CA speeds: a) fueled by diesel oil, in the range of 180–540°, b) fueled by diesel oil, in the range of 340–390°, c) fueled by FAME, in the range of 340–390°

The pressure curves for the engine fueled by FAME (Fig. 1c) are very similar to those presented in Fig. 1a,b. The main differences are in absolute values of investigated parameters. Maximum value of cylinder pressure lies in the range of 8 to 8.5 MPa. Mean indicated pressure varies from 0.95 to 1.08 MPa. Maximum value of the slope of the tangent to the pressure curve decreases from 0.92 to 0.68 MPa/°CA when crankshaft rotational speed increases from 1400 to 2000 rpm.

Selected pressure curves for diesel engine fueled by blends of diesel oil and FAME, called B10, B20 and B30 (which contain 10, 20, and 30 percent of FAME, respectively) are presented in Fig. 2. Cylinder pressure curves are similar for all fuels that were used in experiments. For this reason, the analysis of results for B10, B20, and B30 blends is presented only for crankshaft rotational speed of 1200 rpm. Figure 2 shows that pressure starts to increase rapidly at 2.8 to 3.2 MPa, and at crankshaft position of 352°CA. Maximum cylinder pressure ranges from 8.3 to 8.6 MPa. Maximum value of the slope of the tangent to the pressure curve is almost identical for all fuels in the range of 353 to 354.5°CA (the values lie between 0.95 and 1.03 MPa/°CA). Analysis of the first derivative of cylinder pressure as a function of crankshaft rotation angle shows that the self-ignition of the examined biofuels starts about 2°CA earlier than the self-ignition of diesel oil [10, 11].
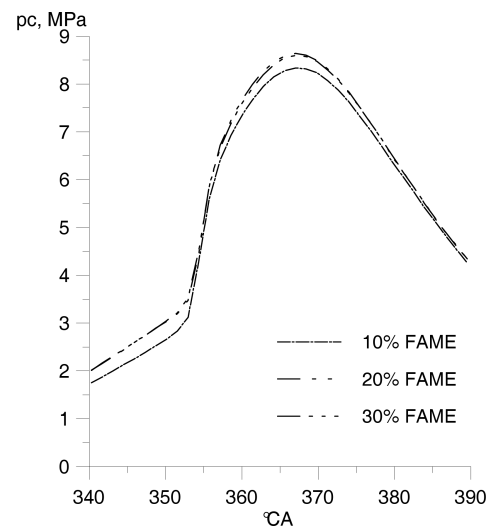

Fig. 2. Indication diagram of cylinder pressure in diesel engine fueled by blends of diesel oil and FAME, in function of crankshaft rotation angle, for crankshaft speed 1200 rpm

The results of experimental measurements when the engine was fueled by diesel oil were used to build the model of engine working cycle, by the method from the field of artificial intelligence (based on fuzzy sets theory). The obtained model was later "tuned" for modeling the operation of engine fueled by other biofuels.

The calculations were made by means of GFSm system, proposed by the authors [11], and rated among genetic-fuzzy systems [12, 13]. GFSm system creates Mamdani (Fig. 3) or Takagi-Sugeno fuzzy model, which describes relations between input and output variables, and given phenomena or process.
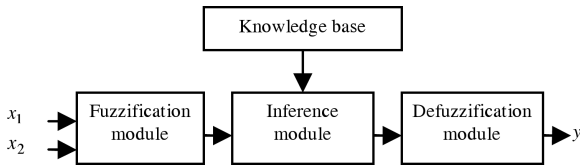
Fig. 3. Mamdani-type fuzzy model with two input variables x_1 and x_2, and one output variable y
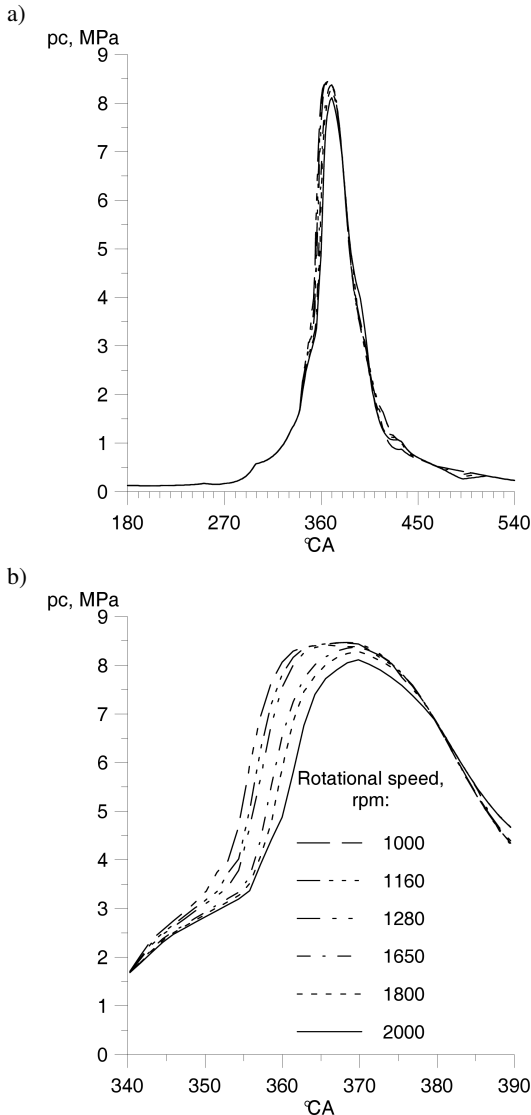
a)

b)

Fig. 4. Computed by the fuzzy system, relationships between cylinder pressure (in engine fueled by diesel oil) and crankshaft rotation angle, for different crankshaft speeds in the range of: a) 180–540°CA, b) 340–390°CA

In experimental research conducted on a test stand the engine was fueled by diesel oil or biofuels. In our calculations we used measurement data for diesel oil to create fuzzy model (and to test its accuracy) by means of GFSm [11] system. The acquired fuzzy model had two inputs, x_1 (crankshaft rotation angle), x_2 (time value, proportional to rotational speed

of crankshaft), and one output, y (cylinder pressure value). The model predicts the value of cylinder pressure (y) for all possible values of crankshaft angle and rotational speed (x_1, x_2) in the engine fueled by diesel oil.

Relationships between input and output variables are collected in the knowledge base, which consists of a set of rules and a set of membership functions of fuzzy sets used in rules. GFSm system builds the fuzzy model on the basis of training data, respecting the settings for the number of rules and number of fuzzy sets [11].

The GFSm system created several models which had different number of rules, depending on program settings. Training data, used in experiments, contained pressure curves only for speeds 1000 and 1800 rpm of CA. The single model built by GFSm describes pressure curves for all allowable crankshaft speeds. With settings "maximum number of fuzzy sets describing one input = 50", "models with small number of rules preferred" and "each rule in the knowledge base must contain a condition (premise) regarding x_1 variable" (this variable represents the crankshaft rotation angle), GFSm system built the model. The acquired model is rather general (only 12 rules) and describes pressure curves for all crankshaft speeds. Figure 4 shows "model" curves (computed with use of this model). We have computed pressure curves for crankshaft rotational speed of 1000, 1800, 2000 rpm as well as for 1160, 1280, and 1650. The first three curves one can compare with the experimental curves. The last three curves showed us the computing power of GFSm model.

The comparison of selected "model" and experimental curves presents Fig. 5. The error of prediction of mean indicated pressure by GFSm model is less than 5% (with regard to experimental data) for all measured crankshaft speeds. Error of prediction of maximum pressure value does not exceed 3.3%. All pressure curves are calculated with high accuracy – root mean square error (RMSE) remains in the range of 0.07 to 0.13 MPa.

The results of measurements of a cylinder pressure curves acquired on the test bench when the engine operated in load characteristic regimes (Fig. 7) were used to complete the existing model with rules describing part-load conditions. Training data for GFSm system consisted of (x_1, x_2, x_3, y) records, where x_1 is crankshaft rotation angle, x_2 – total time of fuel injection (counted as a number of measurements, for which the injector needle lift was bigger than 0.04 mm), x_3 – time counted since the beginning of fuel injection, y – cylinder pressure value. With program settings "maximum number of fuzzy sets describing one input = 30", "models with small number of rules preferred" and "each rule in the knowledge base must contain a condition regarding x_1 variable", the GFSm system created 13 rules for part-load conditions (Fig. 6).

A comparison of "model" and experimental curves for selected load presents Fig. 8. The maximum pressure error does not exceed 5.6% for all loads whereas mean indicated pressure error does not exceed 9.0%.
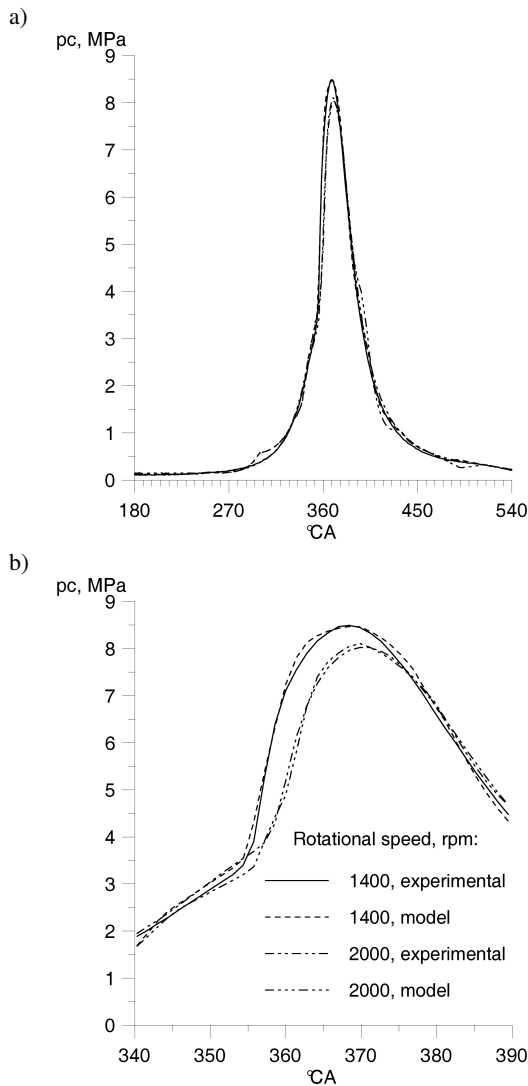
a)

b)

Fig. 5. Comparison of experimental and computed by the fuzzy system (Mamdani model), relationship between cylinder pressure (in engine fueled by diesel oil) and crankshaft rotation angle, for different crankshaft speeds in the range of: a) 180–540°CA, b) 340–390°CA
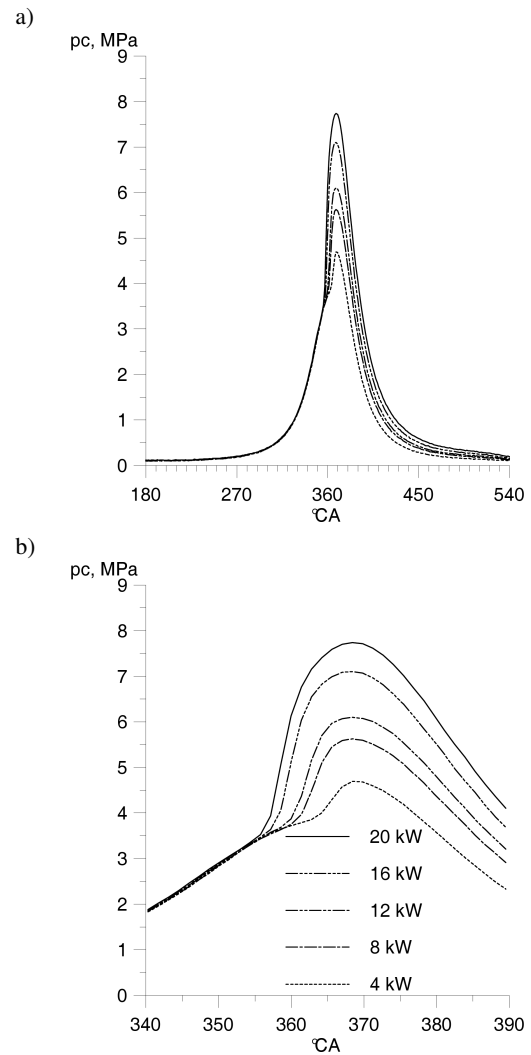
a)

b)

Fig. 7. Indication diagram of cylinder pressure in diesel engine fueled by diesel oil and operating in load characteristic regime, in function of crankshaft rotation angle, for crankshaft speed 1400 rpm and loads of 4, 8, 12, 16, and 20 kW: a) in the range 180–540°, b) in the range 340–390°

if x_1 is $A_{1,1}$ and x_3 is $A_{3,1}$ then y is B_1
if x_1 is $A_{1,7}$ and x_2 is $A_{2,1}$ then y is B_1
if x_1 is $A_{1,8}$ and x_2 is $A_{2,4}$ then y is B_1
if x_1 is $A_{1,9}$ and x_2 is $A_{2,2}$ then y is B_1
if x_1 is $A_{1,10}$ then y is B_1
if x_1 is $A_{1,3}$ and x_3 is $A_{3,3}$ then y is B_2
if x_1 is $A_{1,11}$ and x_3 is $A_{3,1}$ then y is B_2
if x_1 is $A_{1,2}$ and x_2 is $A_{2,5}$ and x_3 is $A_{3,4}$ then y is B_3
if x_1 is $A_{1,4}$ then y is B_4
if x_1 is $A_{1,6}$ then y is B_5
if x_1 is $A_{1,9}$ and x_2 is $A_{2,6}$ and x_3 is $A_{3,2}$ then y is B_6
if x_1 is $A_{1,5}$ and x_2 is $A_{2,3}$ then y is B_7
if x_1 is $A_{1,5}$ then y is B_8

Fig. 6. The model of engine working cycle created by GFSm system for part-load conditions, where $A_{i,j}$ denotes j-th fuzzy set which describes i-th input, and B_j − j-th fuzzy set describing y output
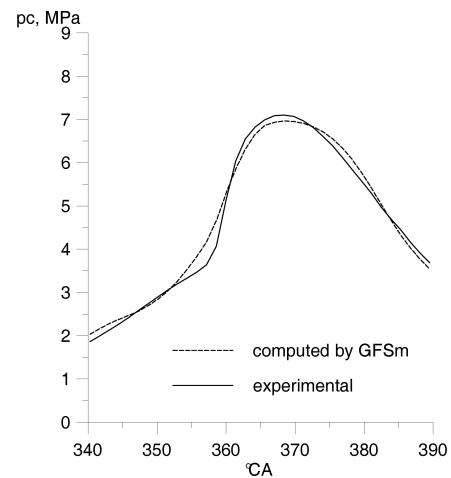

Fig. 8. Comparison of experimental and computed by the fuzzy system, relationship between cylinder pressure (in engine fueled by diesel oil) and crankshaft rotation angle, for crankshaft speeds of 1400 rpm and the load of 16 kW

4. Extension of the proposed model

The model produced by GFSm system predicts cylinder pressure for all possible rotational speeds in engine fueled by diesel oil, as it was presented in the previous section. In order to predict such a pressure curve for another fuel (e.g. FAME or its blends with diesel oil), we added two scaling functions to basic GFSm system: one for input scaling and another for output scaling (Fig. 9). Values of parameters of these functions vary for each fuel. In order to find these values, we measured a cylinder pressure curve only for one rotational speed that was arbitrarily chosen (e.g. 1200 rpm) when the engine was fueled by given fuel other than diesel oil. We used this curve to find the parameters of scaling functions [11], which enabled us to calculate pressure curve for any rotational speed of crankshaft.
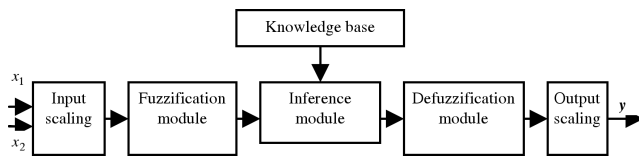

Fig. 9. Mamdani-type fuzzy model (with scaling functions) having two input variables, x_1 and x_2, and one output variable, y

The results of scaling were quite good. Moreover, we obtained also a new GFSm Takagi-Sugeno model for diesel oil, which had better accuracy (maximum pressure error less than 2.1% and mean indicated pressure error less than 3.9% for all rotational speeds) than the Mamdani one, Fig. 10.
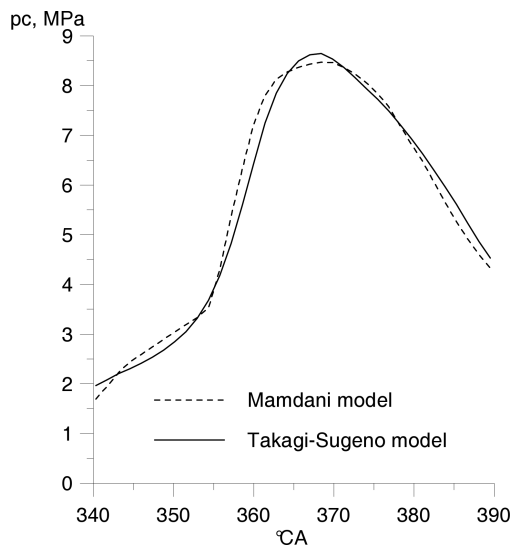

Fig. 10. Comparison of cylinder pressure curves computed by two fuzzy systems, Mamdani and Takagi-Sugeno, for a crankshaft speed of 1400 rpm

The difference between two fuzzy models, produced by GFSm system (Mamdani model and Takagi-Sugeno model) is shown in Fig. 10. Generally, the Takagi-Sugeno model has better accuracy of prediction of mean indicated pressure and maximum pressure for some rotational speeds. Moreover, in the range of 340 to 355°CA, the pressure curve produced

by Takagi-Sugeno model is "smoother" than the one produced by Mamdani model. Nevertheless, the Mamdani model better describes fast pressure change in the range of 355 to 365°CA.

Later, we measured cylinder pressure curves at 1200 rpm for other investigated fuels, and calculated parameters of scaling functions. The resulting models (Fig. 11, 12) had also very good accuracy (maximum pressure error less than 4.3% and mean indicated pressure error less than 4.5% for all rotational speeds).
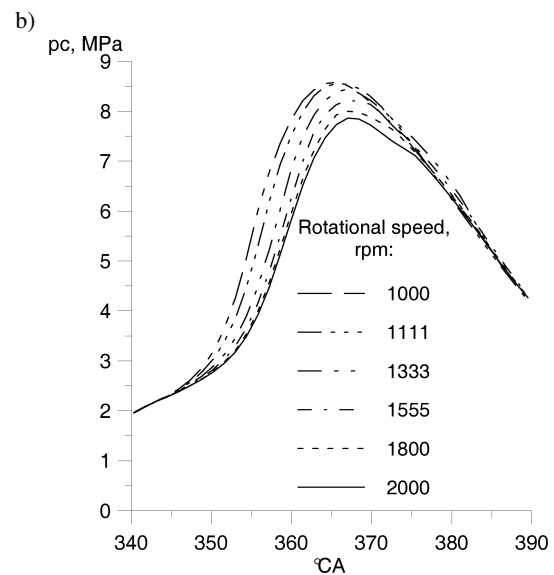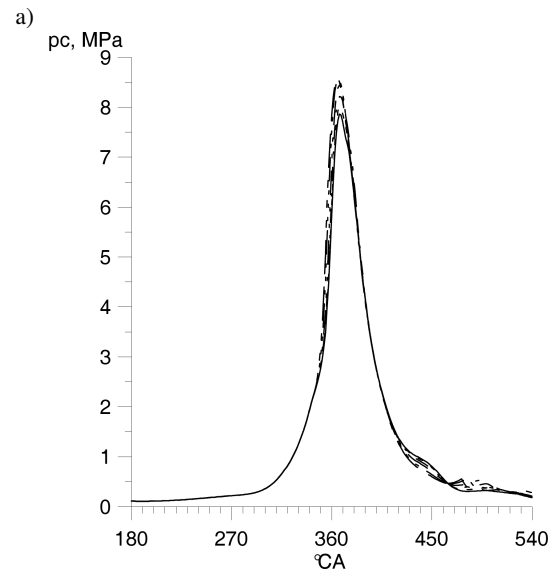

Fig. 11. Computed by the GFSm system (Takagi-Sugeno model), relationships between cylinder pressure in engine (fueled by FAME) and crankshaft rotation angle, for different crankshaft speeds in the range of: a) 180–540°CA, b) 340–390°CA

The accuracy of Takagi-Sugeno model for engine fueled by diesel oil, B10 blend and FAME is shown in Fig. 13 and in Table 1. For diesel oil, maximum pressure error does not exceed 2.1% whereas mean indicated pressure error does not exceed 3.9%. The respective errors for FAME are 2.6% and

4.1%, and for the blends of diesel oil and FAME are higher, up to 4.5%. But in technical applications such accuracy is rather acceptable. The obtained GFSm model is not precise enough in the range of 355° to 370°CA (very important for combustion processes) and should be "tuned". In this range the difference between the value of the slope of the tangent to the experimental and computed pressure curve is too high, for all rotational speeds.
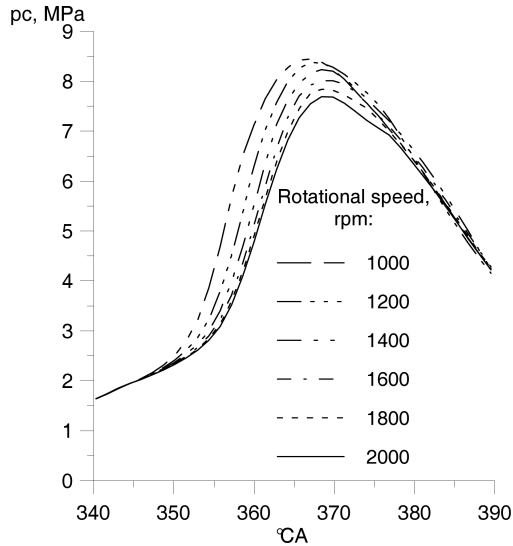

Fig. 12. Computed by the GFSm system (Takagi-Sugeno model), relationships between cylinder pressure in engine (fueled by B10) and crankshaft rotation angle, for different crankshaft speeds in the range of 340–390°CA

Table 1

Accuracy of Takagi-Sugeno model for diesel engine working at 1400 rpm fueled by diesel oil, B10 and FAME

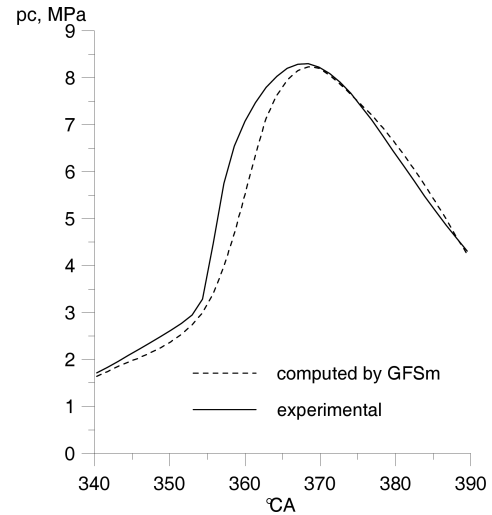| n, [rpm]	diesel oil	B10	FAME
mean indicated pressure error			
1000	0.48%	0.92%	4.06%
1200	−1.27%	0.14%	0.11%
1400	3.89%	0.36%	0.20%
1600	3.49%	−2.75%	−1.28%
1800	1.36%	−4.46%	−2.52%
2000	−2.87%	−3.97%	−3.77%
maximum pressure error. %			
1000	2.05%	2.06%	2.02%
1200	0.48%	0.50%	0.48%
1400	1.81%	−0.76%	−0.26%
1600	0.42%	−3.55%	−2.59%
1800	0.25%	−4.24%	−2.59%
2000	1.30%	−3.04%	−1.82%

Fig. 13. Comparison of experimental and computed by the fuzzy system (Takagi-Sugeno model), relationship between cylinder pressure and crankshaft rotation angle in diesel engine working at 1400 rpm when fueled by B10

5. Concluding remarks

During experimental research the engine was fueled by diesel oil and biodiesel, and the cylinder pressure curves were recorded as a function of crankshaft rotation angle or load. The obtained indicator diagrams were analyzed in the range of 180 to 540°CA, because this enables us to assume that processes in engine cylinder take place in a thermodynamically closed system. The results of experimental research conducted on an engine test bench were used to build analytical-empirical model of engine working cycle, based on fuzzy sets theory. In order to achieve this, the new genetic-fuzzy system GFSm with advanced information encoding and adjustable number of rules, being a modification of Pittsburgh approach, was designed. Using this system, two models of cylinder pressure curves were built. The best accuracy in terms of maximum pressure error and indicated work error (less than 5% for each examined crankshaft speed) was achieved by Mamdani-type GFSm model comprising 12 rules. The model allows simulation of cylinder pressure curves with high accuracy, for all allowable crankshaft speeds. Time of computation and saving the results to disk is 0.04 s. The model can be extended (by means of scaling functions) for modeling pressure curves for the engine fueled by different fuels. There is also a possibility to model selected fragments of pressure curves more precisely (e.g. places where pressure changes are fastest), by means of a separate model. The proposed model can be used to evaluate the quality of working cycles of internal combustion engines, with the accuracy required in practical technical applications. The results obtained in this work can be used for regulation, evaluation and control of the engine working cycle. They also give opportunity to evaluate the usefulness and relevance of fueling the engine with certain biofuel.

REFERENCES

[1] T. Rychter and A. Teodorczyk, *Theory of Piston Engines*, Wydawnictwa Komunikacji i Łączności, Warszawa, 2006, (in Polish).

[2] A.A. Amsden, *KIVA-3V: a Block-Structured KIVA Program for Engines with Vertical or Canted Valves,* Los Alamos National Laboratory, Los Alamos, 1997.

[3] R. Gessing, "Whether the opinion about superiority of fuzzy controllers is justified", *Bull. Pol. Ac.: Tech.* 58 (1), 59–65 (2010).

[4] T. Witkowski, P. Antczak, and A. Antczak, "Multi-objective decision making and search space for the evaluation of production process scheduling", *Bull. Pol. Ac.: Tech.* 57 (3), 195–208 (2009).

[5] S.A. Kalogirou, "Artificial intelligence for the modeling and control of combustion processes: a review", *Progress in Energy and Combustion Science* 29, 515–566 (2003).

[6] F. Kimmich, A. Schwarte, and R. Isermann, "Fault detection for modern Diesel engines using signal- and process model-based methods", *Control Eng. Practice* 13, 189–203 (2005).

[7] K. Brzozowski, and J. Nowakowski, "An application of artificial neural network to exhaust emission modelling from diesel engine", *J. KONES* 12 (1–2), 51–58 (2005).

[8] S. Jakubek and N. Keuth, "A local neuro-fuzzy network for high-dimensional models and optimization", *Eng. Applications of Artificial Intelligence* 19, 705–717 (2006).

[9] S.H. Lee, R.J. Howlett, S.D. Walters, and C. Crua, "Fuzzy logic and neuro-fuzzy modelling of diesel spray penetration: a comparative study", *J. Intelligent and Fuzzy Systems* 18 (1), 43–56 (2007).

[10] D. Kurczyński, "Influence of vegetable fuels and its blends with diesel oil on parameters of work of compression ignition engine", *PhD Thesis*, Kielce University of Technology, Kielce, 2007.

[11] M. Kekez, "Modeling of work of compression ignition internal combustion engine with use of artificial intelligence methods", *PhD Thesis*, Kielce University of Technology, Kielce, 2008.

[12] O. Cordon, F. Gomide, F. Herrera, F. Hoffman, and L. Magdalena, "Ten years of genetic fuzzy systems: current framework and new trends", *Fuzzy Sets and Systems* 141, 5–31 (2004).

[13] O. Cordon, F. Herrera, F. Hoffman, and L. Magdalena, *Genetic Fuzzy Systems: Evolutionary Tuning and Learning of Fuzzy Knowledge Bases* (*Advances in Fuzzy Systems – Applications and Theory* 19), World Scientific, Singapore, 2001.