TRANSACTIONS OF THE INSTITUTE OF AVIATION
1 (250) 2018, pp. 36–48
DOI: 10.2478/tar-2018-0004

THERMODYNAMIC MODEL OF THE ASZ-62IR RADIAL AIRCRAFT ENGINE

Paweł Magryta, Konrad Pietrykowski, Michał Gęca
Department of Thermodynamics, Fluid Mechanics and Aviation Propulsion Systems,
Faculty of Mechanical Engineering, Lublin University of Technology,
Nadbystrzycka Street 36, 20-618 Lublin, Poland
p.magryta@pollub.pl, k.pietrykowski@pollub.pl, m.geca@pollub.pl

Abstract

The article presents assumptions of the one-dimensional model of the ASz-62IR aircraft engine. This model was developed in the AVL BOOST software. The ASz-62IR is a nine cylinder, aircraft engine in a radial configuration. It is produced by the Polish company WSK "PZL-Kalisz" S. A. The model is used for calculating parameters of the fuel stream and the air stream in intake system of the engine, as well as for the analyses of the combustion process and the exhaust flow to the external environment. The model is based on the equations describing the isentropic flow. The geometry of the channels and all parts of the model has been mapped on the basis of empirical measurements of the engine elements. The model assumes indirect injection where the gasoline was used as a fuel with the calorific value of 43.5 MJ/kg. The model assumes a mixture of a stoichiometric ratio of 14.5. This model is only part of the overall the ASz-62IR engine model. After the simulation tests on the full model the obtained results confirmed the correctness of the model used to create the mixture. It was found that the AVL BOOST software is good for the implementation of this type of work.

Keywords: aviation propulsion, AVL BOOST, engine model, charge exchange, mixture formation.

1. INTRODUCTION

Development of aircraft engines takes place in two ways. New engines constructions are developed (base engines) or an upgrade of the existing structures are made. The base of the engine retains, while a gradual introduction of a further developed version of the engine is made in the transitional period between two successive generations. Both techniques are assisted by simulation research. Modelling is particularly useful for designing elements in the field of mechanics, in particular, in the mechanics of aircraft engines. Modelling is a presentation of the system or its components in a simplified form, close to but different from the reality. Although each modelling process is performed in such a manner as to accurately reflect the reality, each of them contains some simplifications. There are some initial modelling processes: an adoption of a proper physical condition, describing its suitable mathematical model and putting it into the computer. Using a computer unit is integral to the process of creating a new product or their improvements. Computer modelling is the initial step in designing a new device or a new item and does not eliminate experimental research. However, its use is very important in terms of shortening the design and production time of new items [1].

In the case of 3D CFD simulation studies a bigger model is necessary to use to achieve good level of studies. Creating a 1D model requires a lower level of detail and is easier and faster to implement. This kind of model is a connector for analyzing a combustion engine with multiple components together. Nowadays such software are used GT-Suite, AVL BOOST, Ricardo Wave and various codes developed at universities [2-5]. In all of them, the 1D engine model is represented as a connection system and includes templates that simulate other engine parts (valves, cylinders, collectors, etc.).

Computer modeling of internal combustion engines is very well described both in the instructions for simulation programs and in literature positions [6]. The books [7, 8] cover various approaches to modeling and optimizing the in-cylinder processes as a mixture, combustion and formation of exhaust emissions in gasoline engines. User Manuals to AVL BOOST very accurately describes the procedures and equations used in creating models with literature [9].

The air-cooled radial piston engines have experienced dynamic development before and during the Second World War. For example BMW 801 engine was developed in 1938 and its prototype was tested in April 1939. Their construction was based on analytical calculations. The exchange of cargo and the formation of the mixture were not investigated by computer simulation methods. Nowadays, high power piston engines are rarely used and there is scarcity of work devoted to researching these old structures. There is a trend of adaptation of refined car engines for aerospace applications.

Recent developments scientific works are focused on the field of new compression-ignition engine with opposing pistons. The main trend of aircraft manufacturers is towards the electrification of the powertrain with More Electric Aircraft (MEA), Hybrid Electric Aircraft (HEA), More Electric Engines (MEE) and so on [10, 11].

All engine modeling programs are dedicated to automotive engines and do not include a niche group of aircraft engines operating under completely different conditions.

The article [12] contains an example of modelling the radial piston aircraft engine. It is the ASz-62IR engine produced by WSK PZL Kalisz since 1961. It is operated, among others, on board of *the PZL M18 Dromader*, *the An-2*, *the DHC-3 OTTER*, *the Li-2*. The view of the engine is shown in Figure 1.

This engine is a product, that has been improved during the implementation of scientific research with the participation of Lublin University of Technology. Originally, the engine was powered through the carburetor. The mixture was supplied to the engine by the radial compressor, which gets power from the crankshaft via the multiplier. In order to improve the engine performance and thus its competitiveness on the market, some works started on replacing the carburetor by an electronically controlled multi-point fuel injection system. After the implementation of the project results, the company began work on the optimization of the ignition system. All previously made and currently performed works were based on the mathematical model of the internal combustion ASz-62IR engine, that was developed [14, 15]. In an earlier work [16], the authors presented a general model of the engine in the AVL BOOST version 2014.2 along with sample results. It included both the process of filling and combustion. In this study, the authors focused on a sub-model of cylinders filling which was built in the 2016 version of AVL BOOST. The new version includes tools to approximate the entered parameters of the compressor map.

Fig. 1. ASz-62IR engine [13]

2. METODOLOGY

In order to determine the engine performance the mathematical model of the engine was made, which is a one-dimensional physical model of the engine. This model enables to investigate the engine performance (power, torque, fuel consumption, etc.). In addition, it enables research under variable environmental conditions to reflect varied flight conditions (altitude, humidity, cruising speed, etc.).

The research involved:

1. studying the ASz-62IR-16 radial engine technical documentation for an engine design;
2. formulating the assumptions for a predictive model and the variability range for environmental conditions;
3. developing an initial structure of the model;
4. developing structures of individual sub-models (to demonstrate charge exchange, combustible mixture formation, combustion, a piston-crank system and gears, an ignition system, a control system, environmental conditions, etc.);
5. introduction of maps of the compressor from the technical documentation of the engine;
6. implementing the model in the AVL BOOST environment;
7. validating the model.

2.1. Model assumptions

AVL BOOST software is a tool dedicated to one-dimensional modelling of internal combustion engines. The engine model can be used to calculate parameters of air and fuel flow in an intake system including charging devices as well as combustion and exhaust flow to the environment. This enables the visualization of time courses of flow parameters (pressure, temperature, gas composition, etc.) at any point of the model as a function of crank angle or mean values over the entire operating cycle.

The following assumptions were used in one dimensional engine model:

1. it can only reflect the diameter and the length of pipes;
2. all 9 cylinders are identical;
3. there is no impact on cylinder performance with the geometric orientation;
4. constant wall temperature of the engine;
5. constant fuel supply (homogeneous mixture, the fuel injectors are 0.5 m away from the intake valve);
6. complicated shapes of pipes were replaced by round shapes;
7. pipes with curvilinear axes (arcs of a specified radius) with variable diameter (conical) were used;
8. instead of small elements with a high volume between the inlet and outlet, an elements with constant volume were used (Plenum);
9. constant mix formation was maintained - automatically selected mass flow through the injector was used.

2.2. Engine model

The model reflects the entire path of charge flow from the air inlet to the exhaust outlet. Figure 2 show the scheme of air and fuel flow in an intake system (ASz-62IR engine). In a radial engine, the cylinders are located around the crankshaft and all pistons are connected by a common crank-piston mechanism. The air is supplied through a radial compressor, which gets power from the crankshaft via a multiplier.The injectors are placed in specially designed adapters at the exit from the compressor to the inlet pipes in the way that enable passing the fuel with the air flow. This solution allows us to place the injectors symmetrically which results in identical supply conditions for all cylinders. The model diagram is shown in Figure 3. The model also demonstrates the process of fuel injection into inlet channels. In the actual engine, the fuel is supply to the intake pipes just behind the compressor. It is injected in a simultaneous way, i.e. 1 injection per rotation of the crankshaft. In the model, the fuel is supplied to the engine continuously. The amount of fuel supplied by the injectors is determined by the assumed air-fuel ratio of 0.9 and the mass flow rate measured in the line before the compressor.

The model is composed of:

a. a model of charge exchange that covers:
   - air inlet;
   - throttle system;
   - compressor connector;
   - charging compressor;
   - inlet pipes and injectors;
   - outlet pipes;

b. a model of combustible mixture formation:
   - a model of fuel injection;
   - a model of fuel mixing and evaporation;

c. a model of an operating cycle composed of:
   - a model of cylinders (to demonstrate a change in cylinder volume);
   - a model of combustion;
   - a model of heat transfer;

d. a model of external conditions.

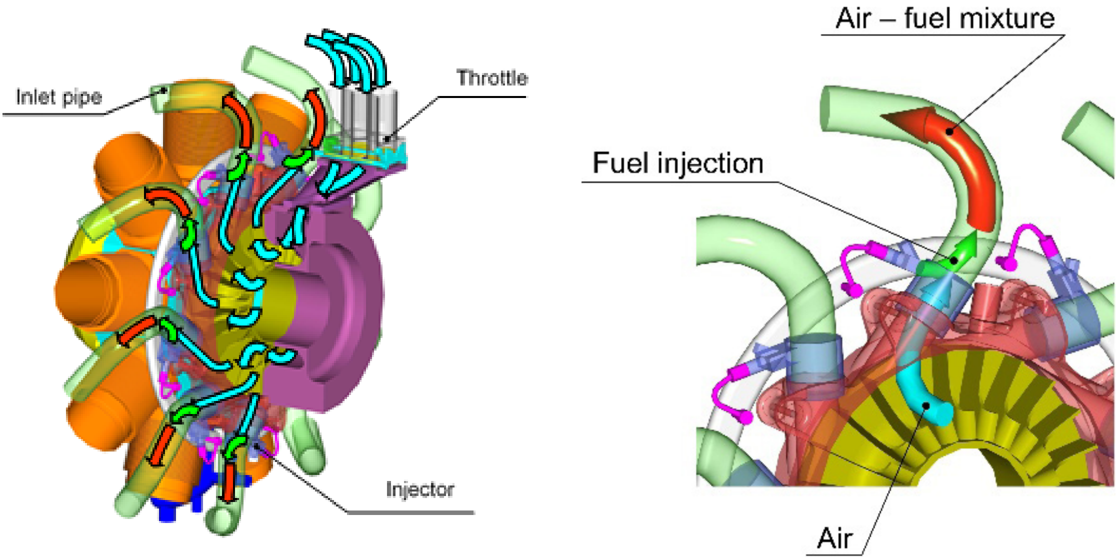
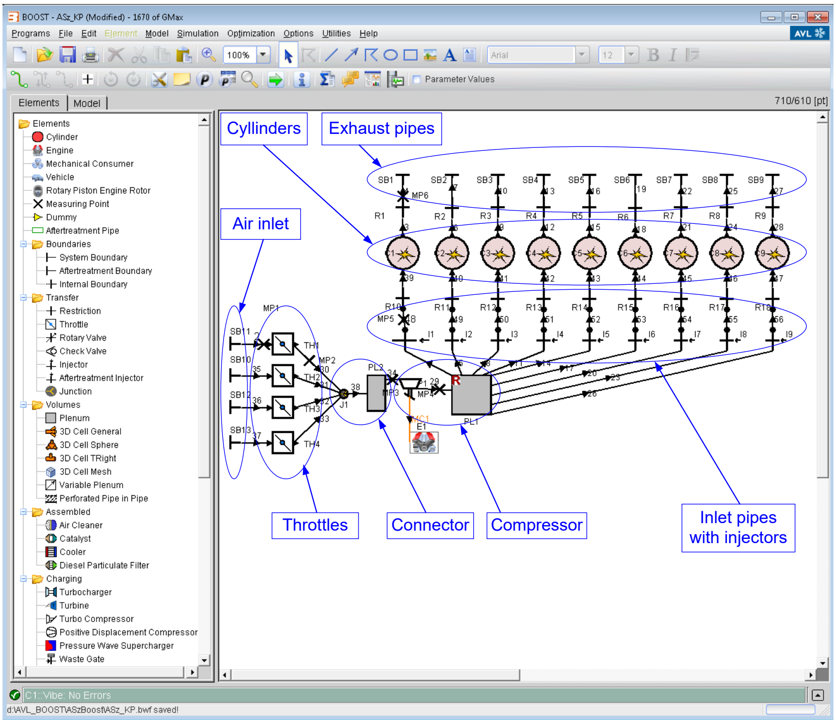


Fig. 2. The scheme of air and fuel flow in an intake system (ASz-62IR engine)



C1::Vibe: No Errors

d:\AVL_BOOST\ASzBoost\ASz_KP.bwf saved!

Fig. 3. AVL BOOST engine model [16]

The complete engine model in the AVL BOOST consists of several sub-models [17, 18]. The article presents only part of the entire model of the ASz-62IR engine (charge exchange model and mixture formation model).

2.3. Charge exchange model

The model of charge exchange is based on the model of mass flow rate in intake and exhaust pipes. This model is based on the equations to describe isentropic flow through the opening. The energy equation to describe flow through the opening under steady conditions can be transformed into the mass flow equation:

$$\frac{dm}{dt} = A_{eff} p_{o1} \sqrt{\frac{2}{R_o T_{o1}}}\varphi \tag*{1)}$$

where: $\frac{dm}{dt}$ – mass flow rate, A_{eff} – effective flow surface, p_{o1} – forward flow stagnation pressure, – forward flow stagnation temperature, R_o– gas constant, φ – velocity potential.
For subsonic flow:

$$\varphi = \sqrt{\frac{K}{K-1}\left[\left(\frac{p_2}{p_{o1}}\right)^{\frac{2}{K}} - \left(\frac{p_2}{p_{o1}}\right)^{\frac{K+1}{K}}\right]} \tag*{2)}$$

where: p_2 – backward flow stagnation pressure, K – ratio of specific heats.
and for transonic flow:

$$\varphi = \varphi_{max} = \left(\frac{2}{K+1}\right)^{\frac{1}{K-1}} \sqrt{\frac{K}{K+1}} \tag*{3)}$$

The real effective flow area can be determined from measured flow rate μσ:

$$A_{eff} = \mu\sigma \frac{d_{vi}^2 \pi}{4} \tag*{4)}$$

where: μσ – channel flow coefficient, d_{vi}^2 – internal diameter of a valve seat (reference diameter).

Flow coefficient μσ varies with the stroke/valve opening and is determined in a steady flow state on a research platform. Flow coefficient μσ demonstrates the ratio of real flow rate measured at a certain pressure difference and theoretical isentropic flow rate under the same boundary conditions. Flow rate relates to the cross-sectional area of the attached pipe/nozzle.

The geometry of the inlet channels and other key components was mapped with reference to the technical documentation of the engine and empirical measurements of the structure components. The volume of elements on the charge flow path between the air inlet and the exhaust outlet was measured by the CAD mapping of the structure. Taken from the technical documentation, the original characteristics of the compressor engine was introduced into the model.

To create a correct model for the process of charge exchange, the original characteristics of valve lifts (Figure 5) and the characteristics of the charging compressor to map its performance and the rotor speed depending on the mass flow rate and pressure were introduced. All the data for those maps and characteristics were provided by the engine's manufacturer.

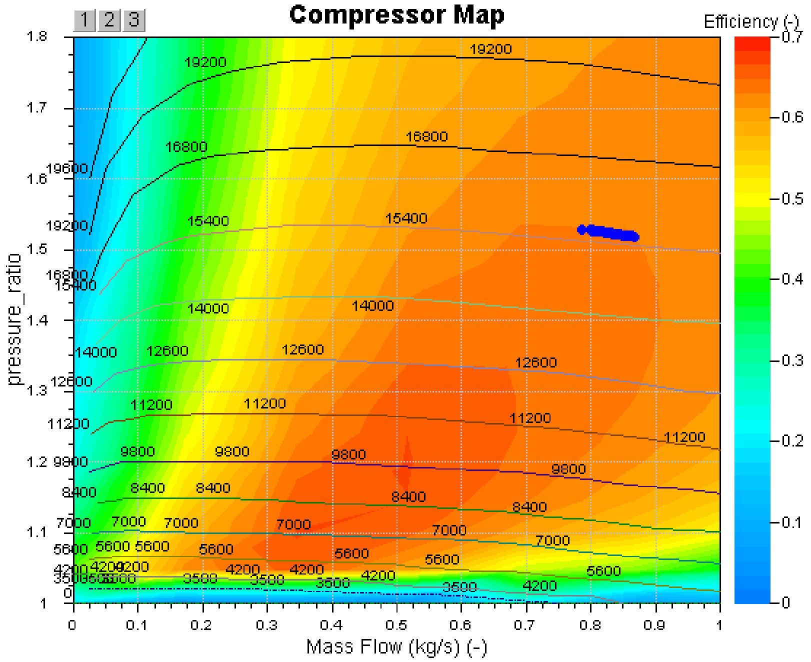


Fig. 4. Compressor map with marked operating points for take-off power [16]

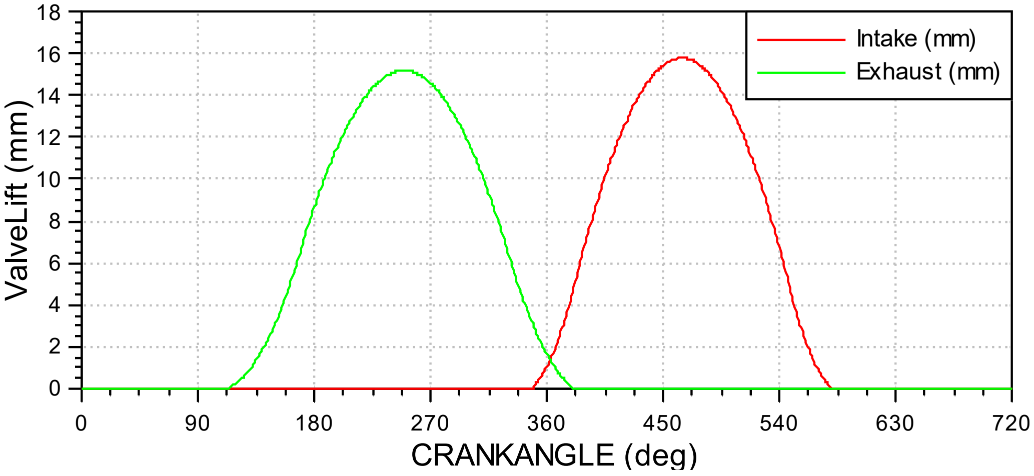


Fig. 5. Characteristics of valve lifts [16]

2.4. Model of mixture formation

The model of mixture formation is based on the calculation of values of gas properties like gas constant or thermal capacity. The AVL BOOST software can calculate the values of gas properties in each cell of each time step for instantaneous gas composition. The presented model uses a general model for the transport of chemical compounds of the mixture. There are 7 compounds used, i.e. fuel, O_2, N_2,

CO_2, H_2O, CO, H_2. A mass conservation equation is calculated for each of the compounds, which is fundamental for determining physical properties of the mixture both in inlet and outlet pipes.

As fuel, gasoline of a calorific value of 43.5 MJ/kg and an air mass fraction for stoichiometric mixture of 14.5 was used. Indirect injection into the intake manifold was used in this model, which is valid for both carbureted and indirect injection engines.

The model assumes the following simplifications:

- the mixture is homogenous at the beginning of combustion (because of AVL Boost software configuration),
- accordingly, mixture stoichiometric coefficient A/F remains constant during combustion,
- combusted and non-combusted charges show identical pressures and temperatures although their compositions change.

With the typical model for compound transport the value of mass fraction of combustion products (including the value of air-fuel ratio) and fuel vapor can be determined. Air mass fraction is calculated from the formula:

$$w_{air} = 1 - w_{FV} - w_{CP} \qquad 5)$$

where: w_{air} – air mass fraction, w_{FV} – fuel vapor mass fraction, w_{CP} – combustion products mass fraction. The value of air-fuel ratio is calculated from the formula:

$$AF_{CP} = \frac{w_{CP} - W_{FB}}{W_{FB}} \qquad 6)$$

where: AF_{CP} – air demand in exhaust gas, w_{FB} – combusted fuel mass fraction.

To calculate the properties of exhaust gas, the model for charge transport uses the air-fuel ratio to measure gas composition. Therefore, the air-fuel ratio is an indicator at which combustion occurred where exhaust gas formed. Exhaust gas composition is obtained from the chemical equilibrium provided for cylinder high temperature dissociation.

3. RESULTS

The validation consisted of a comparison of the engine performance at 4 points on the maximum power and 5 points on the propeller power, obtained from the engine test bench test. All points correspond to the conditions on the ground. The impact of flight altitude changes on engine performance was not analyzed. Figure 6 shows a comparison of pressure in the intake manifold. The consistency of the calculation results with the results of the experimental tests proves a good modeling of the filling process.

Also, the power characteristics (Fig. 7) shows good compatibility in the test results. The maximum pressure error after the throttles and in intake manifold pressure is 4%, which indicates that the inlet manifold is properly aligned with the supercharger. On the other hand, the specific fuel consumption does not exceed 1.5%, which demonstrates the proper modeling of the combustion process and gives the possibility of predicting engine performance after changes in the organization of the combustion process.

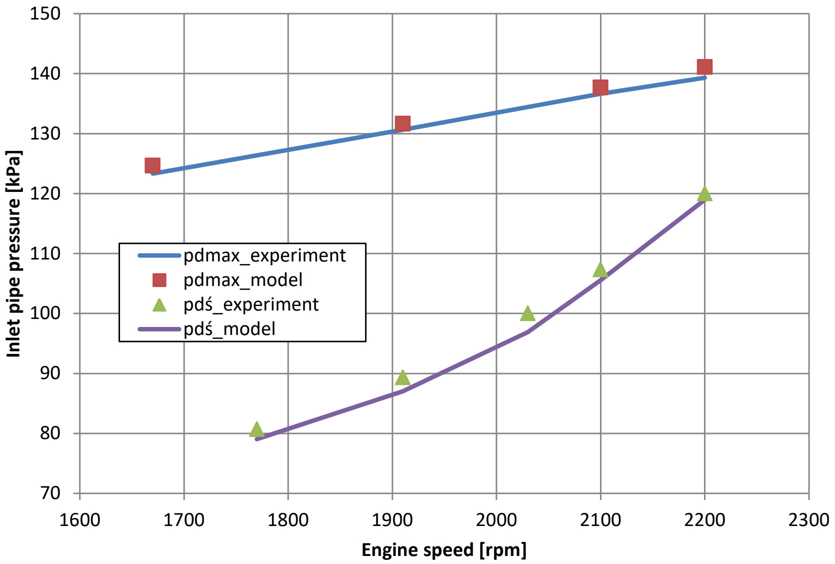


Fig. 6. Comparison of inlet pressure for maximum power and propeller power obtained from real tests and simulation tests

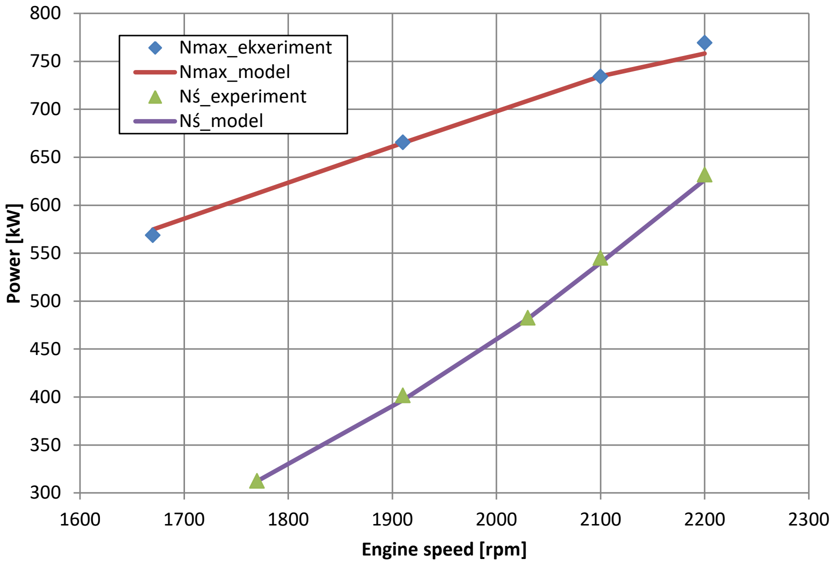


Fig. 7. Comparison of the characteristics of the maximum power and propeller power obtained from real tests and simulation tests

On the basis of the input data, simulations of the engine performance were made. Calculations were made for the operating point of the engine performance corresponding to take-off power, 746 kW (1,000 HP) at 2,200 RPM.

The results of the filling process which applies to discuss charge exchange sub-model are presented below. Figure 8 shows the characteristics of valves flow coefficient as a function of crankshaft rotation.

Flow coefficient increases and assumes a constant value. This situation is the same for the inlet and outlet. This is due to the geometry of the valve seat in the ASz-62IR engine.

Figure 9 shows the characteristics of the mass flow. There is no reverse flow, which is mainly due to the small value of the valves overlap. Visible small changes on the lines of the mass flow during the inlet and outlet occurs because of the wave phenomenon during the flow. This is because the engine is working at maximum power. The timing phases are optimized for heavy duty operation. Backflows increase as the pressure in the intake manifold decreases as the load decreases. Figure 9 shows the fluctuations in mass flow. These are due to the pressure waves in the intake and exhaust systems. In contrast, in Figure 10, it can be seen that the air-fuel mixture mass in the cylinder falls, but not to zero value, which indicates that the rest of the exhaust remains inside the cylinder.

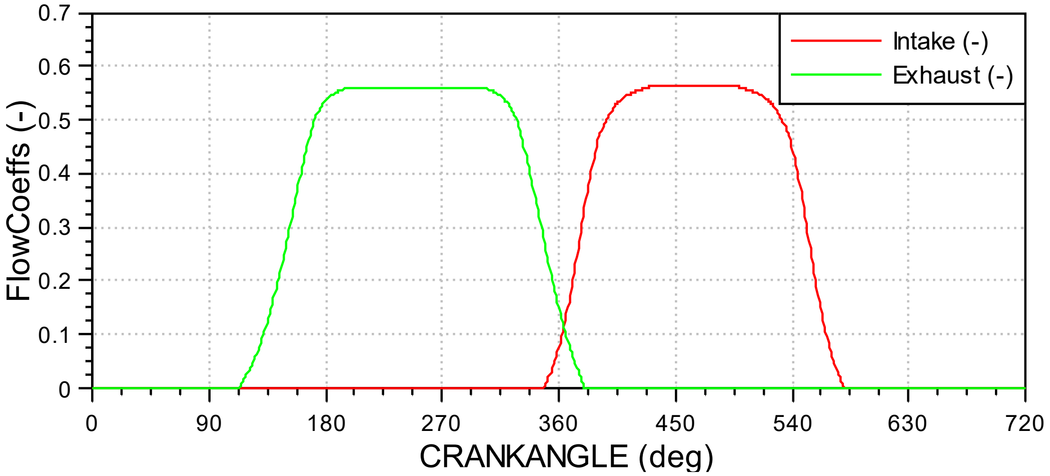


Fig. 8. Characteristics of valves flow coefficient [16]

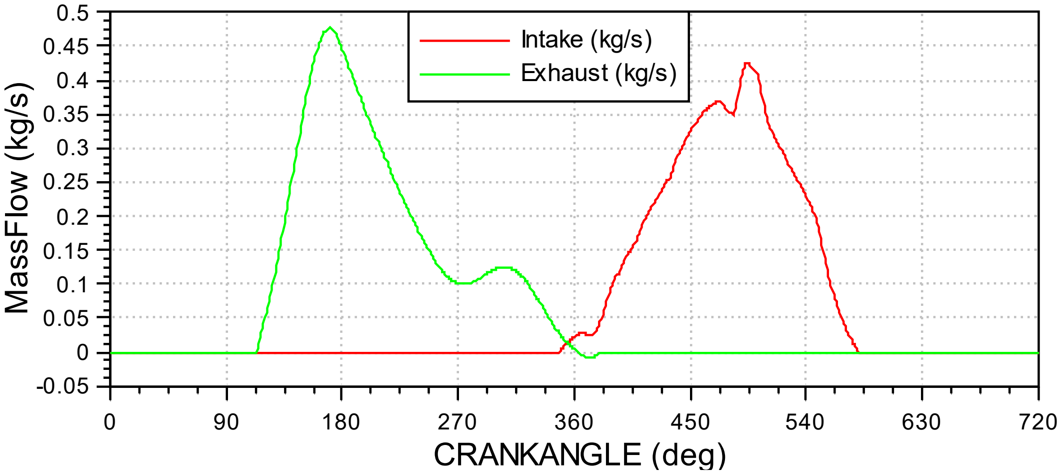


Fig. 9. Characteristics of mass flow [16]

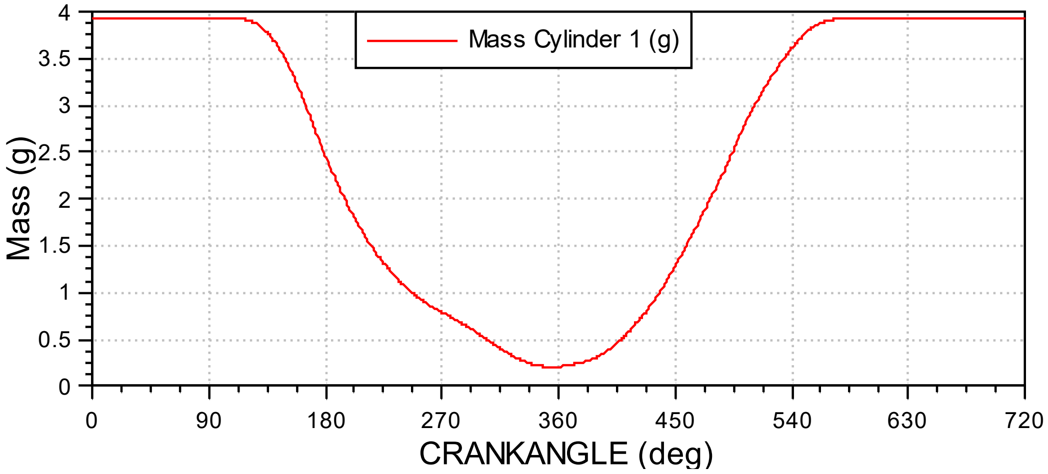


Fig. 10. Characteristics of air-fuel mixture mass in cylinder [16]

4. SUMMARY

The complete engine model in the AVL BOOST consists of several sub-models of the ASz-62IR engine. Authors presented charge exchange model and mixture formation model. The model reflects the entire path of charge flow from the air inlet to the exhaust outlet and the process of fuel injection into inlet channels. The geometry of the inlet channels and other key components was mapped with reference to the technical documentation of the engine and empirical measurements of the structure components. The model, which was made in the AVL BOOST, has been positively validated by comparing the results obtained from the engine performance real tests and received from the simulation studies [16]. The validation consisted of a comparison of the engine performance at 4 points on the maximum power and 5 points on the propeller power on the ground. The results of simulation tests are consistent with the results of experimental research. This applies to the intake manifold pressure and engine power. Such a validation justified the correctness of the charge exchange and the creation of the mixture model. Pressure data show that the inlet manifold is properly aligned with the supercharger. Specific fuel consumption does not exceed 1.5% in the model, which demonstrates the proper modeling of the combustion process. Results show that there is no reverse flow and the air-fuel mixture mass in the cylinder falls, but not to zero value, which indicates that the rest of the exhaust remains inside the cylinder. Additionally, the model assumes the calorific value of fuel (aviation gasoline). The model allows the introduction of the properties of another fuel, for example ethanol, which is commonly used to power ASz62IR engines in Brazil.

Currently, some works are underway to replace the spark ignition system with an electronic ignition system. This will improve the performance and reliability of the engine. The model presented in the article is used to predict the performance of the engine after modification.

In the future, the model will allow the introduction of new valves timing and compressor maps during the modernization of the remaining elements of the aircraft engine. There is a possibility to introduce the revised air-fuel ratio and to define the parameters of fuel (alcohol fuel, gasoline etc.).

BIBLIOGRAPHY

[1] Wendeker, M., Gęca, M., Szlachetka, M., Grabowski, Ł., Sochaczewski, R. and Barański, G., 2011, “Modelling an aircraft fuel system”, Combustion Engines, PTNSS–2011–SC–033.

[2] López, E. J. and Nigro, N. M., 2000 “Validation of a 0D/1D Computational Code for The Design of Several Kind of Internal Combustion Engines”, Technical report, Centro Internacional de Métodos Computacionales en Ingeniería, Instituto de Desarrollo Tecnológico para la Industria Química.

[3] Alqahtani, A., Shokrollahihassanbarough, F., and Wyszynski, M. L., 2015 “Thermodynamic Simulation Comparison of AVL BOOST and Ricardo WAVE for HCCI and SI Engines Optimisation,”, Combustion Engines 161(2): pp. 68-72.

[4] Barros, J. E. M., 2003, “Estudo de Motores de Combustão Interna Aplicando Análise Orientada a Objetos,” Master’s thesis, Universidade Federal de Minas Gerais.

[5] Coble, A. R., Smallbone, A., Bhave, A., Mosbach, S., Kraft, M., Niven, P., and Amphlet, S., 2011, “Implementing Detailed Chemistry and In-Cylinder Stratification Into 0/1-D IC Engine Cycle Simulation Tools”, SAE Technical Paper 2011-01-0849.

[6] Guzzella, L. and Onder, CH., 2010. “Introduction to modelling and control of internal combustion engine systems”, Springer, Berlin.

[7] Baumgarten, C., 2010, “Mixture Formation in Internal Combustion Engine”, Springer-Verlag, Berlin Heidelberg, Stiesch, G., 2003, “Modeling Engine Spray and Combustion Processes”, Springer-Verlag, Berlin Heidelberg, AVL BOOST plc. 2013. AVL Software, www.avl.com/BOOST.

[8] Emadi, A., Ehsani, M., 2000, “Aircraft power systems: technology, state of the art, and future trends”, Aerosp Electron Syst Mag IEEE, 15(1).

[9] Roboam, X., 2011, ”New trends and challenges of electrical networks embedded in “more electrical aircraft” Proceedings of 2011 IEEE International Symposium on Industrial Electronics (ISIE), pp. 26-31.

[10] Pietrykowski, K., 2011, “Research on the mixture formation process in a radial engine”, Combustion Engines, PTNSS–2011–SC–015.

[11] Gęca, M., Wendeker, M., Litak, G., 2012, “Combustion variability and uniqueness in cylinder of a large power radial engine, Journal of Vibroengineering”, Vol. 14, Issue 2., pp. 582-591.

[12] Grabowski, Ł., Tulwin, T., Geca, M. and Karpiński, P., 2016, “Validation Study of Radial Aircraft Engine Model”, International Journal of Aerospace and Mechanical Engineering, 9(3), pp. 2316-2316.

[13] Wendeker, M., Kacejko, P., Duk, M. and Karpiński, P., 2016, “Simulation Research of Innovative Ignition System of ASz62IR Radial Aircraft Engine”, International Journal of Aerospace and Mechanical Engineering, 9(3), pp. 2320-2320.

[14] Pietrykowski, K. and Gęca, M., 2014, „Simulation studies of the aircraft radial engine” (in Polish: “Badania symulacyjne lotniczego silnika gwiazdowego”), Logistyka 6/2014.

[15] Magryta P., Tulwin, T. and Karpiński, P., 2016, “The Charge Exchange and Mixture Formation Model in the ASz-62IR Radial Aircraft Engine”, International Journal of Aerospace and Mechanical Engineering, 9(3), pp. 2319-2319.

[16] Duk, M., Grabowski, Ł. and Magryta P., 2016, “Operation Cycle Model of ASz62IR Radial Aircraft Engine”, International Journal of Aerospace and Mechanical Engineering, 9(3), pp. 2322-2322.

MODEL TERMODYNAMICZNY GWIAZDOWEGO SILNIKA LOTNICZEGO ASZ-62IR

Streszczenie

W artykule przedstawiono założenia jednowymiarowego modelu wymiany ładunku z silnika lotniczego ASz-62IR. Model ten został opracowany w programie AVL BOOST. Silnik ASz-62IR jest dziewięciocylindrowym silnikiem lotniczym w układzie gwiazdy. Jest on produkowany przez polską firmę WSK „PZL-Kalisz" S.A. Opracowany model służy do obliczania parametrów strumienia paliwa i powietrza w układzie dolotowym silnika, jak również do analizy procesu spalania i przepływu spalin do środowiska zewnętrznego. Model jest oparty na równaniach opisujących przepływ izentropowy. Geometrię kanałów i wszystkich przepływowych elementów modelu odwzorowano na podstawie empirycznych pomiarów konstrukcji silnika. W modelu założono wtrysk pośredni, a jako paliwo zastosowano benzynę o wartości opałowej 43,5 MJ/kg. Założono stechiometryczną mieszankę o współczynniku 14,5. Opisany model jest tylko częścią całkowitego modelu silnika ASz-62IR. Po wykonaniu badań symulacyjnych pełnego modelu uzyskano wyniki potwierdzające prawidłowość zastosowanego modelu tworzenia mieszanki oraz stwierdzono przydatność oprogramowania AVL BOOST do realizacji tego typu prac.

Słowa kluczowe: AVL BOOST, model silnika, napędy lotnicze, tworzenie mieszanki, wymiana ładunku.

This work was funded by the National Centre for Research and Development, in the project INNOLOT under contract No. INNOLOT/I /1/NCBR/2013.