3D SIMULATION OF FLOW IN STIRLING ENGINE WITH FIK MECHANISM

Faculty of Mechanical Engineering – University of Zilina, Slovak Republic

Abstract: The article deals with 3D Simulation and design of the Stirling engine regenerator with unconventional FIK mechanism, whose real model is constructing on the field of Department of transport and handling machines the University of Zilina. The FLUENT software was used for the simulation. Boundary conditions were obtained by calculation and experiments performed directly in the selected engine parts. The article presents the results of a research focused on heat transfer inside the regenerator and cylinders.

Keywords: STIRLING ENGINE, HEAT TRANSFER, FIK MECHANISM, SIMULATION, REGENERATOR

1. Introduction

Applications of the patented FIK engine construction with non-conventional mechanism with a swing plate in the modification for the Stirling engine is solved under the project VEGA 1/0763/11 – Stirling engine with non-conventional mechanism FIK on the field of the Department of transport and handling machines the University of Zilina (Kukuca et al., 2002). In this configuration, the Stirling engine uses air, which is heated in the heat cylinder of the cylinder wall and cylinder head, as a power medium. Two heated and two cooled cylinders connected with a regenerator form the basic concept of the Stirling engine with the non-conventional FIK mechanism with a swing plate. The basic dimensions of the piston group were taken from an air-cooled vehicle engine with cylinder diameter of 75 mm and a stroke of 72 mm.

Also other sources of heat can be used for heating, for example a gas-jet.

For directing the flow of hot air around the heated cylinder walls was designed the cylinders sheathing. The limiting factor of heating the cylinders is the temperature at the internal wall of the cylinder, due to the maintaining of lubricating properties of oil. The oil could not go over 240°C. The cooled and heated cylinders are connected with the regenerator by pipes. The phase shift between the pistons in heated and cooled cylinders is 90°. In order to achieve the highest thermal stability in the cylinders, the highest engine efficiency and performance and the best heat utilization, the engine design includes the heat regenerator.

2. Working principle

Both heated cylinders are heated from outside with directed flow of heat air from two independent hot-air devices. The parameters of hot-air devices are: performance 2000W, air flow 650l/min and temperature of heated air from 50 to 600°C.

When designing this engine, theoretical calculations were used (Kukuca et al., 2003, Kukuca et al., 2004, Kukuca et al., 2006). Subsequently, the proposal of the swing plate and other main engine dimensions were made. The project continued with the creation of 3D models using the Catia V5R20 software. The virtual model of non-conventional FIK mechanism is showed in Fig. 1. The engine was designed for maximum operating speeds of 2000 rpm. The maximal engine power depends on the quantity of the input heat and the efficiency of the regenerator. The regenerator consists of the body and the filling.

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3. Cylinders

It is important to put a maximum of input heat in the shortest time. The role of this simulation was to assess the distribution of heat around the perimeter of the heated cylinder and along its inner wall. The directed hot air from the hot-air device provides the cylinder heating. The temperature of the air exiting the hot-air device was set to 723 K.

Fig. 2 The course of velocity of hot air flowing between the cylinder ribs

The heat transfer through the cylinder wall and ribs was simulated. To avoid the local overheating of the cylinder from the source of hot air, the deflector, which directs the hot air flow around the cylinders, had to be used.

Fig. 3 The course of temperatures of heated air in cylinder - through ribs
To ensure the flow of the air through the cylinder ribs and more even distribution of temperature on the whole surface of the cylinder the sheathing with a minimum gap (1mm) between the cylinder ribs and sheathing was designed. Figure 2 shows the airflow around the cylinder and its guidance to hot air exhaust.

About 65% of the cylinder surface flowed around by hot air reaches approximately identical temperature about 680 K (see Fig. 3). The lowest temperature is achieved on the back of the heated cylinder, approximately 540 K, what is quite significant temperature difference.

The course of temperatures of heated air in cylinder - through the volume between the ribs.

As seen in Fig. 5, which shows the inner surfaces of the cylinder, the back part of the cylinder where miss the sheathing and guidance the flow of hot air remain significantly cooler. Because the sheathing is common for both heated cylinders the simulation was solved as symmetrical.

The simulation showed that the designed shape of sheathing can not ensure more even heating of the cylinder on the whole surface and that the hot air flowing the opposite cylinder do not cause sufficient change of the flow in the area between the cylinder and the air outlet of the sheathing. As a result, the hot air will be not guidance on the back of the heating cylinder. To achieve better temperature distribution on the cylinder surface will be necessary to modify the sheathing form and to verify it by next simulations.

The heating of the cylinder and piston in the current position in top dead center is shown in Fig. 7. The simulation was performed at a moving piston and speed 400 rpm.

4. Regenerator

The basic requirement for the regenerator is to capture the maximum amount of heat contained in the air as a working medium when the heated air is moving from the heated cylinder to the cooled cylinder and then to reabsorb it when the cooled air is moving from the cooled cylinder to the heated cylinder.

It is therefore necessary to propose a regenerator with a space large enough and with a reasonable volume, lowering the final compression engine ratio (Bigos, Puskar, 2008).

The simulation of regenerator work was made by Fluent software (Sojcak et al., 2005). In this case was used a standard turbulence k – ε model.

In the beginning was created 2D geometry of cylinders, pipes and regenerator in Catia software for our problem (see Fig.8). Sketch was exported as a step file to the Gambit program, which is used to computing grid creating.

Results of 2D simulations showed the problems which must be solved in 3D simulation. The first regenerator concept showed the...
need to synchronize its size and the engine speed. It was found how the geometry of the regenerator inlet and outlet sections influences flow in the regenerator and how to determine the regenerator volume to avoid an excessive heating of the medium in the cold cylinder as seen in Fig. 8. 2D simulation showed also how the porosity and material of regenerator filling influences the function of regenerator.

Fig. 10 Measuring equipment for measurement of flow resistance in regenerator

It is necessary to know the flow resistance values caused by regenerator filling to get more accurate simulation calculations in 3D geometry. These values are in Fig. 10 and they were obtained by real measurement on the test model shown in Fig. 9. Coefficients $C_2$ and $1/\alpha$ determining the regenerator filling properties were calculated from the values of the flow resistance. Experimental data that is available in the form of pressure drop against velocity through the porous component can be extrapolated to determine the coefficients for the porous media (see Fig. 10).

The optimized conditions with uniformly heated cylinder with maximum temperature on inner side of the cylinder 513 K were selected to simulate the regenerator functions.

Fig. 11 Courses of temperatures in the cylinders and regenerator without filling (red line – heated cylinder, blue line – cooled cylinder, green line – regenerator)

Simulations were made for 3 different solutions of location the regenerator filling. The first solution consisted in the placement of regenerator filling into the regenerator housing and into the both connection bends. The second solution contained the regenerator filling only in the bend connected to the heated cylinder and to the regenerator housing. The third solution contained no filling.

As a material of the regenerator housing and connection bends was chosen copper. Material of the filling was aluminum mesh with a porosity of 0.85. Regenerator dimensions were chosen based on previous 2D simulations so that its volume is equal to the volume of the heated cylinder. 3D simulations showed compared to 2D simulations better approximation to the real state.

Simulations confirmed that it is possible to ensure difference in mean temperatures of heated and cooled cylinder required for the proper function of Stirling engine. Simulations (see Fig. 11, 12, 13) also show that the amplitude of the mean temperature in the heated and cooled cylinder is heavily dependent on the volume of aluminum regenerator filling, what is most apparent in the heating and stabilization of regenerator work.

Too big regenerator volume works at this phase as the heat absorber and significantly prolongs the stabilization phase of motor running. As seen in the Fig. 13, the trend in mean temperature of the cooled cylinder is decreasing (blue line) and the trend of the heated cylinder is rising (red line). The mean temperature in the regenerator gradually increases (green line).

Due to the large volume of the designed regenerator is the time required for stabilization of the temperature conditions too big. Fig. 16 shows that inside of the regenerator remains colder relative to the connection bends. For this reason, it would be useful to reduce the dimensions of the regenerator in order to ensure a sufficiently rapid accumulation of heat in the regenerator and to shorten the time of system stabilization.
As seen from the courses of mean temperatures in Fig. 13, big amplitudes of the heated cylinder temperatures are the result of inadequately working regenerator, respectively the result of its inability to deliver the air entering the heating cylinder enough heat to increase its temperature. Ideally, the red curve of mean temperature of air in the heating cylinder should be straight lines - isotherm.

Laboratory measurements of the flow resistance for a specific regenerator type that were taken were used in a 3D model simulation calculation. 3D simulation of the regenerator showed that is not possible to start from the simpler 2D simulations to propose the dimensions of the regenerator. It turned out that the simulated regenerator coming out of the 2D simulation is too large, resulting in the malfunction or too long temperature stabilization of the system – regenerator heating. It is therefore necessary to make changes of the regenerator dimensions and verify them by re-simulation calculation. The determination of the heat input for the Stirling engine function was another task of the solution. That was based on the heat transfer simulation calculations for the heated engine cylinder with the optimal airflow of heating medium – hot air coming from hot-air device through the cylinder ribs. The calculations showed insufficient heating of the cylinder back on approximately 35% of its circumference even when the hot air flow from another heated cylinder was taken into account. The simulation demonstrated the significant disparity of the cylinder reheating (difference up to 150K) along the inner wall in this way of the cylinder heating. It follows that for the homogeneous distribution of temperature is therefore necessary choose different way of heating, for example by resistance wire.

6. Literature


Kukuca P Engine with the Non-conventional FIK Crank Mechanism - MECCA - Journal of Middle European Construction and Design of Cars, No. 1, 2, 2006, pp. 28 – 34, ISSN 1214-0821, (Kukuca, P., R. Istenik, A. Gasparec)

Sojcak D A Structure of the Cooling System - Communications - Scientific Letters of the University of Zilina, No. 4., 2005, pp. 23-26, ISSN 1335-4205.

Bigos, P., Optimal Value of Compression Ratio - Strojarstvo. No.12., 2008, pp. 84/2-85/3, ISSN 1335-2938, (Bigos, P., M. Puskár)


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