Design of selected parts of non-conventional Stirling engine with FIK mechanism

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Abstract: This paper deals with a design implementation of Stirling engine with a non-conventional FIK mechanism, contains a description of its operation and discusses the possibilities of compression ratio changes. It presents the results of a research focused on individual parts of the engine, including the regenerator, FIK mechanism and heat transfer. These results have been obtained by calculation, simulation and experiments performed directly in the selected engine parts. The FLUENT software was used for the simulation.

Key words: Stirling engine, FIK, regenerator, CFD simulation

Introduction

One of many applications of the patented FIK engine construction with non-conventional mechanism with a swing plate is its modification for the Stirling engine (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.

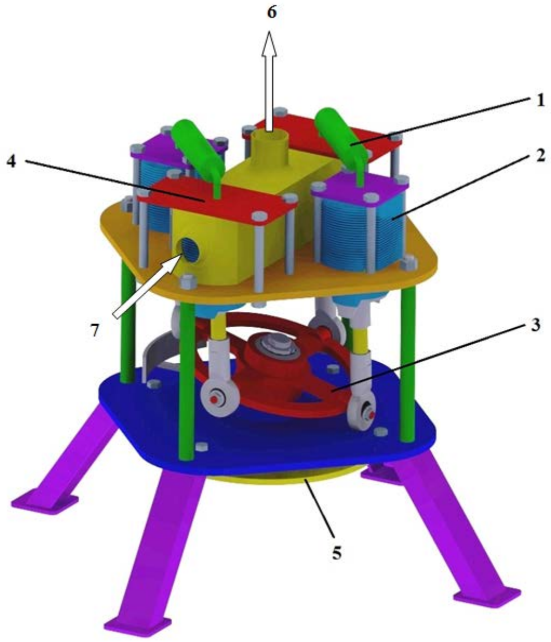


Figure 1: Virtual model of non-conventional mechanism FIK: 1 – regenerator, 2 –cooled cylinder, 3 – swing plate, 4 – heated cylinder, 5 – flywheel, 6 – heat output, 7 – heat input

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 the an air-cooled vehicle engine with cylinder diameter of 75 mm and a stroke of 72 mm. When designing this engine, theoretical calculations were used. 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. Figure 1 shows a virtual model of non-conventional FIK mechanism. The other parts are described below.

Description of constructive units

The basic supporting structure of the engine consists of two steel plates with a thickness of 10 mm. At the top plate, there are holes for cylinders and holes for screws connection.

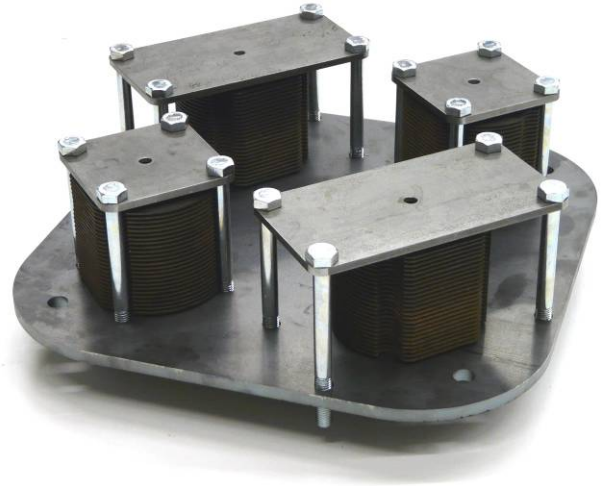


Figure 2: Top plate with cylinders and heads

The bottom plate performs several functions. The gearing that is there is used to assure kinematic movement of the swing plate. The bearing housings where the crankshaft is housed are there too and also the holes for fastening of the stabilization feet. The top and bottom plates are connected with four capped pipe beams with shoulder on the top. Inserting washers under the top plate can change the engine compression ratio and other performance parameters as well. The plate is screwed with four threaded rods M14.

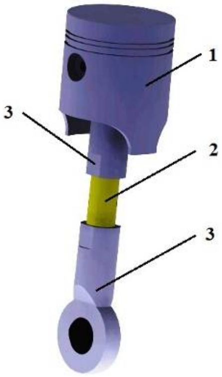


Figure 3: Piston group: 1 – piston, 2 – thread rod, 3. – rod end

The piston group of Stirling engine with non-conventional FIK mechanism was used from the air cooled engine. The ribs of the air–cooled cylinders allow regular and steadier heating of heated cylinders in order to keep the optimal working temperature. On the other hand it allows better cooling dawn of cooled cylinders where the temperature must be stabile – isothermal.

The connecting rod of swing mechanism consists of three parts, two rod ends SKF SI 20ES and a thread rod M20, as can be seen in the figure 3. In the mechanism of the FIK engine the swing plate makes a movement in three axes. Therefore the crank bearings and piston-pin bearings use the rod ends. The rod length is variable. The designed length of connecting rod is L = 164mm (Kukuca et al., 2006).

Figure 4: Swing plate with rod ends and gear

The swing plate in the figure 4 and 5 transfers the straight-line reciprocating motion of the piston to the crankshaft. In the swing plate, there are bearing housings for conical bearing, in which the crankshaft is supported. The same type of conical bearings is used in the bottom plate.

Figure 5: Swing plate with rod ends, crankshaft, bearings and gear wheels

The position of the swing plate stabilizes the helical gearing which transmits forces on the bottom plate and defends the rotation of the swing plate around its own axis. The design of the swing plate is letweight in order to achieve lower mass and lower inertia forces.

Figure 6: Crankshaft

The crankshaft is cranked in the angle 15° – this value was calculated. The pitch diameter of the cylinders and the piston stroke were used as the input data for calculation. The bigger pitch diameter of the cylinders, the lower crankshaft crank at the constant piston stroke. The flywheel for steady running of the engine is located in the lower end of the crankshaft. Below the flywheel, there is an engine-speed sensor.

An important part of non-conventional mechanism FIK is a balancing mechanism. Balancing equipment must secure the balance of inertia forces and moments in the engine. When this is not balanced, the participating mass makes the running around the engine axis unstable. The process of balancing depends on the mass of pistons, connecting rods, piston pins and the swing plate and on the values of basic kinematic parameters. Balancing is realized with counterweight. The counterweight is connected with the crankshaft. The radius of the counterweight arm is bigger than the radius of the swing plate. The correct position and mass of the counterweight reduce the inertia forces and moments. The values of position and mass were calculated from the input parameters. The methodology and process of calculation of FIK mechanism balancing can be found in literature (Kukuca et al., 2003, Kukuca et al., 2004).

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. Figure 7 shows the cut of engine.

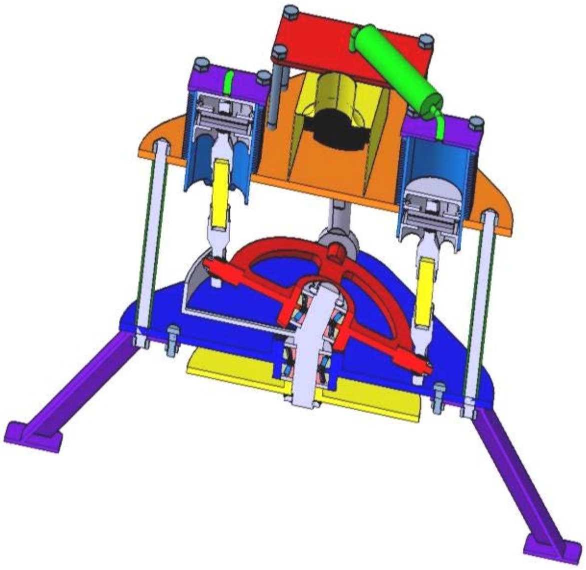


Figure 7: Cut of the engine

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. 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.

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 first regenerator concept showed the need to synchronize its size and the engine speed.

The simulation of regenerator work was made by Fluent software (Sojcak et al., 2005).

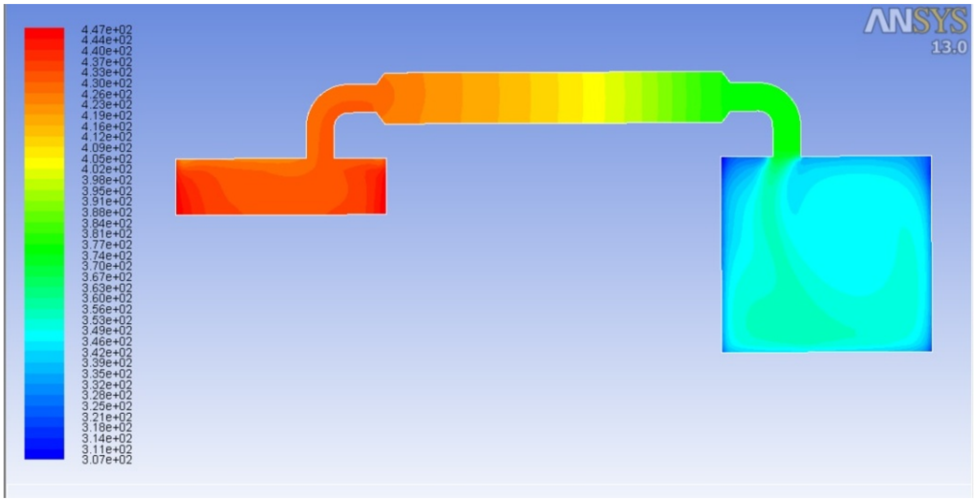


Figure 8: Distribution of temperatures in the cylinders and regenerator - porosity 0.961

Program Fluent use these main steps of CFD analysis:

- the basic formulation of the task (problem definition),
- creating a geometric model and the control area (use of CAD system),
- creating boundary and initial conditions,
- set the correct physical model with regards to the studied problem,
- creation and generation of adequate mesh (structure, size, or local concentration),
- CFD calculation (the assessment of convergence solution, eventually review of model parameters),
- data processing to obtain results,
- comparison with other results (experimental when available),
- critical evaluation of the obtained results.

In this case was used a standard turbulence k – ε model. This model is simplest "complete model" of turbulence with two-equation models in which the solution of two separate transport equations allows the turbulent velocity and length scales to be independently determined. The k - ε standard model in FLUENT software falls within this class of turbulence model and has become the workhorse of practical engineering flow calculations in the time since it was proposed by Launder and Spalding. Robustness, economy, and reasonable accuracy for a wide range of turbulent flows explain its popularity in industrial flow and heat transfer simulations.

For our problem was created 2D geometry of cylinders, pipes and regenerator in Catia software. 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. 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 the figure 8. 2D simulation showed also how the porosity and material of regenerator filling influences the function of regenerator.

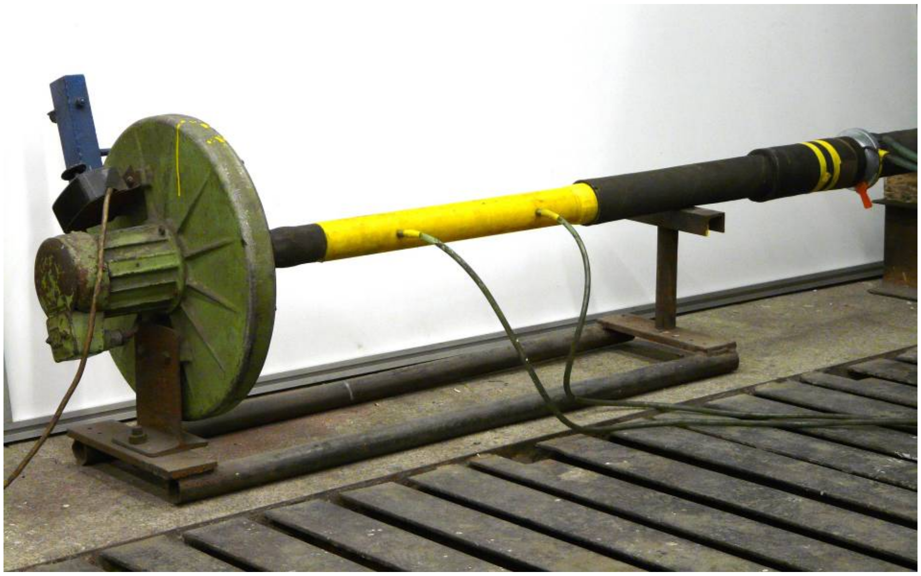


Figure 9: Measuring equipment for measurement of flow resistance in regenerator

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 figure 11 and they were obtained by real measurement on the test model shown in figure 9. Coefficients C_2 and $1/\alpha$ determining the regenerator filling properties were calculated from the values of flow resistance as follows:

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

Then a p-v curve can be plotted to create a trend line through these points yielding the following equation

$$\Delta p = 11{,}592v2 + 7E\text{-}13v$$

where Δp is the pressure drop and v is the velocity.

For the coefficients we can write

$$11{,}592 = C_2 \frac{1}{2} \rho \Delta n$$

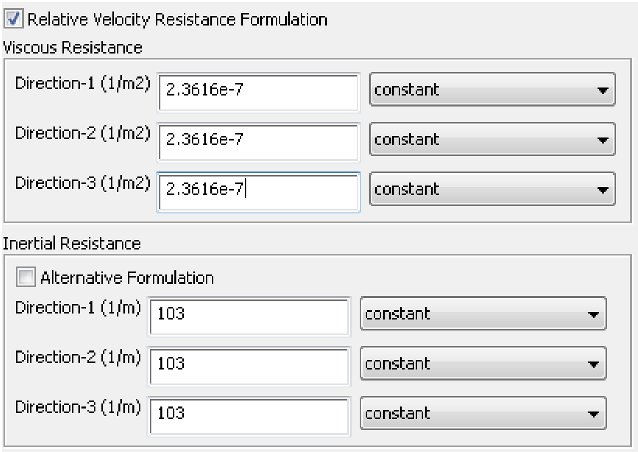
with ρ=1,1845 kg/m3 at 25° Celsius, porous media thickness Δn = 0,19 m, inertial resistance factor

$$C_2 = 103$$

$$7.10^{-13} = \frac{\mu}{\alpha}\Delta n$$

with air kinematic viscosity μ = 1,56E-5 m2/s, the viscous inertial resistance factor

$$\frac{1}{\alpha} = 2{,}3616^{-7}$$



☑ Relative Velocity Resistance Formulation

Viscous Resistance

Direction-1 (1/m2) 2.3616e-7 constant

Direction-2 (1/m2) 2.3616e-7 constant

Direction-3 (1/m2) 2.3616e-7 constant

Inertial Resistance

☐ Alternative Formulation

Direction-1 (1/m) 103 constant

Direction-2 (1/m) 103 constant

Direction-3 (1/m) 103 constant

Figure 10: Formulation of porous media coefficients in Fluent software

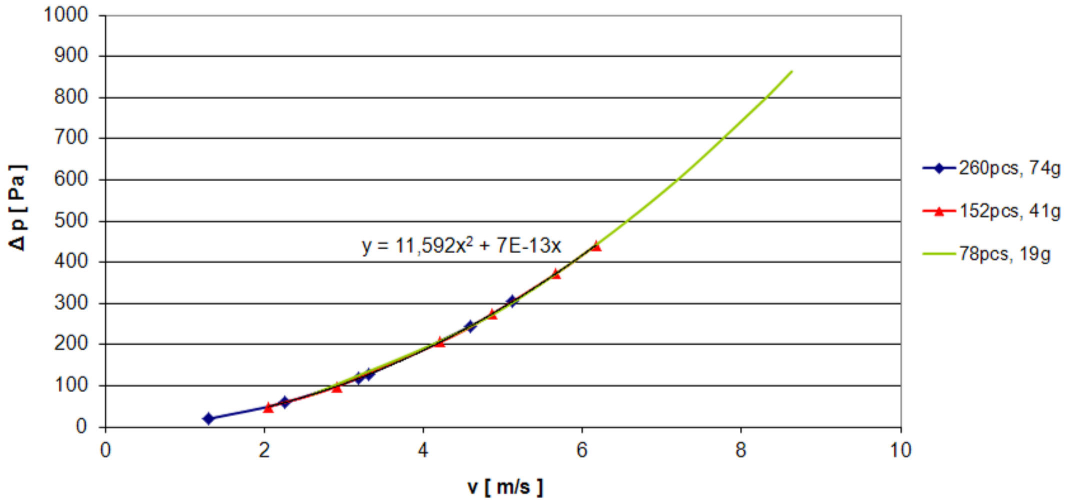


Figure 11: Measuring equipment for measurement of flow resistance in regenerator

Cylinders

It is important to put a maximum of input heat in the shortest time. 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. 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 12 shows the airflow around the cylinder and its guidance to hot air exhaust.

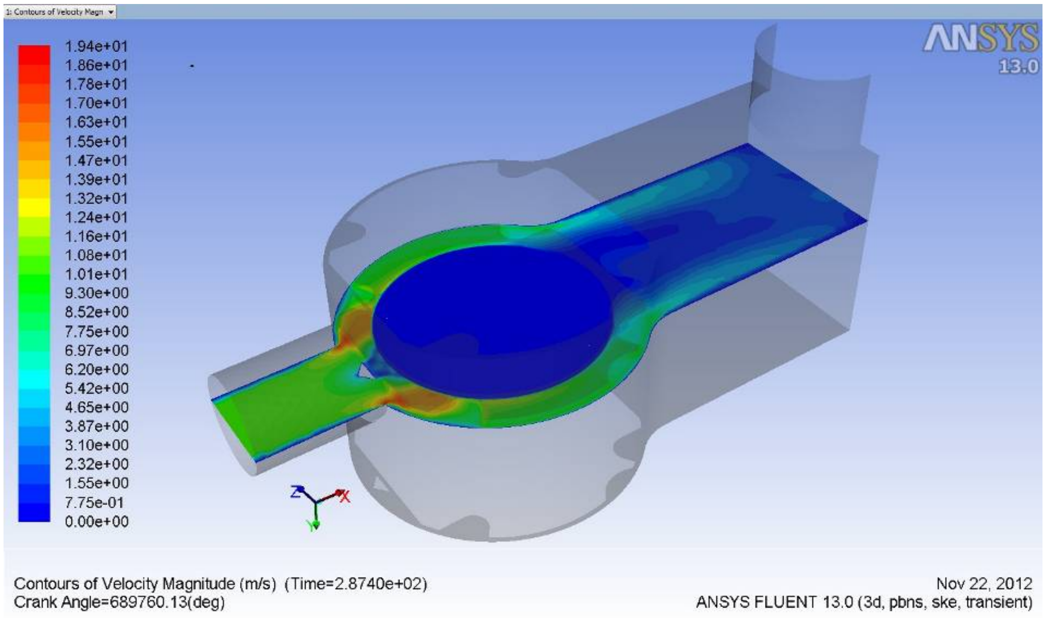


Figure 12: The course of velocity of hot air flowing between the cylinder ribs

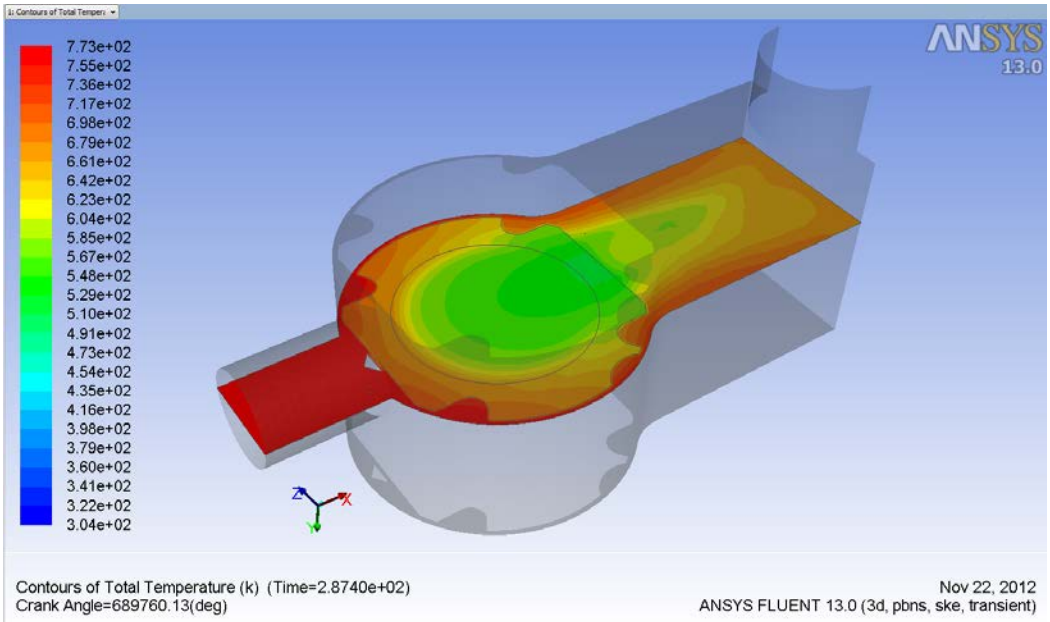


Figure 13: The course of temperatures of heated air and the cylinder through the ribs

As seen in the figure 13, about 65% of the cylinder surface flowed around by hot air reaches approximately identical temperature, about 680 K. The lowest temperature is achieved on the back of the heated cylinder, approximately 540 K, what is quite significant temperature difference.

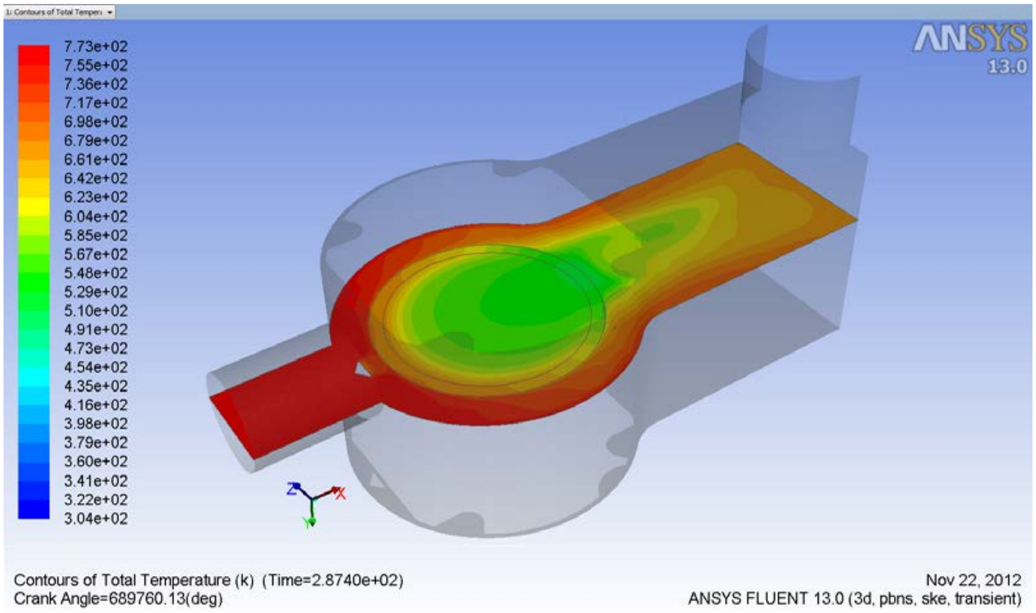


Figure 14: The course of temperatures of heated air and the cylinder through the volume between the ribs.

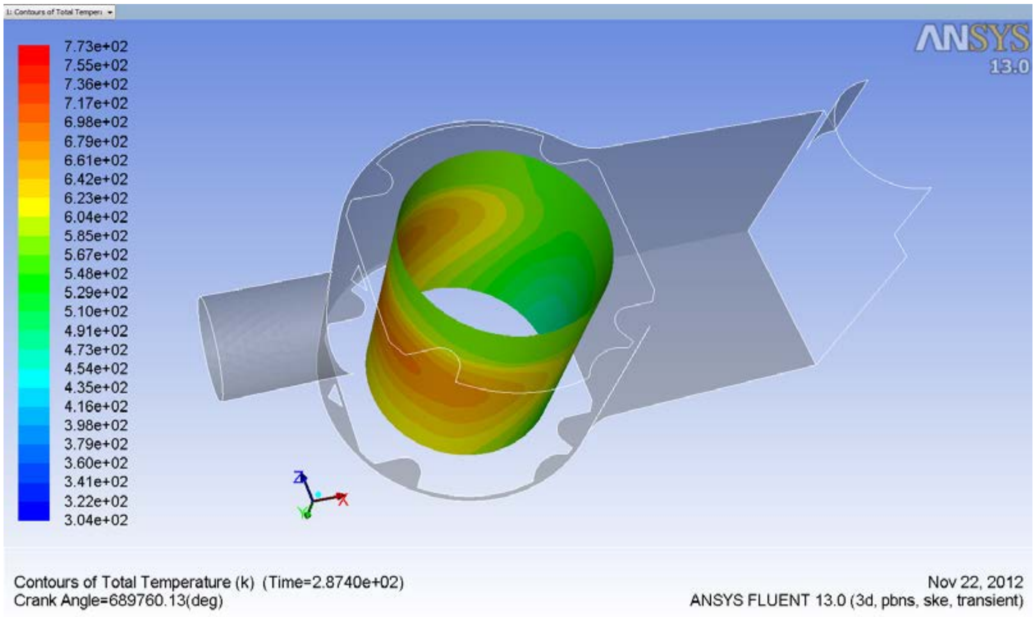


Figure 15: The course of temperatures inside the heated cylinder

As seen in figure 15, 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.

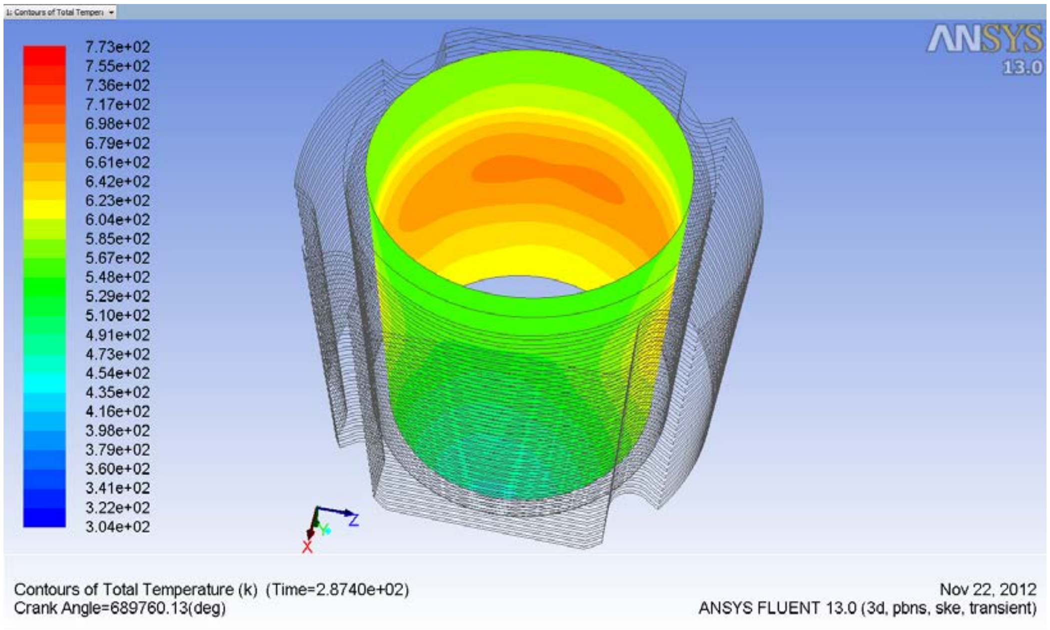


Figure 16: The course of temperatures inside the heated cylinder with ribbing

Figure 17 shows the heating of the cylinder and piston in the current position in top dead center. The simulation was performed at a moving piston and speed 400 min^{-1}.

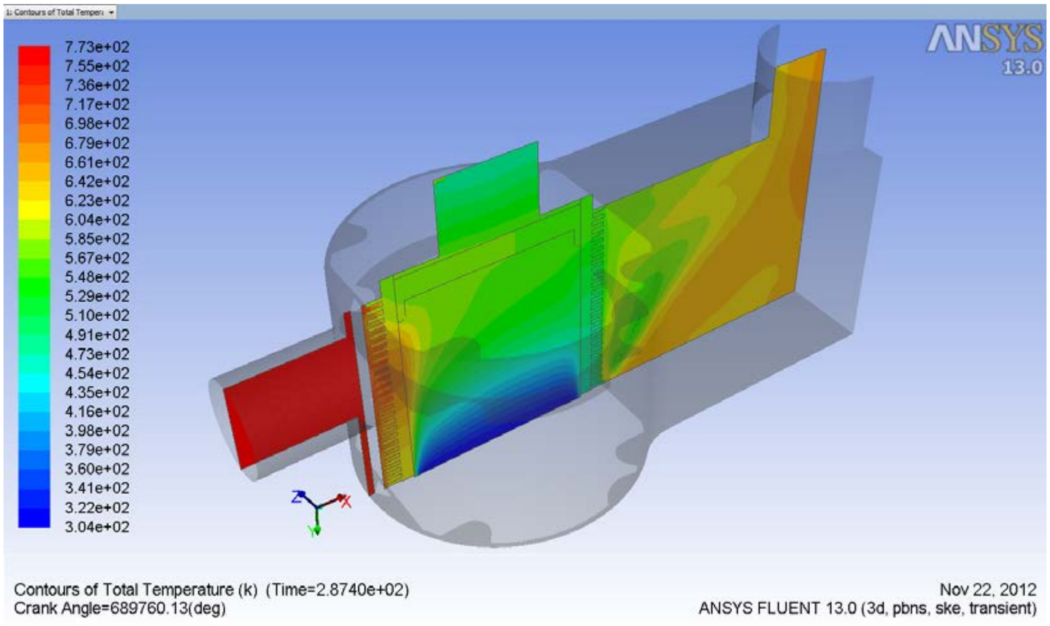


Figure 17: The course of temperatures in the cross-section of heated cylinder with ribbing

Conclusions

The design of the non-conventional Stirling engine with the FIK mechanism was created as a part of the VEGA 1/0763/11 project. The paper describes the current state of the project. The project's goal is the construction of a functional engine. The engine parts that are already available are shown in the figures above. Simulations by the Fluent software were used when designing some heat-affected parts such as the regenerator, cylinders, cylinder sheathing . The regenerator Simulations showed a need to modify some regenerator parts to improve the flow and to ensure a sufficient regenerator output. It will be needed to perform a 3D simulation of the real state with accurate computation input conditions.

Laboratory measurements of the flow resistance for a specific regenerator type that were taken will be used in a 3D model 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 heat guns 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.

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