MECHANIKA
CZASOPISMO TECHNICZNE
TECHNICAL TRANSACTIONS
MECHANICS
WYDAWNICTWO
POLITECHNIKI KRAKOWSKIEJ
3-M/2012
ZESZYT 8
ROK 109
ISSUE 8
YEAR 109

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HEAT REGENERATOR OF STIRLING ENGINE WITH AN UNCONVENTIONAL MECHANISM FIK

REGENERATOR CIEPŁA W SILNIKU STIRLINGA Z NIEKONWENCJONALNYM MECHANIZMEM FIK

A b s t r a c t

The paper deals with the solution of the parts internal Stirling engine with an unconventional mechanism of FIK. In order to increase its efficiency the internal engine includes the heat regenerator. Its task is the accumulation of heat released from combustion chamber. It is therefore necessary to consider its appropriate design and material solutions. This paper deals with the simulation of media flow through the regenerator made with Fluent software

Keywords: regenerator, engine, FIK

S t r e s z c z e n i e

W artykule przedstawiono rozwiązanie wewnętrznych części silnika Stirlinga z niekonwencjonalnym mechanizmem FIK. Aby zwiększyć jego skuteczność, wewnątrz silnika umieszczono regenerator ciepła. Jego zadaniem jest akumulacja ciepła wydzielanego z komory spalania. Konieczne jest zatem przeanalizowanie odpowiednich rozwiązań konstrukcyjnych i materiałowych. W artykule przedstawiono symulację przepływu czynników przez regenerator, wykonaną za pomocą programu Fluent.

Słowa kluczowe: regenerator, silnik, FIK

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1. Introduction

One way how to use the unconventional mechanism of engine FIK (Fitz, Istenic, Kokuca) [1] with inclined board is his modification in Stirling engine. In this design configuration Stirling engine use air as a driving medium which is heated in the heat cylinder from the cylinder wall and the cylinder head.

The basic concept of the Stirling engine with unconventional mechanism FIK with inclined board compose two heated and two cooled cylinders connected with regenerator. The basic dimensions of the piston group were taken from air cooled vehicle engine with the diameter of cylinders 75 mm and stroke 72 mm. At the proposal of this engine were used the theoretical calculations. Subsequently, was made the proposal of inclined board and other main dimensions of the engine. Then the 3D model was created in Catia V5R20 software. Figure 1 shows virtual model of unconventional mechanism FIK.

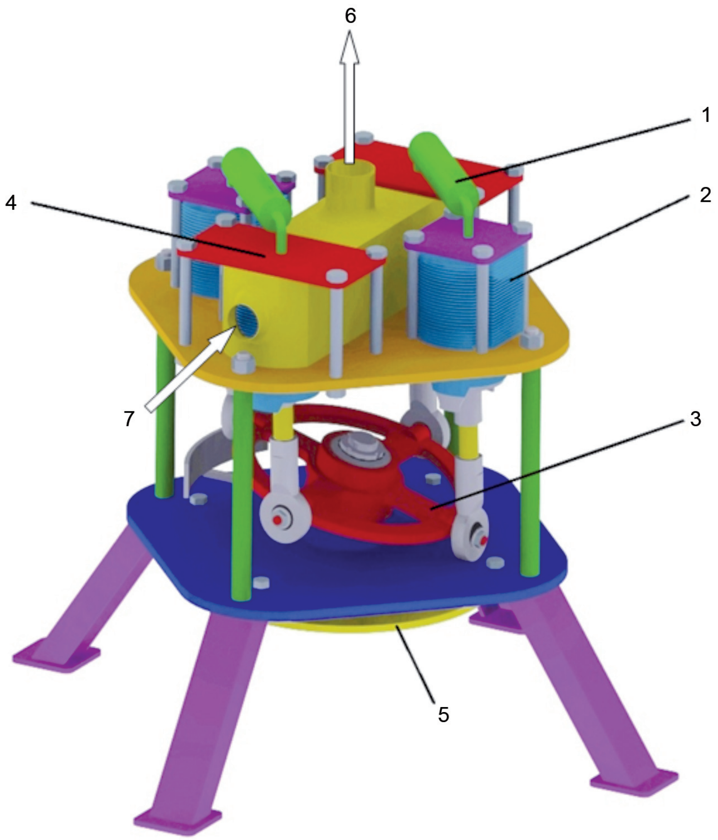

Fig. 1. Virtual model of Stirling engine with unconventional mechanism FIK: 1 – regenerator, 2 – cooled cylinder, 3 – swing plate, 4 – heated cylinder, 5 – flywheel, 6 – heat output, 7 – heat input

Rys. 1. Wirtualny model silnika Stirlinga z niekonwencjonalnym mechanizmem FIK: 1 – regenerator, 2 – cylinder chłodzony, 3 – płyta wahadłowa, 4 – ogrzany cylinder, 5 – koło zamachowe, 6 – odprowadzenie ciepła, 7 – doprowadzenie ciepła

2. Working principle

The heated cylinders are heated from outside with directed flow of heat air from hot-air device. The parameters of hot-air device are performance 2000 W, air flow 650 l/min and temperature of heated air from 50 to 600°C. Also next sources of heat can be used for heating for example gas-jet. The limiting factor is the temperature at the internal wall of cylinder, which due to maintain of lubricating properties of oil could not go over 240°C. In case of mechanism FIK are successive cylinders connected with regenerator by pipes. 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 efficiency and performance of engine and the best utilize of heat, the design of engine includes the heat regenerator. Its role is to capture heat from the hot medium at his transfer to the cooled cylinder and backwards to release the heat to the heated cylinder when moving back. The thermodynamic properties of the Stirling engine are influenced by shape and dimensions of regenerator.

3. Regenerator and its simulation

Regenerator consists of a steel shell and core made of different filler (steel, aluminum spoons, respectively sawdusts with different porosity, rolled aluminum sheet, aluminum net with size 0.5 mm), see Fig. 2.

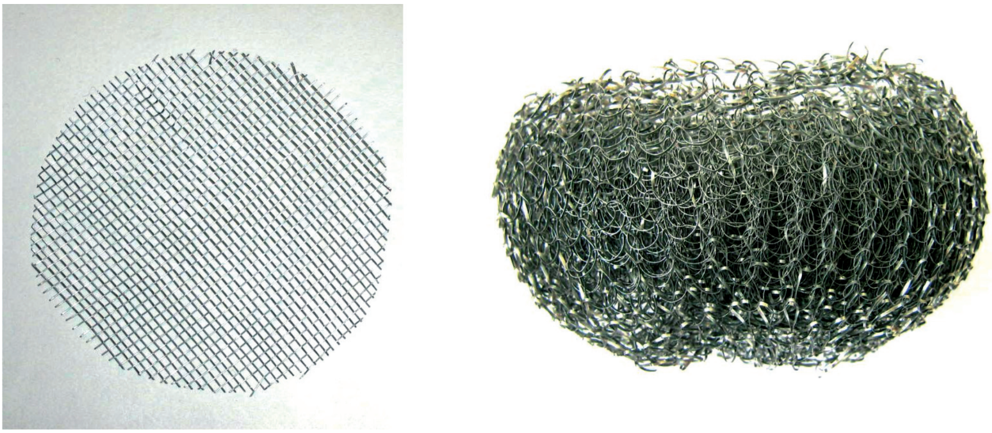

Fig. 2. Filler of the regenerator – steel spoons, aluminium net

Rys. 2. Wypełniacz regeneratora – stalowe łyżki, siatka aluminiowa

Using of software FLUENT, we performed several simulation of work of regenerator connected to heated working and cooled swap cylinder. The Fluent program includes the possibility of modelling fluent flow, turbulence, heat transfer, reaction for the industrial applications, combustion in internal combustion engines and boilers. FLUENT provides complete mesh flexibility, including the ability to solve your flow problems using unstructured meshes that can be generated about complex geometries with relative ease. Supported mesh types include 2D triangular/quadrilateral, 3D tetrahedral/ hexahedral/ pyramid/wedge/ polyhedral, and mixed (hybrid) meshes.

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.

For our problem was created 2D geometry of cylinders, pipes and regenerator (Fig. 3) in Catia software. Skatch was exported as a step file to the Gambit program, which is used to create of computing grid.

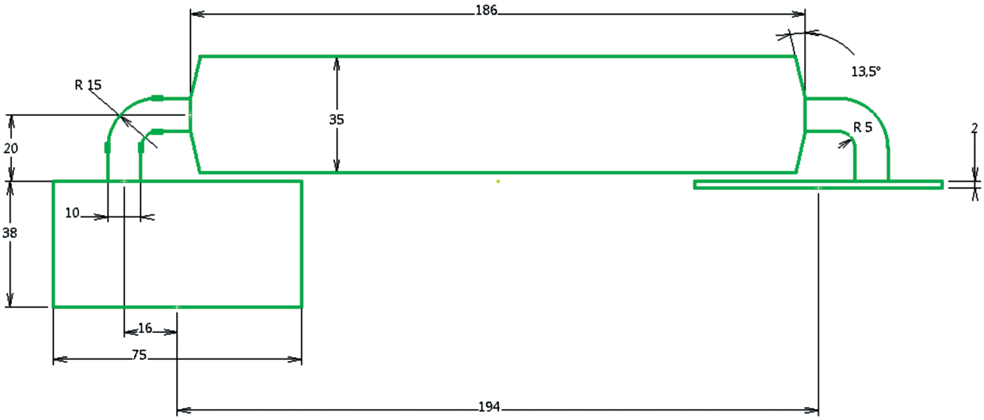

Fig. 3. Scatch of 2D geometry of cylinders, pipes and regenerator

Rys. 3. Szkic w 2D geometrii cylindrów, przewodów i regeneratora

The mesh presents system of distribution computing areas on 2D cells in two-dimension space as you can see on Fig. 4. Cell number belong among the main limiting factor of mathematical modelling, therefore the goal of every investigator is to reduce the number of cells to the minimum necessary regarding to the length of calculation time. Minimizing the number of cells should not be detrimental to the quality of the mesh.

Quality mesh consists of the sequential geometrically regular elements which are have approximately the same size and are regularly distributed throughout the computing area. A mesh can be triangular, square, tetrahedral or their combination.

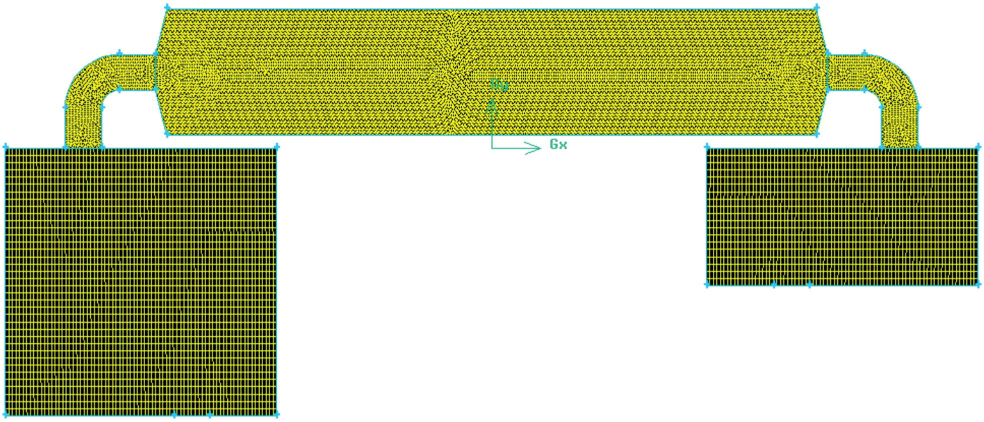

Fig. 4. Computing mesh

Rys. 4. Siatka obliczeniowa

In our case it was used triangular elements of size 1 for meshing the regenerator and knees area. Cylinders areas were divided by rectangular elements. So divided areas can be easily used to set dynamic mesh with system layering.

Gambit allows also the definition of boundary conditions, which may be of two types:
– boundary conditions at the border,
– conditions for the continuity areas.

After mesh creating and definition of the boundary conditions was the mesh exported to the FLUENT program as a .msh file. To move the pistons we use existing in-cylinder function in FLUENT.

For the simulation of air flow between the heated cylinder, cooled cylinder and regenerator of Stirling engine was necessary creating a profile file containing the values of piston stroke depending on the angle of rotation of the swing plate. The profile file was created on the base of the theory which is describing the kinematics unconventional mechanism FIK. In the calculation of piston stroke for each cylinders was used the equation (1).

$$z_p = z + \sqrt{l_0^2 - \left(x_{ov} - x\right)^2 - \left(y_{ov} - y\right)^2} \tag{1}$$

where:

z_p – piston stroke
z – coordinate (z) of the piston pin on swing plate,
y – coordinate (y) of the piston pin on swing plate,
x – coordinate (x) of the piston pin on swing plate,
x_{ov} – coordinate (x) axis of cylinder according to crankshaft axis,
y_{ov} – coordinate (z) axis of cylinder according to crankshaft axis,
l_0 – length of the connecting rod.

The piston stroke is influenced by pitch angle of swing plate, radius of swing plate, length of connecting rod, position of the cylinders axis.

In the case that the swing plate is not moving, the turning of the top plate according to the bottom plate can change the compression ratio and piston stroke. Above – mentioned data are referred to the base coordinate system, which passes through the crankshaft axis. The basic coordinate system, as well as the methodology calculation of the piston stroke is reported in the literature [1].

Proposed and considered were regenerators with different size, work areas, different volume, filling, material and porosity. The basic requirement for regenerator is to capture the maximum amount of heat contained in the working medium-air, when moving from the heated to cooled cylinder and then backward to reabsorb it when moving of cooled air from cooled cylinder to heated cylinder.

It is therefore necessary to propose a regenerator with a space large enough and not too big volume, lowering the final compression engine ratio. The first draft regenerator highlighted the need to synchronize the regenerator size and rotational speed of rotation plate.

Higher speeds reduce time for heat transfer from the working medium into the regenerator material and increased demands placed on the resulting effective surface area of regenerator. The simulation shows the problem of local overheating of the thermal energy recovery system in the knee over the cooled cylinder what was occurred due to a high speed and insufficient dimensioned surface of regenerator.

Regenerator in this case remained cold, respectively was heated only about small temperature. Due to too intense flow through the regenerator the accumulation of heat was not sufficient. Reducing the engine speed was obtained slower flow and increase of the value of accumulated heat in the regenerator. The value of the accumulated heat depends on the properties as regenerator fillers porosity, thermal conductivity, its surface and shape.

Comparison of the effect of regenerator on the course of temperatures in the cooling and the heating cylinder, depending on the regenerator material can be seen in Fig. 5 to 8. As the filler were used steel and aluminium spoons. In both cases the regenerator had the same dimensions, the porosity and the engine speed.

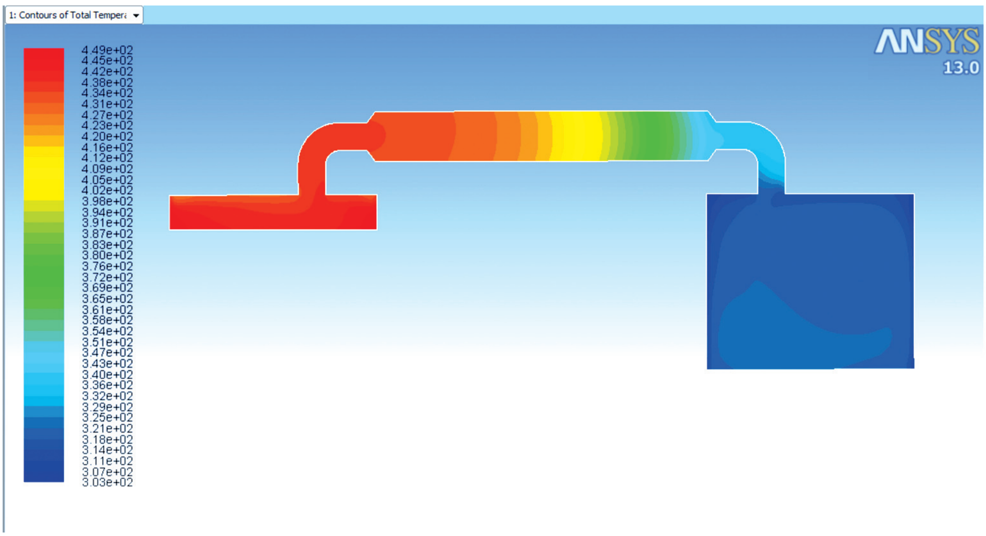

Fig. 5. Distribution of temperatures in the cylinders and regenerator – filler regenerator material steel

Rys. 5. Rozkład temperatur w cylindrach i w regeneratorze – wypełniacz regeneratora: stal

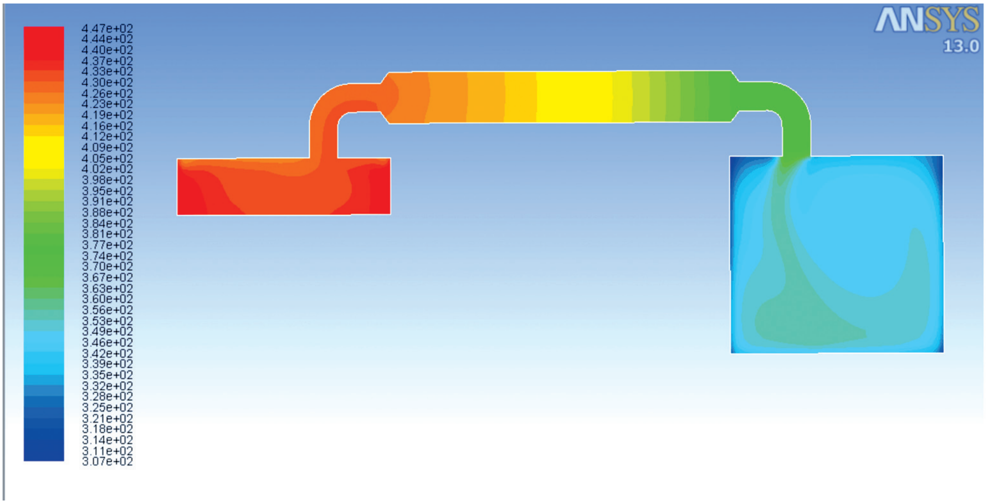

Fig. 6. Distribution of temperatures in the cylinders and regenerator – filler regenerator material aluminium

Rys. 6. Rozkład temperatur w cylindrach i w regeneratorze – wypełniacz regeneratora: aluminium

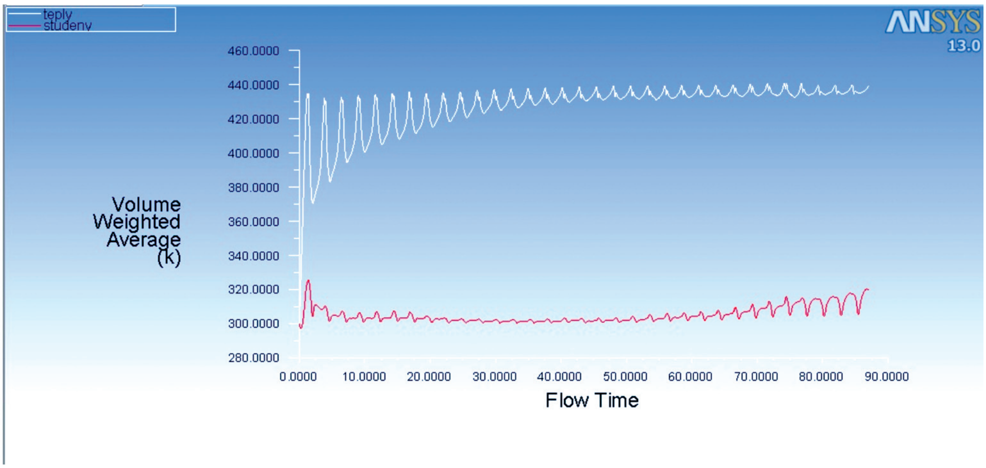

Fig. 7. The course of the temperatures in heating (white) and cooling (red) cylinder – steel

Rys. 7. Przebieg temperatur w cylindrze grzanym (biały) i chłodzonym (czerwony) – stal

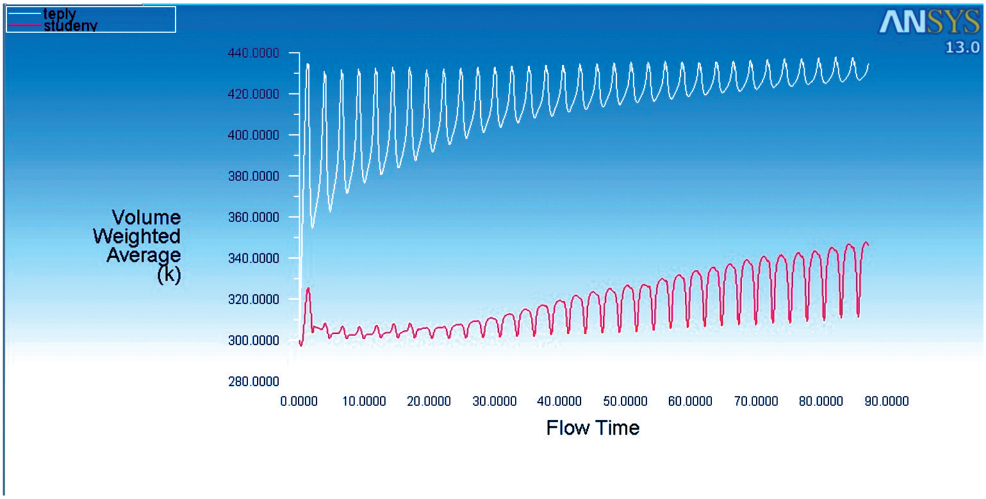

Fig. 8. The course of the temperatures in heating (white) and cooling (red) cylinder – aluminium

Rys. 8. Przebieg temperatur w cylindrze grzanym (biały) i chłodzonym (czerwony) – aluminium

As shown in Fig. 5 and 6 the temperature difference between beginning and end of the regenerator in the case of steel filler was approximately 90 degrees after 90 seconds of the calculation and in the case of aluminium only 50 degrees. In both cases, there came to overheating of the regenerator along the entire length and to penetrating of cooled cylinder with heated air. It caused that the air temperature in the cooled cylinder has risen to unacceptable values. See red line in Fig. 7 and 8.

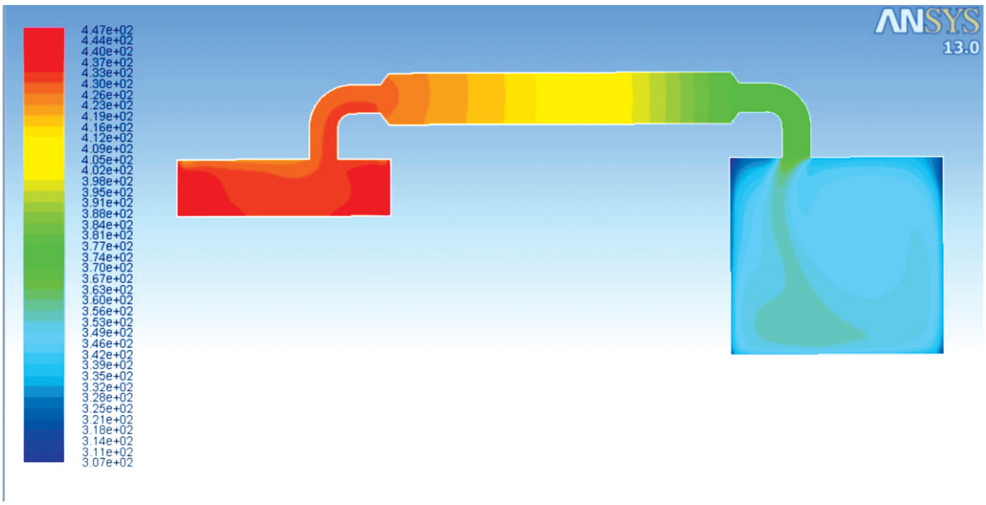

Fig. 9. Distribution of temperatures in the cylinders and regenerator – porosity 0.961

Rys. 9. Rozkład temperatur w cylindrach i regeneratorze – porowatość 0,961

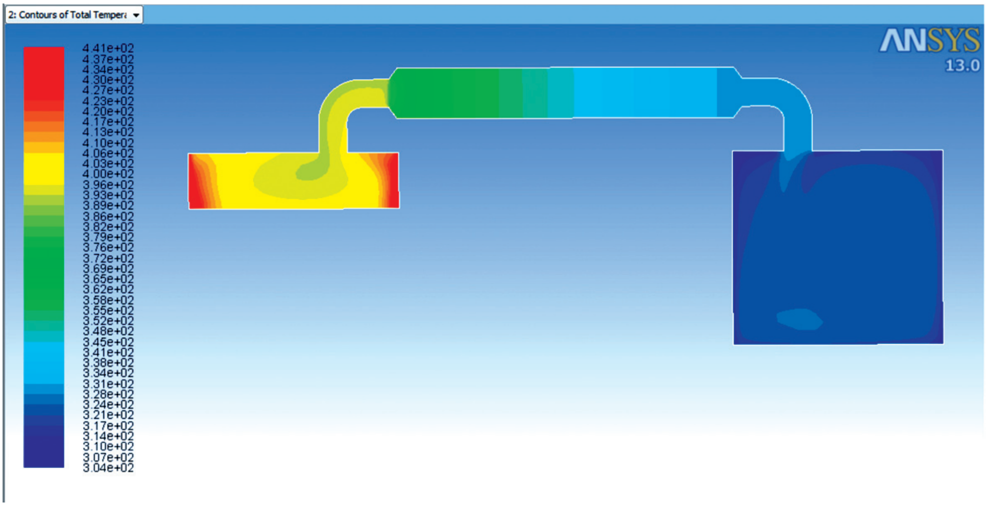

Fig. 10. Distribution of temperatures in the cylinders and regenerator – porosity 0.85

Rys. 10. Rozkład temperatur w cylindrach i regeneratorze – porowatość 0,85

At the design of the regenerator was considered with metal spoons respectively saw-dusts as the filler of the regenerator. These were simulated as a porous material with a porosity of 0.961 or 0.85 and it corresponding resistances. The simulation considered with constant engine speed, regenerator diameter 18 mm, aluminium wire net as filler. Effect of porosity on the distribution and course of temperatures can be observed in Fig. 9 to 14.

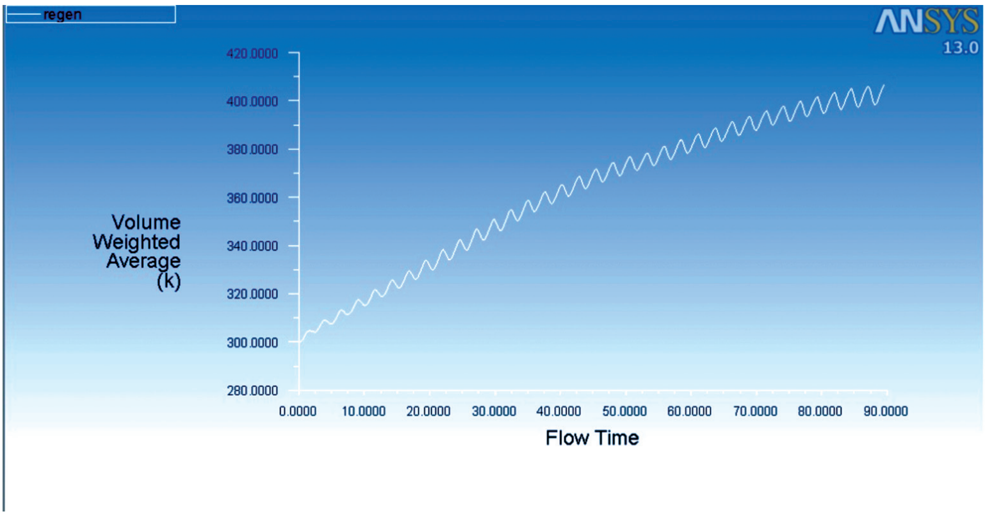

Fig. 11. Average temperature of regenerator – porosity 0.961

Rys. 11. Średnia temperatura regeneratora – porowatość 0,961

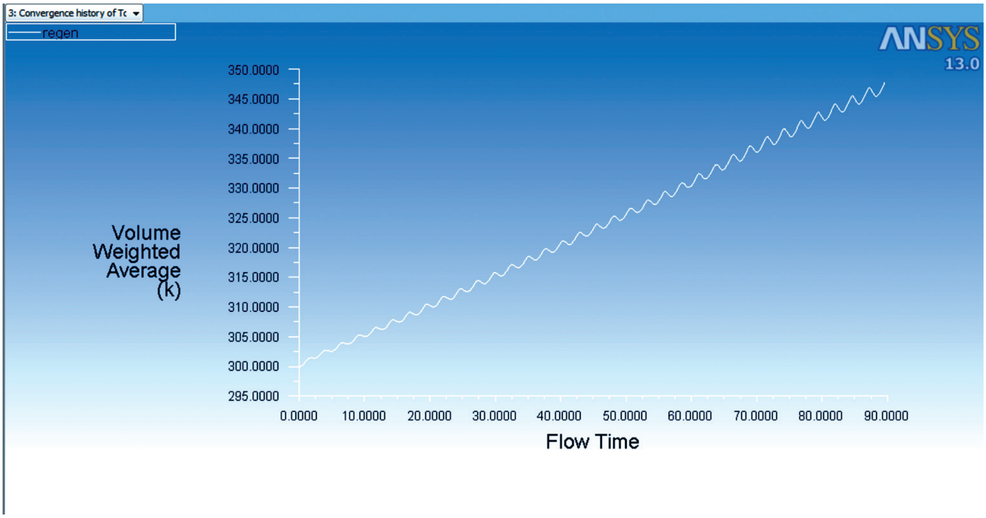

Fig. 12. Average temperature of regenerator – porosity 0.85

Rys. 12. Średnia temperatura regeneratora – porowatość 0,85

Figures 9 and 10 show that at the filling with the lower value of porosity the heat transfer from warmer to colder part of regenerator is not so fast. Using of more porous material will be at the same time period obtained higher average temperature of regenerator but lower temperature of air in heated cylinder. It means that less porous material can better accumulate and backward release accumulated heat.

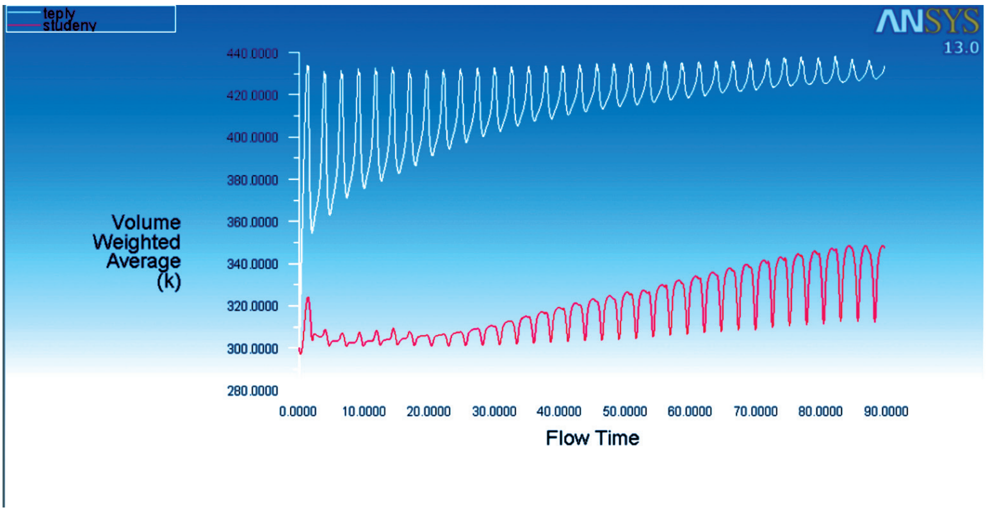

Fig. 13. The course of the temperatures in heating (white) and cooling (red) cylinder – porosity 0.961

Rys. 13. Przebieg temperatur w cylindrze grzanym (biały) i chłodzonym (czerwony) – porowatość 0,961

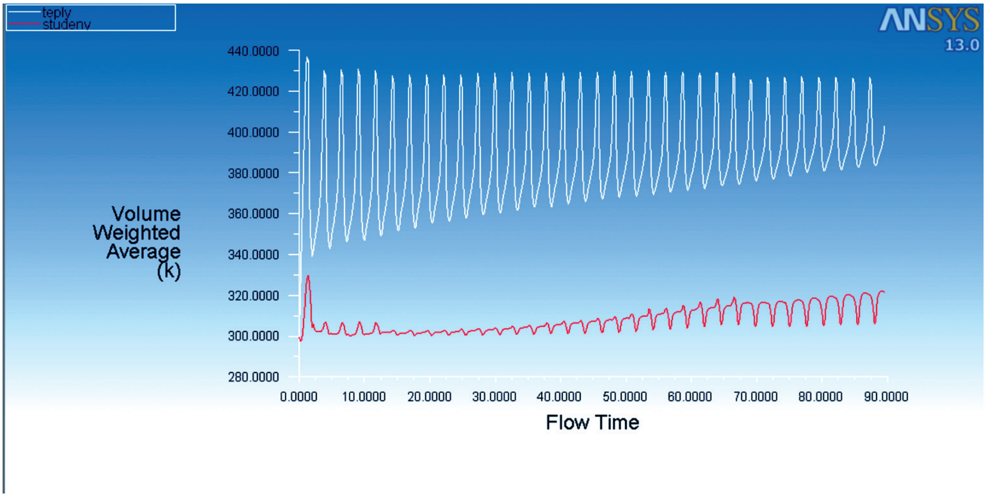

Fig. 14. The course of the temperatures in heating (white) and cooling (red) cylinder – porosity 0.85

Rys. 14. Przebieg temperatur w cylindrze grzanym (biały) i chłodzonym (czerwony) – porowatość 0,85

The temperature difference in heated cylinder during piston stroke is at less porous material almost four times higher, see Fig. 13 and 14. Decreasing of porous amount decrease transfer area what affects regenerator power. On the other side the increase of transfer area causes increase of power but only to certain extent depending on heat amount which is the material able to absorb.

Effect of active surface of regenerator on the course of temperatures was observed too, see Fig. 15 to 20. In this case, it must be said, that there was no unregistered some temperature difference between hot and cold part of the regenerator. In connection with the increase in the diameter of regenerator there was an overall downward shift in the temperature field.

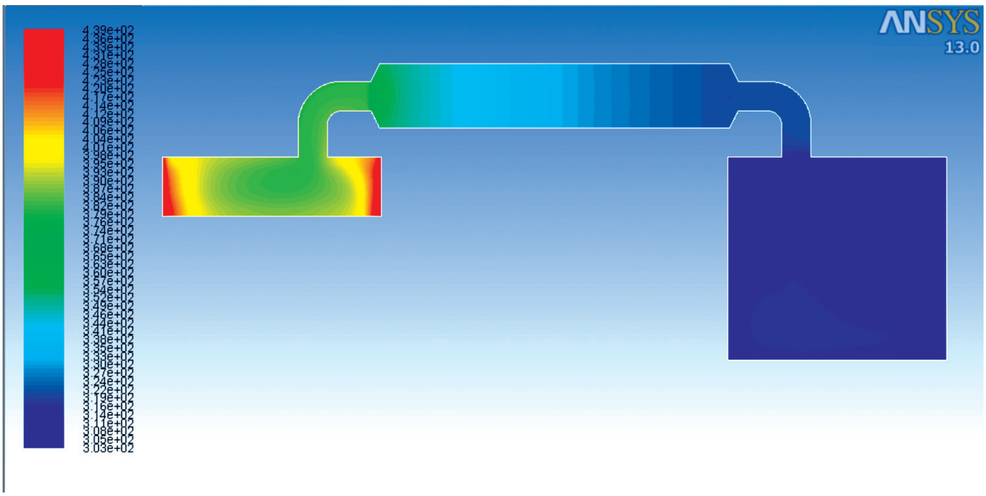

Fig. 15. Distribution of temperatures in the cylinders and regenerator – Dreg = 22 mm

Rys. 15. Rozkład temperatur w cylindrach i regeneratorze – Dreg = 22 mm

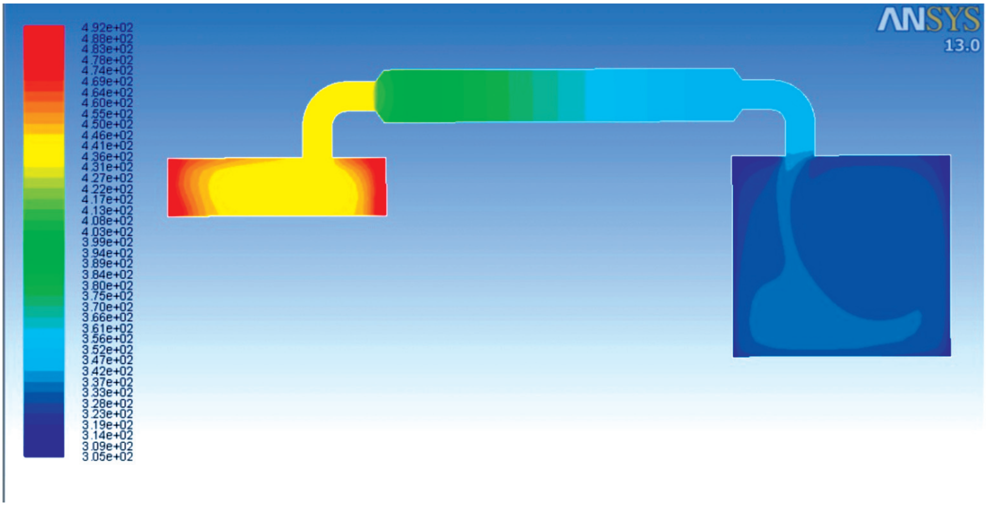

Fig. 16. Distribution of temperatures in the cylinders and regenerator – Dreg = 18 mm

Rys. 16. Rozkład temperatur w cylindrach i regeneratorze – Dreg = 18 mm

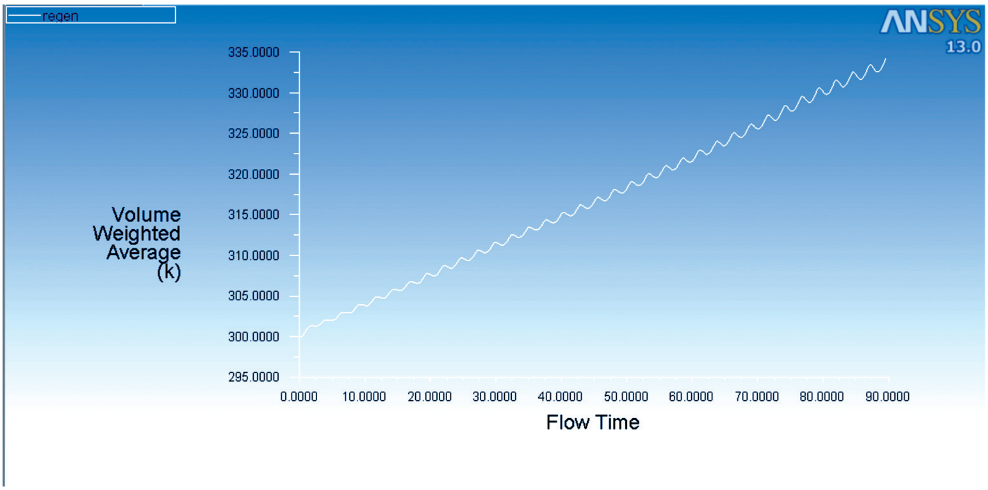

Fig. 17. Average temperature of regenerator – Dreg = 22 mm

Rys. 17. Średnia temperatura regeneratora – Dreg = 22 mm

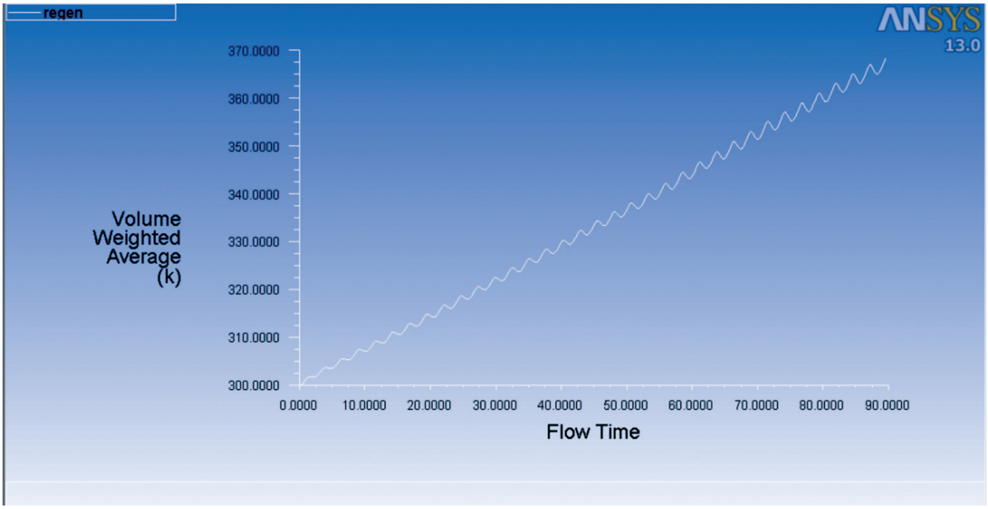

Fig. 18. Average temperature of regenerator – Dreg = 18 mm

Rys. 18. Średnia temperatura regeneratora – Dreg = 18 mm

At the regenerator with smaller diameter Dreg = 18 mm were achieved higher average temperatures in heated cylinder than in the regenerator with Dreg = 22 mm and it in the ratio 490/430 K. Simultaneously the variance of temperature during the working stroke of a smaller diameter was bigger and it in proportion 90/60 K. Also the regenerator temperature was higher in smaller regenerator.

Larger transfer area allows increase the engine speed. Whilst maintaining the same speed increasing area does not make sense.

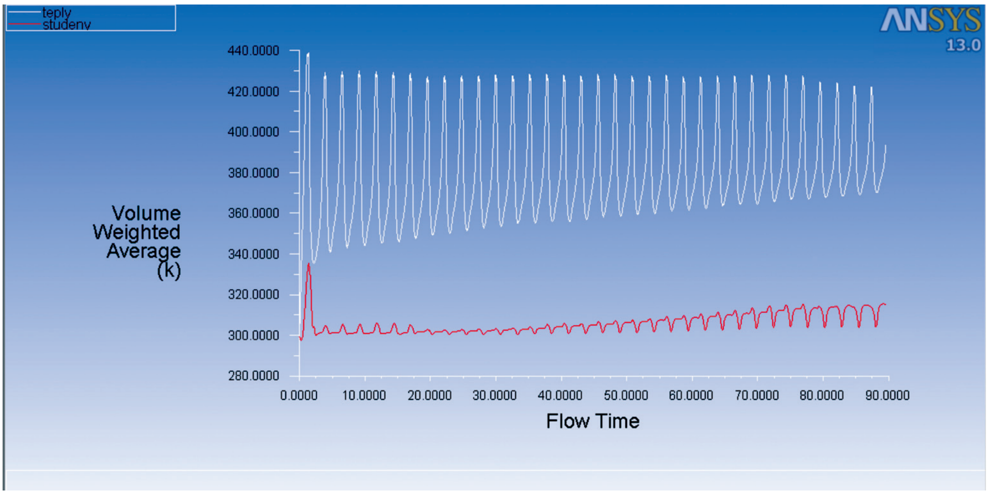

Fig. 19. The course of the temperatures in heating (white) and cooling (red) cylinder – Dreg = 22 mm

Rys. 19. Przebieg temperatur w cylindrze grzanym (biały) i chłodzonym (czerwony) – Dreg = 22 mm

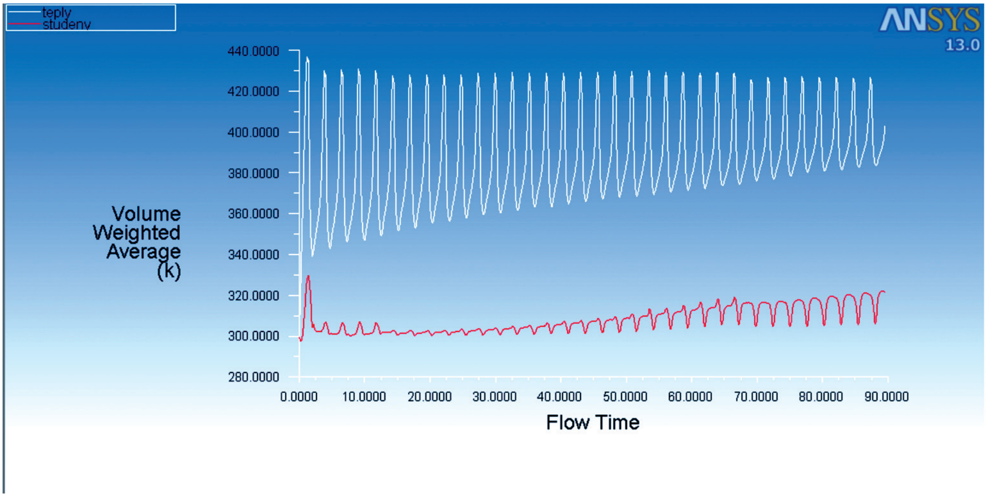

Fig. 20. The course of the temperatures in heating (white) and cooling (red) cylinder – Dreg = 18 mm

Rys. 20. Przebieg temperatur w cylindrze grzanym (biały) i chłodzonym (czerwony) – Dreg = 18 mm

During simulations was investigated the ability to capture the heat in regenerator as much as to cause the least affect of temperature of air entering the cooled cylinder, ergo, that the air leaving the regenerator has the temperature closest to the temperature in a cooled cylinder. Comparing flow and heat transfer in the regenerator was shown that the number of air embossed from hot cylinder must be smaller than the volume of the regenerator. This ensures that the end of the regenerator will be not heated and there will not come to penetrating of uncooled air to the cooled cylinder, see Fig. 21 and 22.

Fig. 21. Distribution of temperatures in the cylinders and regenerator – Dreg = 35 mm, steel

Rys. 21. Rozkład temperatur w cylindrach i regeneratorze – Dreg = 35 mm, stal

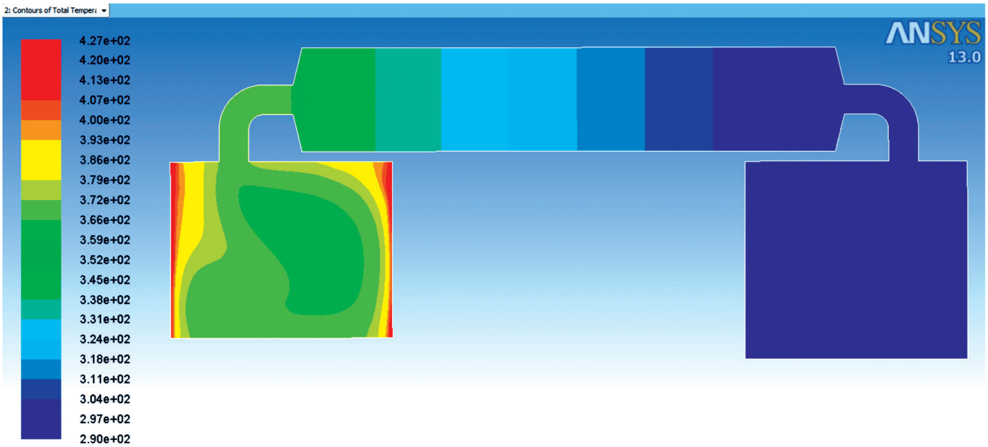

Fig. 22. Distribution of temperatures in the cylinders and regenerator – Dreg = 35 mm, aluminium

Rys. 22. Rozkład temperatur w cylindrach i regeneratorze – Dreg = 35 mm, aluminium

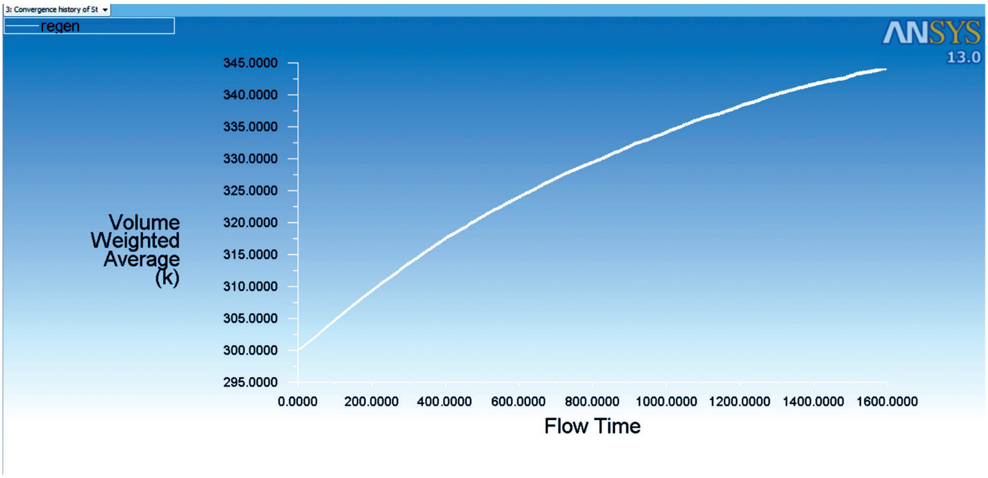

Fig. 23. Average temperature of regenerator – Dreg = 35 mm, steel

Rys. 23. Średnia temperatura regeneratora – Dreg = 35 mm, stal

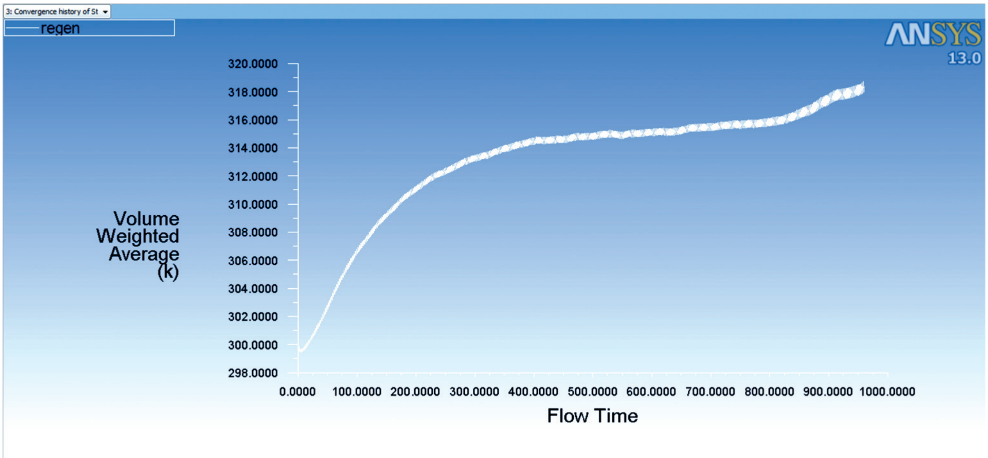

Fig. 24. Average temperature of regenerator – Dreg = 35 mm, aluminium

Rys. 24. Średnia temperatura regeneratora – Dreg = 35 mm, aluminium

On the Fig. 24 we can show that aluminium regenerator steadied after a relative short time compared to steel regenerator in the Fig. 23. This was due better ability aluminium heat transfer and together higher value of specific heat capacity. As seen in Fig. 26. aluminium filling is able to absorb and release the gained heat much more which corresponds with higher difference of temperature in the heated cylinder. Because the steel can not release enough heat in short time, the average temperature of regenerator with steel filling continue in increase as shown in Fig. 23. On the basis of this solution is able to suppose that the steel regenerator would overheat after definitely time along its entire length and release the heat into the cooled cylinder, what is undesirable.

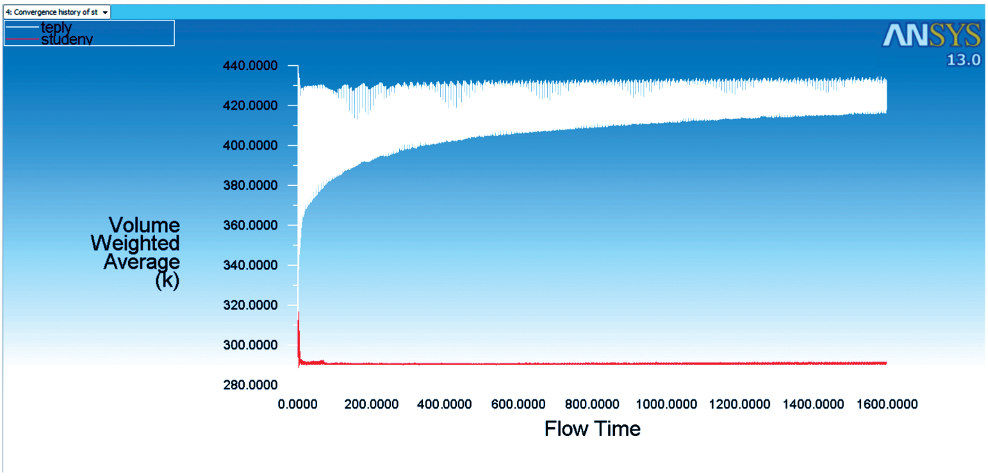

Fig. 25. The course of the temperatures in heating (white) and cooling (red) cylinder – Dreg = 35 mm, steel

Rys. 25. Przebieg temperatur w cylindrze grzanym (biały) i chłodzonym (czerwony) – Dreg = 35 mm, stal

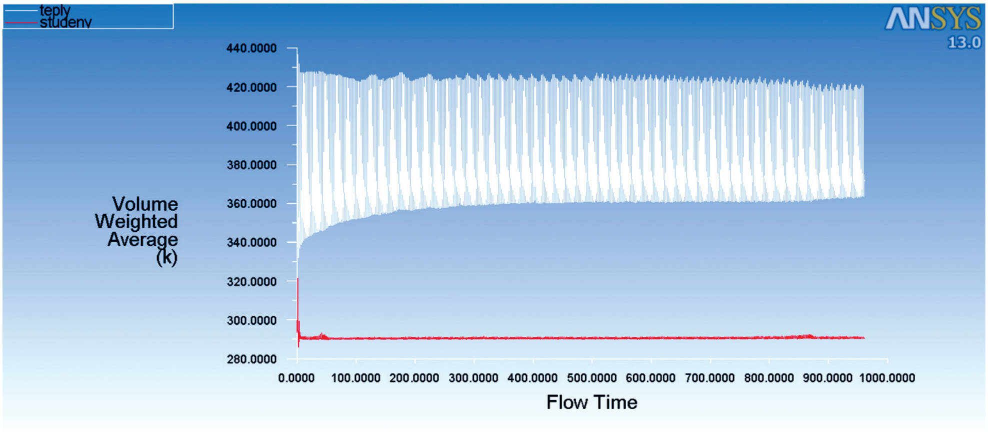

Fig. 26. The course of the temperatures in heating (white) and cooling (red) cylinder – Dreg = 35 mm, aluminium

Rys. 26. Przebieg temperatur w cylindrze grzanym (biały) i chłodzonym (czerwony) – Dreg = 35 mm, aluminium

5. Conclusion

Thermodynamic properties of regenerator directly affect the size engine speed. On their size has a similar effect ability heated cylinder warm transform fed heat into the inside of the cylinder.

Simulations showed that at the regenerator design is important to ensure the correct choice of material filling regenerator, its shape, dimensions and transfer area. The paper reviewed two materials with different physical properties. It was investigated the regenerator filling in terms of porosity, the size of the optimum regenerator volume and material properties.

Materials with higher porosity allow better heat storage and its subsequent release, what results in decreased average temperature in the regenerator. Too low value of porosity can result in an excessive increase in flow resistances through the porous regenerator, which will worsen the thermodynamic properties of the system.

By designing a very large volume of regenerator, it loses its function because there is no sufficient accumulation of heat in the whole volume. Too little volume of regenerator conversely causes its overheating, what result in entry hot medium into the cooled cylinder and the violation of its isothermal equilibrium.

The decisive criterion for the optimal design of the regenerator is chose of material with appropriate physical properties. The simulation showed that aluminum as a material has the best properties for the function of regenerator. In contrast to steel, aluminium allows to release and accumulate approximately three times more heat, resulting in higher performance of the Stirling engine. The advantage of aluminium regenerator is also that it is able to stabilize itself, compared with steel, for a very short time.

This contribution was created within the framework of the project VEGA 1/0763/11, which is supported by the Ministry of Education of the Slovak Republic.

L i t e r a t u r e

[1] K u k u č a P. et al., *NEKOMOT 2002*, Vydavateľstvo EDIS ŽU v Žiline, 2002.