FUNCTIONAL DESIGN, MODELING AND NUMERICAL ANALYSIS OF THE REGENERATOR OF STIRLING ENGINE WITH UNCONVENTIONAL MECHANISM FIK

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Abstract: *The paper deals with a design of a regenerator of Stirling engine with unconventional mechanism of engine FIK. The final design of the regenerator is based on previous simulations of flowing of a working fluid, created in software Fluent. The paper presents basic requirements to be followed in the design of the regenerator. The contribution also contains a dimensional computation of the regenerator, which describes basic procedures and boundary conditions in the computation of the designed shape of the regenerator.*

Keywords: REGENERATOR, THERMAL EFFICIENCY, UNCONVENTIONAL MECHANISM OF ENGINE FIK, NUMERICAL ANALYSIS

1. Introduction

One of the possibilities of utilization of unconventional mechanism of engine FIK with inclined board is its modification in Stirling engine. [5] In the figure 1, there is a sectional view of a virtual model of the mechanism shown. Stirling engine is a displacement machine, which performs work on the basis of changes of temperature, pressure and volume of the working medium. Stirling engine belongs to a group of engines with external continuous combustion. [6] Its characteristic feature is a closed circulation of the working medium. Nowadays, as the working medium in the design of Stirling engine is used air, helium and hydrogen.

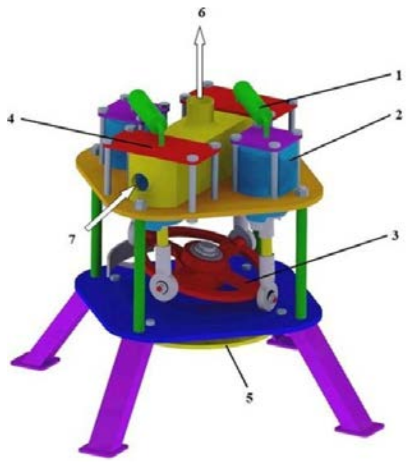

Fig. 1 *Virtual model of unconventional mechanism FIK: 1 – regenerator, 2 – cooled cylinder, 3 – swing plate, 4 – heated cylinder, 5 – flywheel, 6 – heat output, 7 – heat input.*

Regenerator represents the heat exchanger and temporary heat accumulator between the heated and cooled side of the engine. Regenerator has a great impact on the efficiency and overall performance of the Stirling engine. Sufficiently large temperature gradient between the heated and cooled side of the engine has favourably influence at a thermal efficiency of the Stirling engine. The greater the temperature difference, the higher the thermal efficiency.

2. Synthesis of knowledge in the design of the regenerator

Regenerator, from the design point of view, may be of a various shape and arrangement. In most cases, the regenerator consists of one or more axial passages. The individual passages are filled with a filler of the regenerator (Fig. 2). Regenerator together with the connecting pipes must be designed for the smallest lossy volume. The lossy volume of engine means the volume, into which, during the work cycle, does not interfere neither the heated cylinder nor cooled cylinder [7].

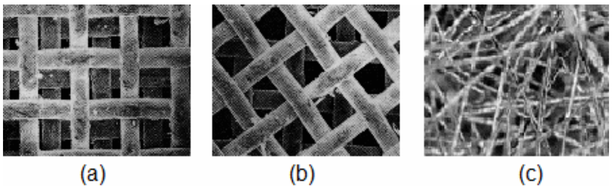

Fig. 2 *Examples of arrangement of filler of the regenerator: a) network filler regularly arranged, b) network filler irregularly arranged, c) filler created from wires of irregular arrangement. [3]*

In the designing of the regenerator, the right choice of the filler material of the regenerator is very important. The filler of the regenerator must satisfy certain requirements, so that the Stirling engine operates properly. The filler material of the regenerator, which creates the regenerator´s core, must have good thermal conductivity, high thermal capacitance, corrosion resistance, low thermal expansion. Suitable materials for the filler of the regenerator are aluminium, copper, steel and the like. With respect to the structural design of the shape of the regenerator, the filler must have low porosity to avoid an increase of a harmful volume. The filler regenerator must have as great as possible heat - exchange surface and must ensures the flow of working medium with as little pressure loss as possible. On the bases of the above findings, the basic requirements for the regenerator to satisfy could be deduced:

- must allow the accumulation (regeneration) of the required amount of heat to maintain the required temperature differential,
- must have the least pressure loss,
- must have the minimal lossy volume

3. The Functional design of the regenerator

The design of the shape and main regenerator dimensions was made on the basis of selected parameters of the designed mechanism. In the designing of the shape of regenerator was necessary to take into account certain design parameters of Stirling engine with unconventional mechanism FIK such as diameter and stroke of heated and cooled cylinders and a spacing distance between the cylinders. The designed engine was chosen as short - stroke (under - squared) engine with diameter of cylinders 75 mm and a stroke of 72 mm [2]. In the design of the regenerator it was necessary to take into account besides design parameters also performance parameters, which Stirling engine with conventional engine FIK must achieve. Required parameters of the mechanism:

Performance P = 2 kW, the compression ratio $\varepsilon = 2$, a thermal gradient of 190 ° C, the engine speed $n = 200\ \text{min}^{-1}$, excess pressure in the engine $p = 0.2$ MPa [1].

Virtual model of the regenerator was created by using CATIA software, on the base of engine construction with mechanism FIK. Subsequently, for the designed shape of the regenerator was designed filler of a various materials. The designed regenerator together with the filler was exposed to simulation in Fluent software. Functional properties of the regenerator and its filler were verified by using the Fluent software [4]. During the simulations were monitored various parameters such as the temperature inside the regenerator, the speed of heat transfer between the working medium and the filler, the direction of flow of the working medium in its transition between heated and cooled side of the engine, the pressure progressions in the regenerator and more other parameters. On the basis of simulations of flow of the working medium through the various constructional designs of the regenerator was created the final shape of the regenerator, which is shown in Figure 3:

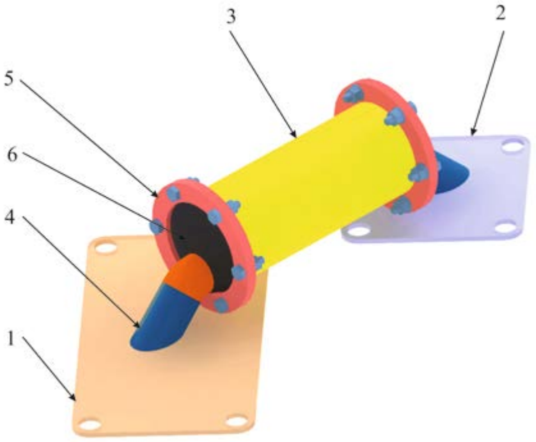

Fig. 3 *Virtual model of the regenerator: 1 - flange of the cooled cylinder, 2 - flange of the heated cylinder, 3 - body of the regenerator, 4 - connecting tube, 5 - coupling flange, 6 - transition cone.*

The bodies of the regenerator with flanges create a major part of the regenerator. The body of the regenerator is made of a copper sheet with thickness of 2 mm and an internal diameter of 51 mm. The steel coupling flanges are welded to the end faces of a regenerator. The inside of the regenerator body is filled with filling from an aluminium material. Used filler of the regenerator depicted at the figure 4 has louvre structure. Aluminium filler is set along in a body of the regenerator. The frontal areas of individual elements of the filler in the body of the regenerator are oriented normal to an axis of the regenerator. These elements are asymmetrically swing concerning to an axis of the regenerator, whereby similar structure as in the figure 2 b) is created.

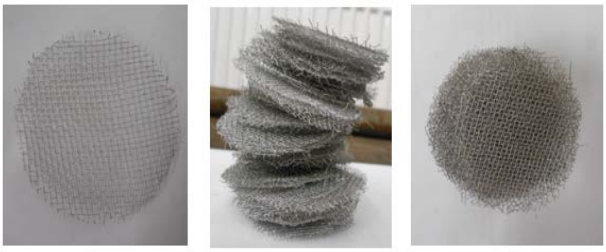

Fig. 4 *Structure of the filler of the regenerator.*

A transition piping of the heated and cooled cylinder are screwed on the body of the regenerator by flanges. A material of the body of the regenerator and transition piping were designed on the basis of requirements on good heat conductivity and low weight of the entire system. According to figure 5, the construction of both transition pipes is the same. The difference between each of transition piping is just in particular flanges, which are made from steel and by which the whole assembly of the regenerator is screwed on the cylinder head of the nonconventional engine FIK. The transition piping is made from a copper sheet metal thickness 2 mm and inside diameter 19 mm. A part of the transition piping is also a non-coaxial conic passage. This way designed atypical shape of the conic passage is significant due to better flow of the working fluid through the regenerator. Individual parts of the transition pipes are welded to each other. A material of individual flanges, which creates connecting elements between individual parts of the regenerator, is designed on the bases of requirement on higher stiffness of the construction [3].

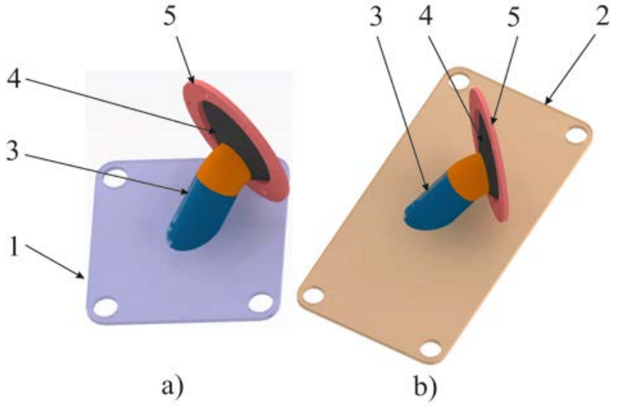

Fig. 5 *Transition piping: a) heated cylinder, b) cooled cylinder.*

In the figure 6 there is a real model of the regenerator depicted. Before production of the regenerators, numerical computation was realised to verify safety against overloading of admissible stress of the body of the regenerator by an influence of internal overpressure.

Fig. 6 *Real model of the regenerator.*

This computation was realised by computing program Adina. Numerical analyse is in major part of cases markedly less expensive than real testing and experiments. With its help, it is possible to realise many versions of a solution in a very short notice and to appoint a variant, which meets the needs of the production and the usage of the specific mechanical component the best.

4. Dimensionally verification of the regenerator by the numerical analyse

By using a finite element method it is possible to simulate loading of a component and so compute an effect of the loading in its volume. It is concerned about a distribution of load and critical position finding with high local value of stress (e. g. sharp edges, step change of a cross section of a component, etc.). Primarily, it is necessary to provide a model of a component to program (fig. 7), which may be built directly in the FEM program or in whatever computer aided program for design and subsequent import to FEM program.

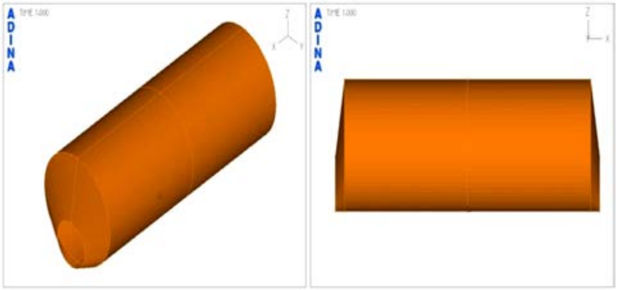

Fig. 7 *3D model of body of the regenerator created in the program Adina (left), on the right 2D depiction for better illustration of the shape of frontal area of the regenerator.*

If the model of the component is created, it is necessary to put material properties to program. For simple computation of static loading (most of components in engineering), a program for its correct function, makes do with values of elastic modulus, Poisson´s ratio (presents absolute value of fraction of specific strains), if appropriate density. Chosen material of the regenerator body was a high purity copper 99, 9 % with a value of elastic modulus E = 1, 1 x 1011 Pa, elastic limit Re = 60 MPa, density ρ = 8 940 kg.m-3, Poisson´s ratio μ = 0, 34 (-). A computation was carried out with these values of parameters. If we consider thermal loading, it is necessary to assign values of dilatability and heat conductivity factor with known value of elastic modulus at the temperature of the heated regenerator. Whereas this temperature (about 250 °C) presents small value against fusion point of copper (1084.62 °C), an influence of increased temperature (difference between elastic modulus at 20 °C and 250 °C) will be intercept by increasing of surety factor k, which will include the influence of loading of regenerator (disappearing compression stress) and increased operating temperature of the regenerator (250 °C). Therefore it was chosen required surety factor kmin = 2,7 (-). The following is a loading of component, which needs to be "anchored", thus define number of degrees of freedom for some of points or surfaces of the component (fig. 8 left).

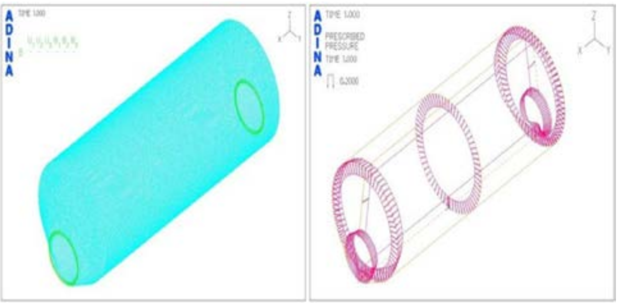

Fig. 8 *Gripping of the regenerator (left) and loading of the regenerator by inside pressure p = 0, 2 MPa (right).*

Gripping of the regenerator is practically solved as fixing into transition piping (as seen on fig. 1, 3, 5 and 6). Therefore gripping of the component was chosen to be a fixing into an area, where transition piping will be attached at assembly (fig. 8 left – green coloured circles). Subsequently, we can apply external loading, if appropriate temperature (at some of surfaces, points or entire solid). In this case, it is a distributed inside pressure about the size p = 0, 2 MPa (fig. 8 right). After defining material properties and boundary conditions, designing and creating of the mesh follow (fig. 9). A component is divided into many small finite elements and each element has defined material properties in its nodal points.

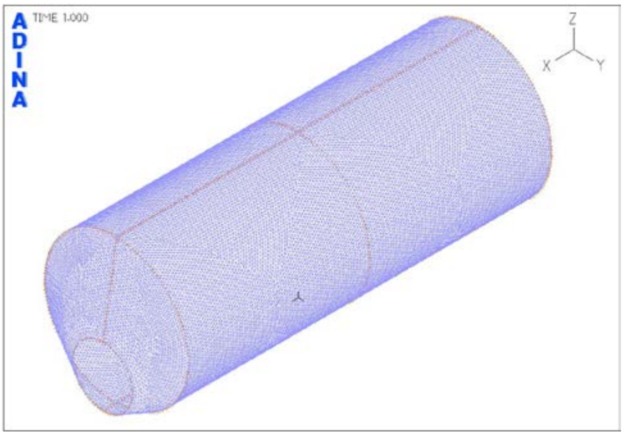

Fig. 9 *FEM mesh of the regenerator.*

The entire component is meshed by triangular four – nodal elements (as it is solved as a shell, owing to small thickness of a body wall of the regenerator – 2 mm). Creation of the mesh is the most important step before the computing, because at generation of a wrong designed mesh may come to deformation of the elements in areas with complicated shape of the component – this, during computation, leads to inability of program to accomplish the computation. An important step is setting of time step length of computation or number of steps, because the computation is iterative and must converge. Iterative methods are useful at solving (generally) large systems of non-linear equations by successive approximation to an exact solution.

If we use very dense mesh from complicated elements (i.e. elements from many nodes), it is necessary to enlarge number of steps of the computation to ensure faultless running of computation. After accomplishing of computation by the program, we can display results by post processor (fig. 10 and 11).

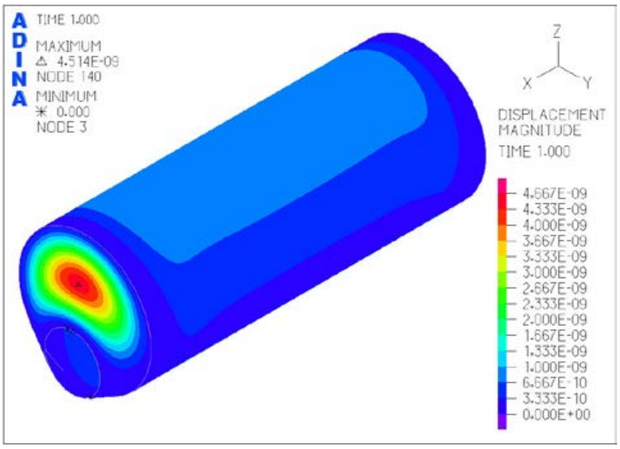

Fig. 10 *Displayed displacements on the body of the regenerator by the influence of the loading.*

5. Conclusion

By numerical analyses it is possible to simulate a process of the loading very real and on the bases of the reached results (stress and strain, temperature field, material structure, hardness, plastic deformation, etc.) is possible to effectively perform optimalization of technologies. In this case, maximal effective stress detected by numerical analyse at program Adina, as seen in fig. 11, is located in frontal area of the body of the regenerator in fixing area.

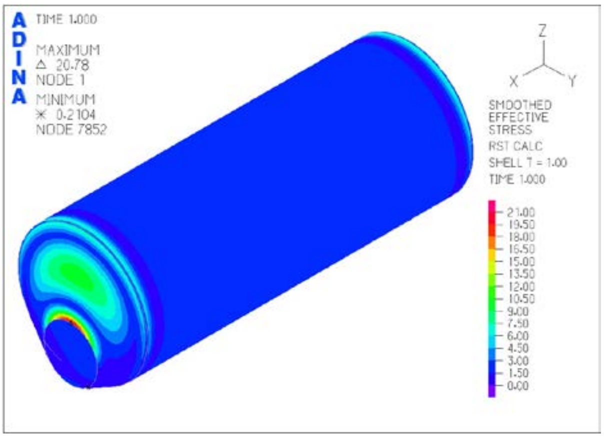

Fig. 11 *Simulated effective stress von Mises detected on the regenerator´s body.*

Value of this effective stress is 20.78 MPa, what is third of the value of admissible stress of the material, which the component is made from. It means that regenerator´s body designed in this way (geometry, loading) is suitable for utilisation at purpose for which has been engineered with sufficient surety factor in running.

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Subject of research was TiAl6V4 alloy in the form of the fine powder. This light alloy (see Fig. 2) has excellent mechanical properties Tab. 2 and corrosion resistance in combination with low specific weight and biocompatibility. The material is mainly used in aviation, in the manufacturing of racing cars and in medical applications (manufacturing of implants, see Fig. 3).

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