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COMPUTER ANALYSIS OF AERO-GAS-THERMODINAMIC PARAMETERS OF FLOW OF WORKING FLUID IN A PISTON ENGINE WITH EXTERNAL SUPPLY OF HEAT

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Abstract: *Currently there exist no universal analytical or numerical methods for calculation of internal circuit of piston engines with an external supply of heat, in particular of Stirling engines. In practice during the engineering and refining process of Stirling engines often are required theoretical and experimental data about the parameters of pulsating flow of working fluid with a periodic change of flow direction. To obtain such data, in general, is needed a solution of complex inter-related problems of dynamics of mechanical parts of engine taking into account the thermoelasticity at unsteady heat transfer between the working fluid and the walls of cylinder of engine, heater, cooler, regenerator and other heat exchangers.*

In this paper is developed a method of computer simulation and numerical analysis of gas - thermodynamic parameters of individual units of engine with an external supply of heat (Stirling engine) with stationary and pulsating flow of working fluid in regenerative heat exchangers in order to optimize them. Mathematical model of gas flow is described by the Navier-Stokes equations for a compressible fluid taking into account heat transfer processes. Computer simulation and numerical solution were implemented using known CAD/CAE/CFD engineering software.

KEYWORDS: STIRLING ENGINE, RECUPERATIVE HEAT EXCHANGER, PULSATING FLOW, COMPUTER SIMULATION NUMERICAL COMPUTATION.

1. *Introduction*

In the process of design and development of Stirling engines [1,2] we experienced a lack of theoretical and experimental studies on applied thermodynamics, unsteady gas dynamics and convective heat transfer in case of rapid change of current direction. A need for a complex solution for some thermodynamic, mechanical, technological, heat- and gas-associated problems became especially apparent.

In a classic Stirling engine thermal energy is converted into mechanical energy through the compression of a fixed mass of working fluid under low temperature and its subsequent expansion after heating. Since the work of the piston during compression is less than its work during expansion, the engine generates mechanical output.

Due to regeneration, one only needs to supply heat to keep the working fluid hot during expansion and remove the heat generated after its compression.

The temperature change is provided by locking the working fluid in two separate cylinders, one hot and the other - cold, between which it travels under the action of pistons.

Volume change cycles in these cylinders must have a phase difference, and so does the resulting total volume change cycle comparing to the pressure cycle. This is a necessary condition for net power output.

The present paper discusses a single-cylinder single-acting engine with a power piston and a displacer piston. The engine was developed in Riga Technical University as part of ERAF project. Unlike classical Stirling engine, this engine has recuperative heat exchangers [3,4]. The working fluid travels in separate streams, heating in the heater and cooling in the cooler. This provides a greater power output at an equivalent volume of the cylinder.

This particular Stirling engine consists of the following basic elements: a power piston, a locked cylinder, a heater and a cooler.

The purpose of this paper is to develop a method of computer modeling and numerical analysis of gas- and thermodynamic parameters of the individual components of an external combustion engine (Stirling engine) with stationary and pulsing working fluid currents in regenerative heat exchangers at the aim of their optimisation.

2. Background.

There is currently no universal analytical or numerical method for designing the core of an external combustion engine and Stirling engine in particular.

Generally, to obtain such data it is necessary to solve a series of complex interconnected problems concerning the dynamics of mechanical components of the engine under conditions of unsteady heat transfer between the working fluid and the walls of the cylinder, heater, cooler, generator etc..

The computer modelling of the aerogasdynamic and thermodynamic properties of the basic elements of the Stirling engine was executed with the help of CAD/CAE software, such as SolidWorks and Cosmos Floworks [6], which ensures the completion of all necessary tasks within an acceptable timeframe.

The gas-thermodynamic input parameters can be described using a set of Navier-Stokes equations with additional equations for laminar and turbulent exchange. A three-dimensional geometrical computer model was created using SolidWorks CAD software to later obtain the numerical solution in CosmosFloworks CAE. The initial set of Navier-Stokes equations was solved in CosmosFloworks using the finite-volume method.

The flow of working fluid in a Stirling engine is unsteady and periodically pulsating.

To emulate the action of Stirling engine pistons we used CosmosMotion software, which is integrated in SolidWorks and functions on its geometrical model. All calculated and output data were saved using the SolidWorks model framework.

3. Problem solution

The choice of the heat exchanger was made by taking into account the design simplicity, material costs and the heat transfer conditions on both sides of the heat-transferring surface. Finned tubular exchanger is an example of a balanced choice.

3D models of tubular air-coolers with longitudinal, threaded and spiral fins were created in SolidWorks (fig. 1 (a-e)).

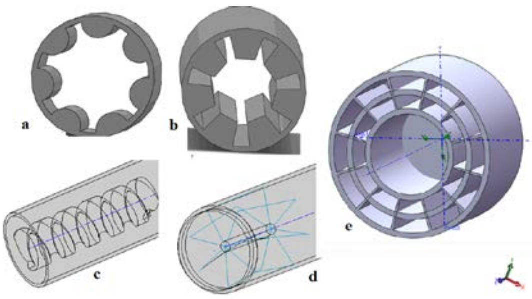

Fig.1. *3D models of tubular air-coolers with longitudinal, threaded and spiral fins*

A study on the effect of pulsating movement of hot heat carrier (air) on the cooling process in the air cooling unit was made using finned and unfinned versions of a tubular heat exchanger (fig.1e), in which air is being cooled by cold water in counter-flow (fig.4). The temperature on the inlet of the cooling unit is 600^{o}C, with redundant pressure of 10 atm. The required output temperature is about 400^{o}C. A detailed method for computer analysis of heat exchangers of a Stirling engine with nonsteady pulsating flow is described in this paper [5].

It is worth noting that the pulsations of air volume flow rate Q(t) are connected with the changes of the speed, at which the work piston moves the hot gas into the cooler. Linear movements of the pistons were modelled using CosmosMotion software.

The temporal variation of the upper and lower piston movements at 500 rpm is plotted in Fig.2. Mass and volume flow rate variation in time on both ends of the cooler are shown in Fig.3.

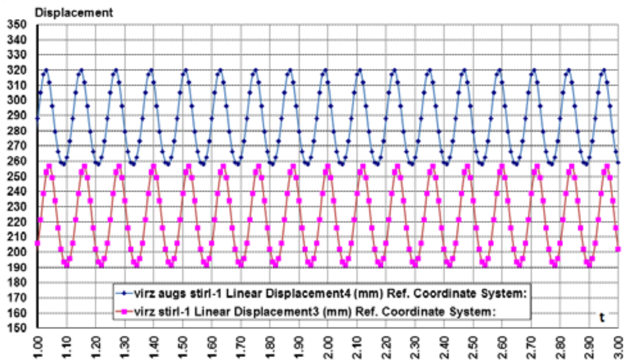

Fig.2. *The temporal variation of the upper and lower piston movements at 500 rpm*

To justify the use of quasistationary computation methods for approximate evaluation of the time-average parameters of the heat exchanger, two air movement modes were analysed:

- *nonsteady*, with pulsating volume flow rate Q(t) and mass flow rate Q(m);

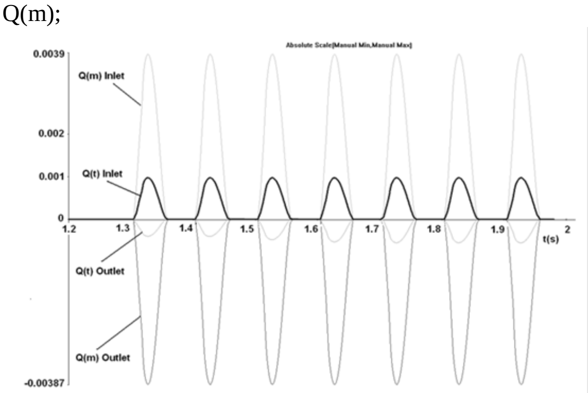

Fig.3. *Nonsteady mode: Q(t)inlet- volume flow rate at the inlet; Q(t)outlet- volume flow rate at the outlet; Q(m)inlet- mass flow rate at the inlet; Q(m)outlet- mass flow rate at the outlet;*

- *stationary*, with time-average volume flow rate

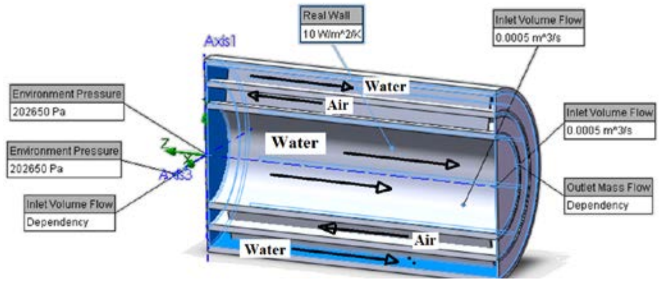

Fig.4. *Boundary conditions of the finned tubular cooler.*

According to the results, the flow pulsations significantly affect the equitability of air distribution and its temperature after cooling.

The temperature distribution in the longitudinal section of the finned cooler with stationary and nonsteady air movement modes is shown on Fig.5.

Steady-state conditions *Nonsteady state*

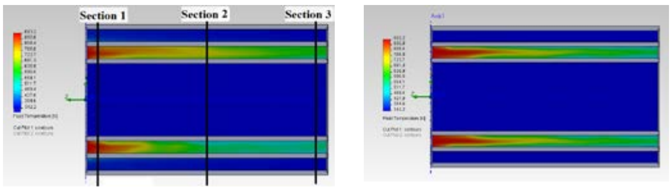

Fig. 5. *The distribution of temperature in the longitudinal section of the finned cooler with stationary and pulsating flow rate.*

The corresponding temperature distribution patterns for lateral sections 1,2,3 (fig.5) are shown in fig. 6.

Steady-state conditions *Nonsteady state*

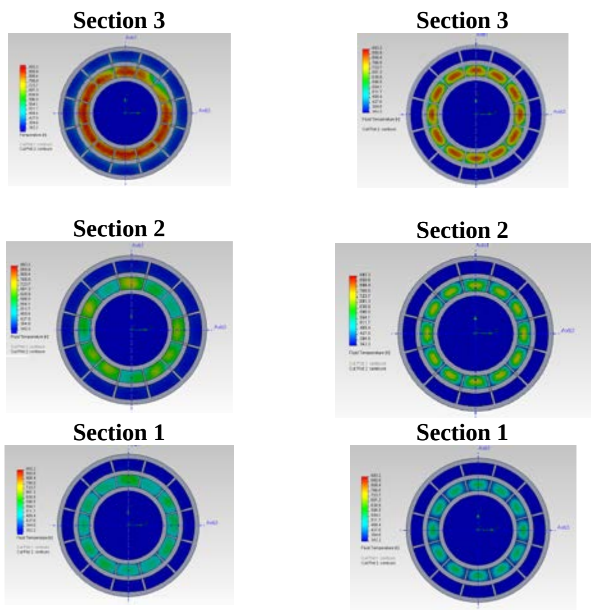

Fig. 6. *Temperature distribution patterns for lateral sections 1,2 and 3 of a finned cooling unit in cases of stationary (left row) and pulsating (right row) hot air flow.*

Results proved that it is possible to use the quasistationary method for approximate calculations, given the heat exchanger is relatively short.

We then analysed the parameters of the annular air-cooler installed on the outside of the Stirling engine cylinder. Again, two air flow modes were considered. A predictive geometrical model of such annular cooler is shown in figure 7 placed on the engine cylinder model.

A stream of hot air (T=893.2 K) enters a two-sectioned annular air cooler through a system of openings on the perimeter with a stationary mode volume flow rate of Q=0.00032 m^3/s, under atmospheric pressure (P=101325 Pa) (fig. 10). The required temperature on the outlet is T = 343.2 K. If the input is unsteady, the volume flow rate is described by a time dependent function (fig.8).

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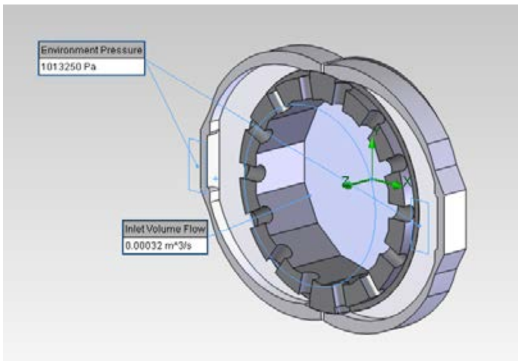

Fig.7. *A predictive geometrical model of such annular cooler on the engine cylinder model.*

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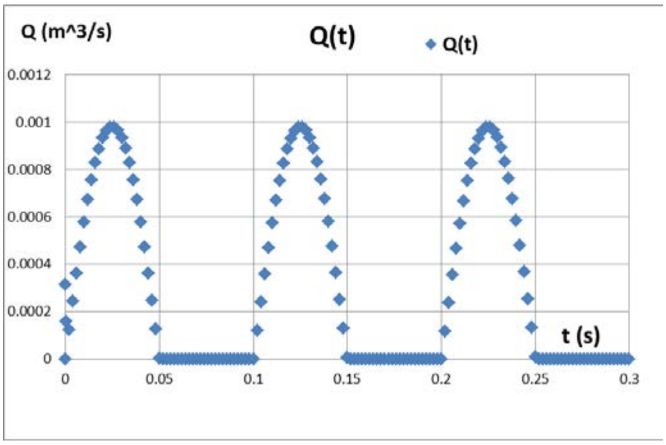

Fig.8. *Time dependence of the volume flow rate.*

Since the openings, through which hot air enters the cooler, are positioned in a circle (fig.9), the distribution of temperature along the section middle line (radial arc, fig. 9) is quite uneven, as shown in fig.10.

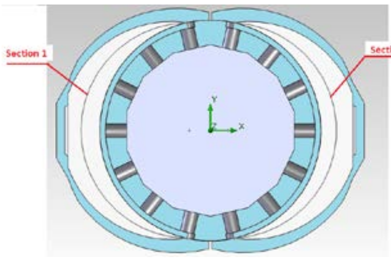

Fig.9. *Annular air-cooler section middle lines. Section 1, Section 2.*

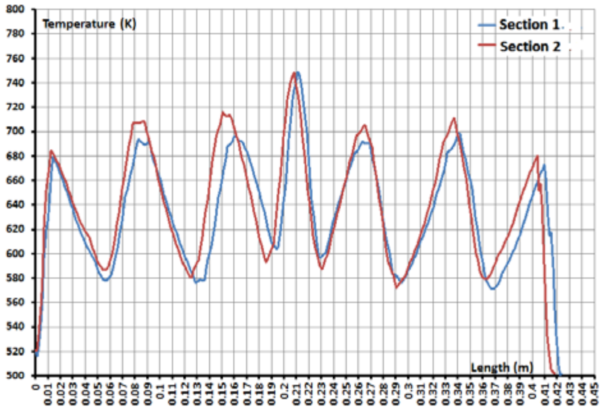

Fig.10. *The distribution of temperature along the section middle line*

The corresponding 3D image of hot air stream movement (direction marked by arrows) and temperature distribution is shown in fig. 11.

Steady-state conditions *Nonsteady state*

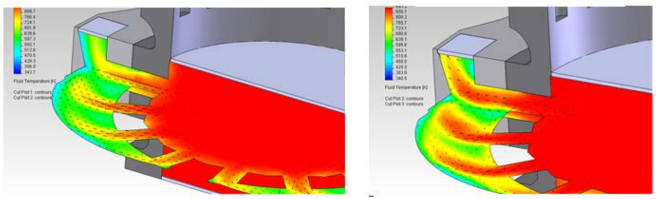

Fig.11. *The 3D image of temperature distribution and hot air stream vectors in the annular air-cooler.*

The pattern of temperature distribution inside the two-sectioned annular cooler with stationary or unsteady hot air currents is shown in fig. 12.

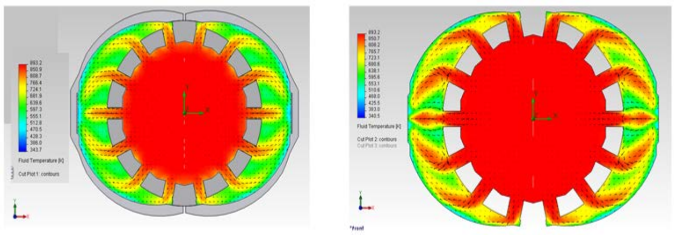

Fig.12. *The pattern of temperature distribution inside the two-sectioned annular cooler.*

Analyzing the results showed that due to a substantial inequality of temperatures inside the cooler its geometrical model needs to be improved.

4. Conclusions

- ✓ A method was developed for computer modelling and numerical analysis of gas-thermodynamic parameters of the individual engine elements with stationary and pulsating working fluid currents.
- ✓ We justified the use of quasistationary calculation method for the evaluation of the heat exchanger parameters.
- ✓ The research of the two-section annular air-cooler showed that its base geometrical model needs to be improved, due to the unevenness of temperature distribution inside the cooler.

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Acknowledgments

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