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METHOD FOR MODELLING TEMPERATURE DISTRIBUTION IN EXHAUST SYSTEM OF DIESEL ENGINE IN THE LIGHT OF MINE SYSTEMS OF HEAT RECUPERATION

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Abstract

Analysis of temperature distribution and heat flow in the exhaust system of diesel engine to determine technical parameters of the system for heat recuperation and changing of thermal energy into electric energy was presented. Temperature of exhaust gases as well as geometrical and material features of exhaust system were the input data accepted for modelling. Computational Fluid Dynamics (CFD) was used to determine temperature distribution in the exhaust system. The software by use numerical methods (finite volume method) enables solving partial differential equations consisting of equations of: continuity, Navier-Stokes, Fourier-Kirchoff and complemented with other equations important as regards the discussed phenomenon (e.g. with turbulences models)transforming them in the algebraic equations or common differential equations. CFD software enables gaining some information as regards flow rate, distribution of speed field, and pressure field as well as heat flow, temperature field and mass field.

Design and principle of operation of Peltier's cell, model of recuperator, exhaust system, and diesel engine, finite elements meshing, boundary conditions assumed in analysis of exhaust gases and water flow, distribution of temperature field (maximal temperature of scale 335 K and maximal temperature of scale 400 K) on external wall of exhaust system and cross-section of exhaust system are presented in the paper.

Keywords: *recuperation, diesel engine, Peltier's cell, temperature distribution, CFD*

1. Introduction

Analysis of methods for recuperation and transformation of thermal energy [1] as well as prospects of development of recuperation systems in mine diesel drives [2], on the basis of which the concept of the system implementation, was the basis for carrying out further research work in that area. From three presented solutions an installation of recuperator, which bases on Peltier's cell, in the exhaust system of diesel engine (Fig. 1) was selected and realized. The thermoelectric cell is based on the principle of transformation of thermal energy into electric energy basing on Seebeck effect [6].

An idea of using Peltier's cells assumes constructing a recuperator's chamber on which bank of termocells, connected with each other, will be installed (Fig. 2). The chamber task will be to limit the maximal temperature of cells to 250° C. Control of temperature will be realized by changing flow rate of cooling medium passing the recuperator. It is planned to install the system in the inlet system of diesel engine, behind a turbocharger (Fig. 3).

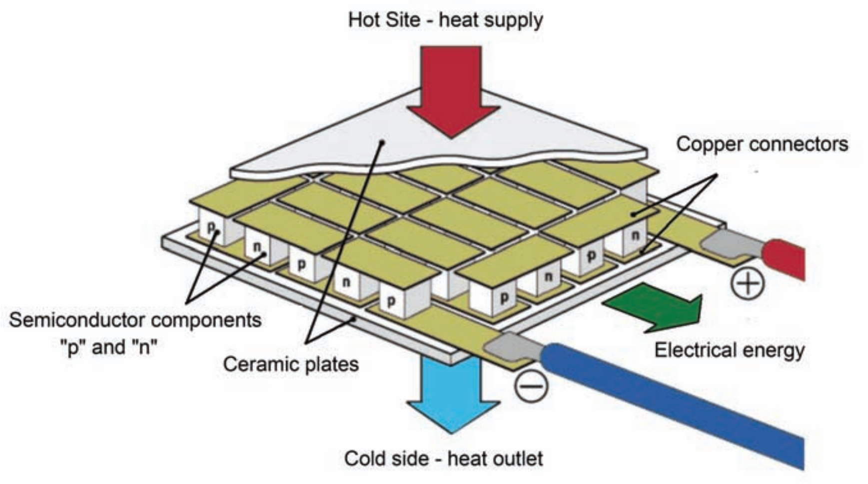

Fig. 1. Design and principle of operation of Peltier's cell [3]

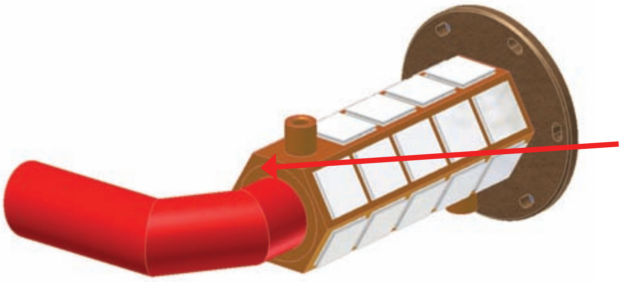

Fig. 2. Model of recuperator

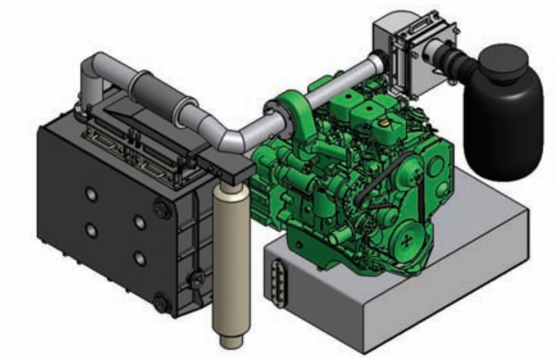

Fig. 3 .Model diesel engine

Due to some limits in using termocells we have to set proper operational conditions of the recuperation system by determination of technical parameters. The initial research work, carried out in that range, consisted in modelling and analysis of temperature distribution and heat flow in diesel engine exhaust system. Temperature of exhaust gases as well as geometrical and material features of the exhaust system was the input data for the analysis.

2. Defining of calculation model in Fluent software

Fluent solver enables precise calculations as regards heat flow effects (air flow, heat exchange, burning, rotor machines, multi-phase flow) of different. Due to libraries attached the user can select any type of flow e.g. laminar, transitional or turbulent. Properties and physical parameters of tested material of the object with its nearest surroundings were included for calculations. Fluent enables solving both single and complex states of heat exchange process [3, 5]. Due to high number of the software options the calculations are accurate and take reasonable time.

The user when using application can stop next iterations, change meshing (make it denser ar more dispersed at any place) and then restart the calculation process. All can be done without leaving the solver module.

2.1. Conservation equation of flow continuity

Continuity equation (Navier-Stokes) [4, 5] is one of basic conservation equations on which code of Fluent software bases. According to law of conservation of mass in a closed physical system mass of medium cannot neither increase nor decay. Assumption of fluid stream continuity leads to the conclusion that it covers all space of flow (there is so called homogenous flow). On the basis of those assumptions we can make balance mass and in the result we obtain following equation of flow continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v} \right) = 0 \,, \tag{1}$$

where:
t - time [s],
v - fluid flow rate [m/s],
ρ - fluid density [kg/m³].

Navier-Stokes equation is used for description of principle of conservation of mass and momentum of flowing fluid. The equation was used for description of exhaust gases parameters (treated as fluid) and parameters of cooling water in water coat.

2.2. Models of turbulence

Turbulent flow is most common form of flow of fluids in the nature. Basic flow parameters such as speed, pressure and density change quickly in each point but they change not much and changes are of random character. Amounts of those parameters are random functions in time and position. So in the software we can select the flow model that refers to tested process. As there are no physical reasons for correlation of turbulent stresses with other parameters characterizing fluid, creation of additional equations makes the problem in turbulent flow theory. Models of turbulences including many parameters that are determined experimentally that can be divided into two main groups: analytical models and semi-empirical models can solve the problem [5].

At present in CFD calculations the models from group $k-\varepsilon$ and $k-\omega$ are used. The models are effective and universal so they are used in simulation of complex single-phase and multi-phase systems. Models of turbulence that belong to group $k-\varepsilon$ are semi-empirical two-equation models basing on differential equations that describe transport of turbulence kinetic energy k and its dissipation ε. The equations were introduced assuming isotropy of turbulence. That assumption eliminates possibility of using the models without additional relationships in the case of near-wall flow. For the first time the model of such type was suggested by Launder and Spalding in 1972. Now we have few modification of the model: RNG k-ε and Realizable k-ε [4].

2.3. Heat exchange

Modelling of heat exchange process in Fluent software is possible only when we use the following energy transport equation [5]:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot \left(\vec{v}(\rho E + P) - (k \nabla T + (\overset{=}{\tau} \cdot \vec{v}) - \sum_j \hat{h}_j \vec{J}_j) \right) - S_Q = 0, \tag{2}$$

where:

E - specific energy of the system [J/kg],
h_j - unit enthalpy of j component [J/kg],
J_j - density of diffusion stream of j component [kg/(m³ s)],
k - heat transfer coefficient [W/(m K)],
P - pressure [Pa],
S_Q - source term [W/m³],
T - temperature [K],
v - speed [m/s],
ρ - density [kg/m³],
τ - stresses tensor [Pa].

Equation (2) consists of terms describing heat transport in the result of convection, heat transfer and diffusion of mixture components as well as heat generation due to dissipation of kinetic energy at viscous flow. Modelling based on the above equation enabled determining parameters of heat exchange between:

- exhaust gases and internal wall of exhaust system,
- internal wall of exhaust system and cooling medium,
- cooling medium and external wall of exhaust system,
- external wall of exhaust system and environment.

3. Numerical model of diesel engine's exhaust system

Spatial model of exhaust system with cooling subsystem was made in Autodesk Inventor software. It makes a unit comprising ten or so components shown in Fig. 4.

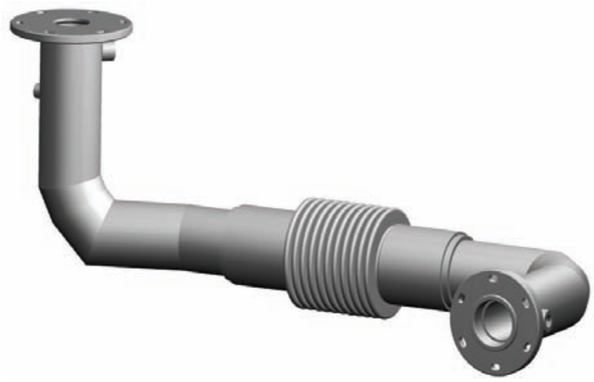

Fig. 4. Geometrical model of exhaust system

Creation of numerical model that is based on geometric form presented in Fig. 4 in not possible as differences between connected components are significant and when trying to put meshing on them the errors in form of double nods and double components appear and that fact causes generation of numerical meshing discontinuity. So, basing on the model from Autodesk Inventor a simplified model was made in MSC Patran software. Simplifications that were applied are as follows:

- elimination of rounds of small radiuses,
- removal of opening for screws in the flange,
- simplification of compensator model.

Also recuperator chamber was considered (Fig. 5).

In Fig. 6 sequence of actions in creation of numerical model of exhaust system was shown.

Sequence of actions in creation of numerical model of connector and new cooling system is the same as in the case of above exhaust system with cooling system.

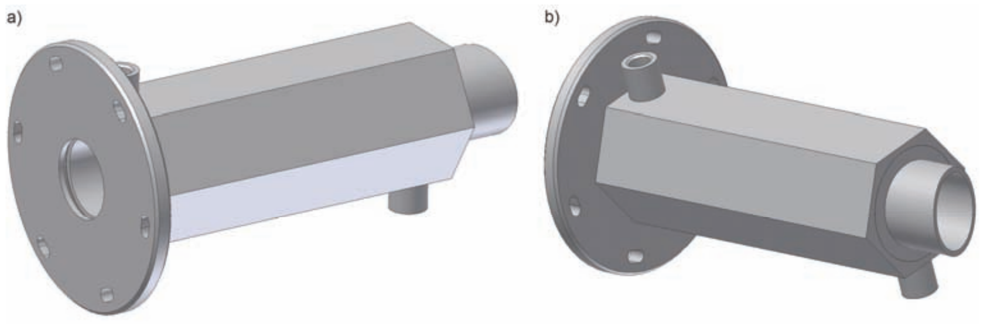

Fig. 5. Geometrical model of recuperator

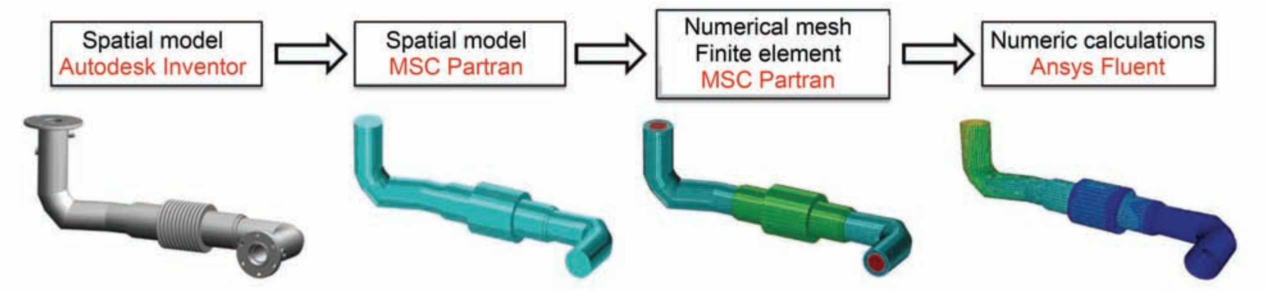

Fig. 6. Sequence of actions in creation of numerical model of exhaust system

3.1. Finite elements meshing

On the basis of simplified geometrical models (Fig. 4, Fig. 5) finite elements meshing was created in MSC PATRAN software. Simplifications that were applied during modelling enabled using four-wall elements of Hex8 type for creation of meshing. Their advantage is good recreation of geometrical features at small number of elements.

Meshing of elements of exhaust system with cooling system (Fig. 7a), consists of 95474 nods and 91296 four-wall elements. Calculations of fixing flanges were made separately. Meshing of elements of recuperator (Fig. 7b), consists of 50871 nods and 47906 four-wall elements.

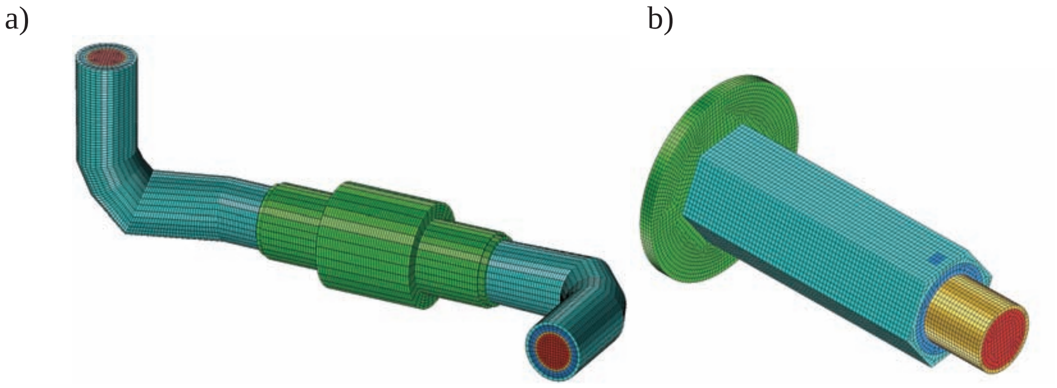

Fig. 7. Finite elements meshing: exhaust system with cooling system (without flanges), b) recuperator

3.2. Calculation model

Calculations were made in 3D system in a steady state. Turbulent flow of both exhaust gases and cooling water was accepted as well as the following boundary conditions were assumed (Fig. 8):

- temperature of exhaust gases 405.9°C,
- temperature cooling water at outlet 60°C,

- water volume flow rate 1.75 m^3/s,
- exhaust gases volume flow rate 133.21 m^3/s,
- laminar flow of air surrounding the exhaust system.

The following equation was used to determine coefficient of heat transfer α on external surfaces of engine exhaust system:

$$\alpha = \frac{Nu \cdot \lambda}{l_0}, \tag{3}$$

where:

λ - heat transfer coefficient [W/mK],
Nu - Nusselt number,
l_0 - characteristic dimension depending on the surface for which it has to be determined [m].

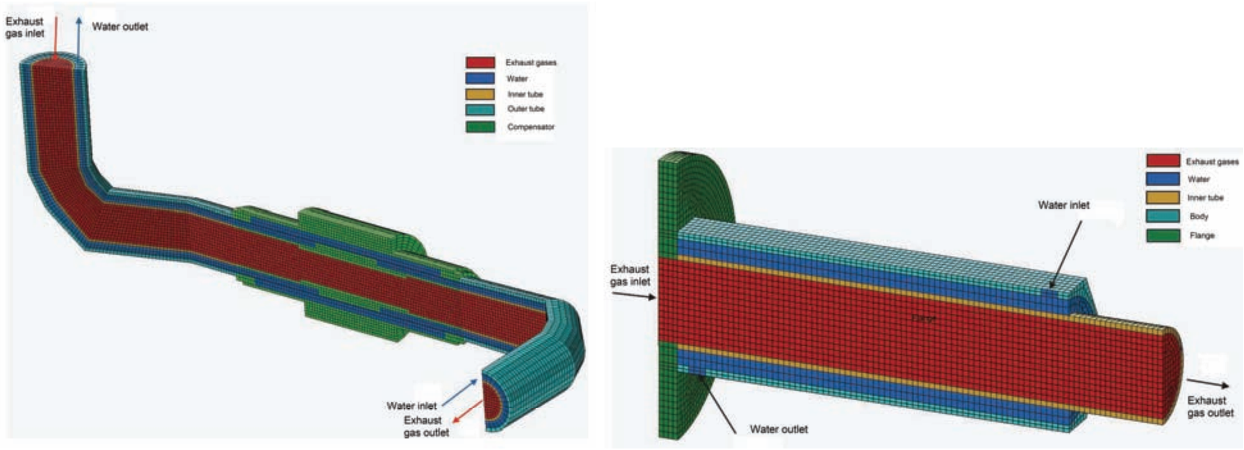

Fig. 8. Boundary conditions assumed in analysis of exhaust gases and water flow

4. Calculation results

Calculation results were presented in graphical form in Fig. No. 9-11. The results were discussed in summary.

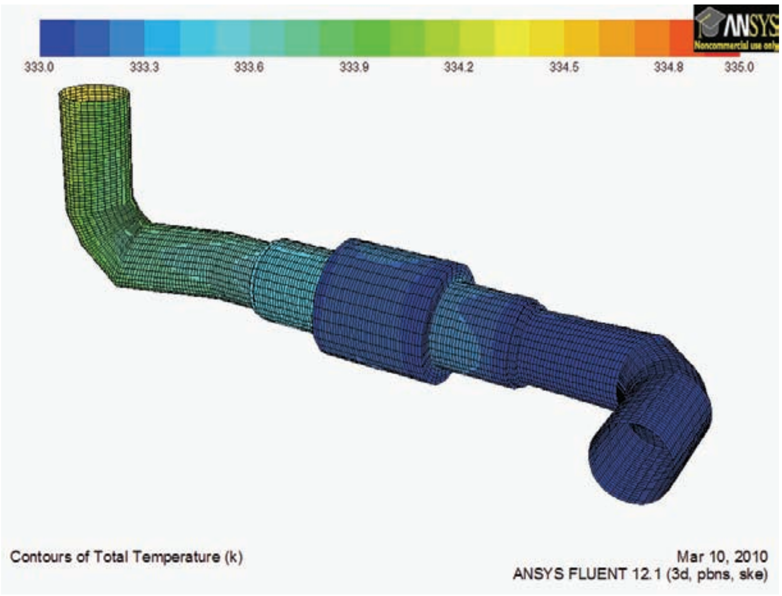

Fig. 9. Distribution of temperature field (maximal temperature of scale 335 K) on external wall of exhaust system - isomeric view

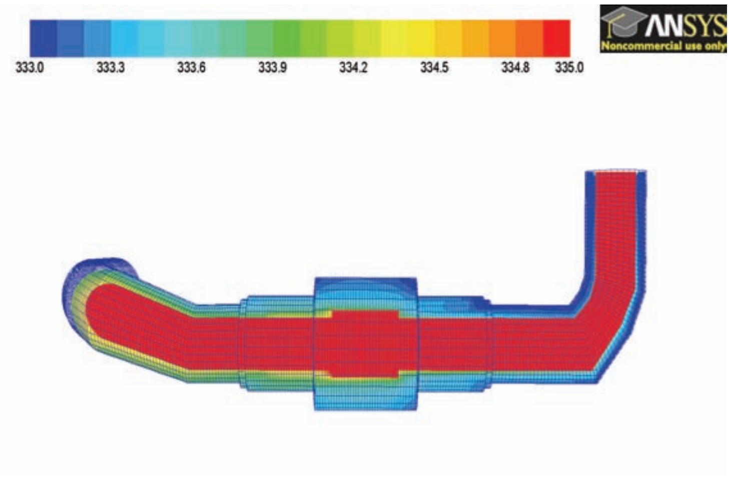

Fig. 10. Distribution of temperature field (maximal temperature of scale 335 K) - cross-section of exhaust system

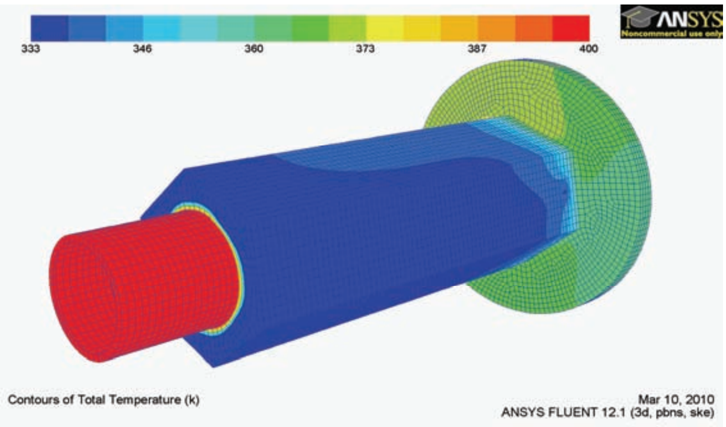

Fig. 11. Distribution of temperature field (maximal temperature of scale 400 K) on external wall of exhaust system - isomeric view

5. Summary and conclusions

Due to simulation carried out in Ansys Fluent software, information about distribution of temperature field in exhaust system and in modified system (recuperator) were obtained. Below the results from the discussed variants were given:

a) Exhaust system with cooling system (Fig. 9, Fig. 10)

On the basis of numerical calculations we can say that cooling water that flows all the time through entire exhaust system in a direction opposite to exhaust gases flow significantly reduces gases temperature. Cooled gases have maximal temperature cat outlet of about 335° C what means that temperature dropped by 70° C. Such a significant cooling of exhaust gases does not mean increase of water temperature. Water temperature at the system outlet increased only by 1.5°C. The same increase of temperature was observed on external wall of the exhaust system. In Fig. 10 we can observe a process of warming up of cooling water. The coldest zone is the place of water introduction. As the water flows through the exhaust system it is warming up and gases are cooled.

b) Recuperator (Fig. 11)

Design of the developed recuperator is characterized first of all by shape of channels in which cold water flows (in a direction opposite to exhaust gases flow) and by the place of installation of channels with cold water. The cooling system is installed at the place of exhaust gases inlet to the exhaust system, just after connector that that joins flange with turbine. Use of such a cooling system caused reduction of exhaust gases temperature by 24°C. Smaller temperature decrease than in the first discussed case is caused by a shorter contact time of exhaust gases with cooled surfaces. Increase of temperature of cooling water at the system outlet by 6°C is caused by high temperature of the flange that additionally warms up the water. Temperature of external wall of not cooled pipe is 362°C. When using the cooling system its temperature significantly reduces to about 157°C.

The results of numerical analyses allow concluding that basing on exhaust system of diesel engines used in the mining industry it is possible to develop conceptual design of recuperator, to make its prototype and to carry out laboratory tests. Selection of proper geometrical parameters and parameters of cooling water stream is a condition. Each modification introduced to the project would require another computer simulation to optimize conditions of operation of Peltier's cells and in result to achieve their maximal effectiveness.

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