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GASEOUS EMISSIONS OF A COMBINED COGENERATION UNIT

Problem of harmful gaseous emissions is solved in the paper in two ways. Firstly it is the design of a mathematical model of flow and combustion in a combustion chamber of an engine, which is a component of a combined cogeneration unit with a proposal of solutions enabling the decrease in amount of harmful gaseous emissions. Secondly it is the verification of the solutions through the computation by means of mathematical models considering these solutions.

1. Introduction

Cogeneration units operating as a part of energetic units of industry complexes adapt their operational mode to their needs [2]. Consequencies arising from that fact are often the increased environment loads through the increased formation of harmful gaseous emissions.

The problem of harmful gaseous emissions is solved in the paper in two ways. In the first place it is a proposal of the mathematical model of flow and combustion in an internal combustion engine, which is a part of a combined cogeneration unit with a proposal of solutions enabling the decrease in the amount of harmful gaseous emissions. Secondly, it is the verification of the mentioned solutions through the computation by means of mathematical models. Preparation of the CAD data is done in the CAD software CATIA 5, the mesh preparation in the preprocessor Gambit and the calculation itself and visualisation of results are done in the professional CFD (Computational Fluid Dynamics) software Fluent.

Fig. 1 Combined cogeneration unit

The experimental part of the paper deals with the measurement of harmful gaseous emissions of the combined cogeneration unit (see Fig. 1) operating in the technological process of a food processing plant.

2. NO_X emissions produced by the combined cogeneration unit

The combined cogeneration unit consists of a heat pump compressor, generator and natural gas fuelled combustion engine – Fig. 1. It operates in the energetic system of industry complex as the one of electric power sources and low-, central- and high potential heat sources.

The scheme of the measurement system is shown in Fig. 2. One part of the data is evaluated and recorded by the control system of the combined cogeneration unit as a subsystem of the controlling of the entire energetic system and the other one by the measurement device TESTO 300M. The probe of this analyzer takes an exhaust sample behind the heat exchanger for the exhaust gases cooling. The engine is running at the speed constant value of 1500 min^{-1}.

The comparison of the amount of NO_x emissions corresponding to the different operational modes characterised by the electric generator watt power value and connected or disconnected compressor of the heat pump (HP) (input 17 kW) is shown in Fig. 3. In the figure it can be seen that the measured combined cogeneration unit is optimised for production of minimum harmful gaseous

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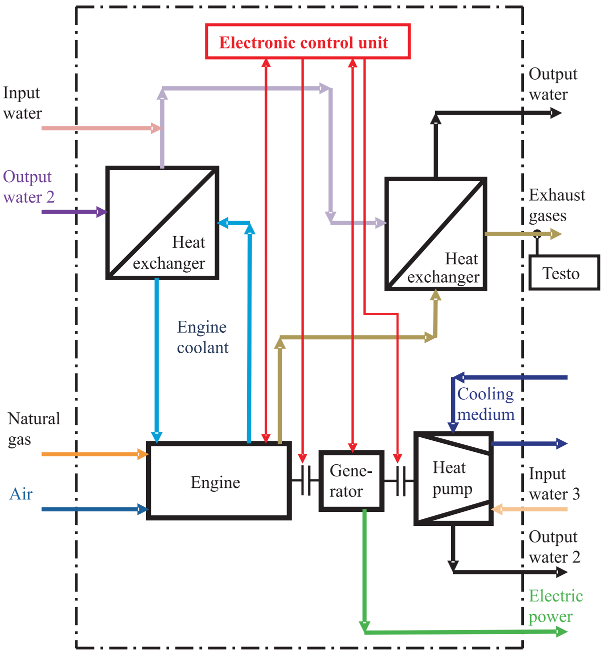


Fig. 2 Scheme of the measurement system

emissions in the main operational mode characterized by the electric generator watt power value of 36 kW and attached compressor of heat pump [7].

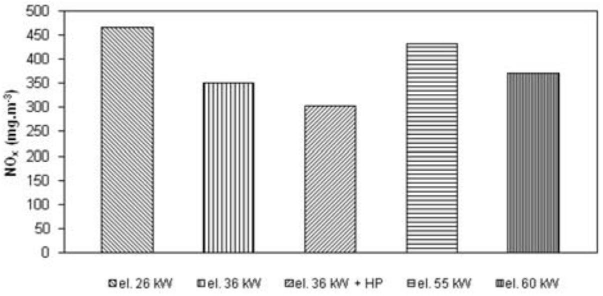


Fig. 3. NO$_x$ emissions produced by the combined cogeneration unit operating at different modes

The cogeneration unit also works at other operational modes on the ground of adapting its running to the needs of the energetic complex, whose component it is. Consequently, the environment load is higher than it is in the case of running only at the main operational mode. From the experiments it results that the combined cogeneration unit meets the exhaust-emission regulations.

3. Mathematical modelling of flow and combustion

The continuity relation for one component α of the flowing medium at a chemical reaction has the following form:

$$\frac{\partial \rho_\alpha}{\partial t} + \nabla \cdot (\rho_\alpha \vec{u}) = \nabla \cdot \left[\rho D \nabla \left(\rho_\alpha / \rho\right)\right] + (\dot{\rho}_\alpha)_c \,, \tag{1}$$

where:

ρ_α - partial density of the component α,
D - diffusion coefficient,
$(\rho_\alpha)_c$ - speed of the change of the partial density of the component α by the chemical reactions influence, whereby

$$\rho = \sum_\alpha \rho_a \,. \tag{2}$$

Momentum equation:

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u}\, \vec{u}) = -\nabla p + \nabla \cdot \left(\mu \overleftrightarrow{\tau} + \lambda \overleftrightarrow{I} \nabla \cdot \vec{u}\right), \tag{3}$$

where:

μ - viscous coefficient,
λ - viscous coefficient,
$\overleftrightarrow{\tau}$ - viscous stress tensor,
$\overleftrightarrow{I}$ - unit tensor.

Energy equation:

$$\begin{aligned} &\frac{\partial \rho I}{\partial t} + \nabla \cdot (\rho I \vec{u}) + p \nabla \cdot \vec{u} = \nabla \cdot K \nabla T + \frac{\mu}{2} \overleftrightarrow{\tau} : \overleftrightarrow{\tau} + \\ &+ \lambda (\nabla \cdot \vec{u})^2 + \dot{q}_c \end{aligned} \,, \tag{4}$$

where:

I - specific internal energy,
K - mixture heat conductivity,
T - temperature,
$\dot{q}_c$ - heat release speed due to chemical reactions.

Continuity, momentum and energy equations in the case of moving mesh (u_g - mesh speed) have the form:

$$\begin{aligned} &\frac{d}{dt} \int_V \rho_\alpha dV - \int_S \rho_\alpha (\vec{u}_g - \vec{u}) \cdot \vec{n} dS = \int_S \left(\frac{\rho D \vec{\nabla} \rho_a}{\rho} \right) \cdot \\ &\cdot \vec{n} dS + \int_V (\dot{\rho}_\alpha)_c dV \end{aligned} \,, \tag{5}$$

$$\begin{aligned} &\frac{d}{dt} \int_V \rho \vec{u} dV - \int_S \rho \vec{u} (\vec{u}_g - \vec{u}) \cdot \vec{n} dS = \int_S p \vec{n} dS + \\ &+ \int_S \left(\mu \overleftrightarrow{\tau} + \lambda \overleftrightarrow{I} \vec{\nabla} \cdot \vec{u} \right) \cdot \vec{n} dS \end{aligned} \,, \tag{6}$$

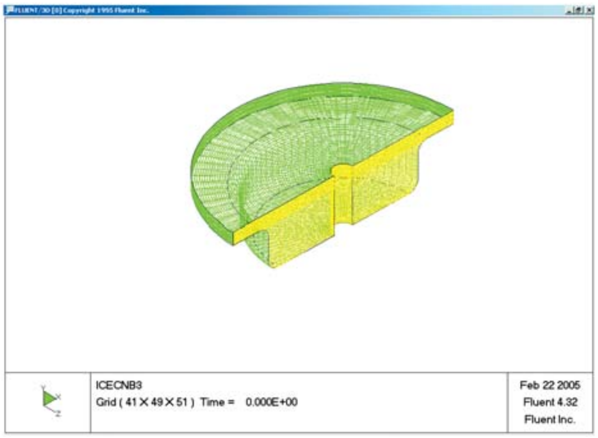
$$\begin{aligned} &\frac{d}{dt} \int_V \rho I dV - \int_S \rho I (\vec{u}_g - \vec{u}) \cdot \vec{n} dS + \int_V p \vec{\nabla} \cdot \vec{u} dV = \\ &= \int_S (K \vec{\nabla} T) \cdot \vec{n} dS + \int_V \left(\frac{\mu}{2} \overleftrightarrow{\tau} : \overleftrightarrow{\tau} + \lambda (\vec{\nabla} \cdot \vec{u})^2 + \dot{q}_c \right) dV \end{aligned} \,, \tag{7}$$

where:

V - volume,
$\vec{n}$ - surface S normal vector.

In the professional CAD software CATIA V5 the space geometrical model corresponding to the geometry of the examined engine combustion chamber is created with regard to the needs resulting from the following use of simulation software Fluent 4.

As the calculation is done for the deforming mesh, it is needed to create geometrical models corresponding to single partial meshes, from which the resulting mesh is then created or between which it is then interpolated. Partial models are created for the combustion chamber shape from 340° crankangle up to 490° crankangle with the step of 10° crankangle. In term of the combustion monitoring it is sufficient to monitor the time sequence up to 410° crankangle, but in terms of flow monitoring the longer time sequence is simulated. Only one half of the combustion chamber is calculated because of the decrease in the demand on the used hardware. The computational mesh with defined boundary conditions is shown in Figure 4. The mesh corresponds to the value of 340° crankangle. Particular meshes have all the same definition of boundary conditions and mesh topology.



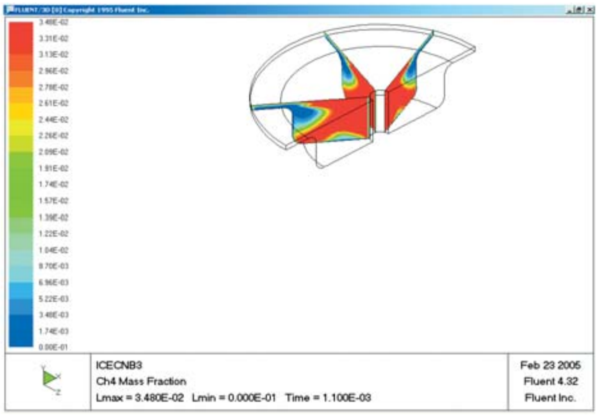
ICECNB3
Grid (41 X 49 X 51) Time = 0.000E+00
Feb 22 2005
Fluent 4.32
Fluent Inc.

Fig. 4 Computational mesh with boundary conditions for the value of 340 °crankangle (green colour - wall, yellow colour - symmetry area)

From the combustion point of view the flame is calculated as kinetic in the turbulent mode and the problem is solved as unsteady. The mathematical model considers methane oxidation (through CO), dissociation of CO_2, N_2, O_2 and NO formation, altogether 7 equations:

$$2CH_4 + 3O_2 \rightarrow 2CO + 4H_2O$$
$$2CO + O_2 \rightarrow 2CO_2$$
$$2CO_2 \rightarrow 2CO + O_2$$
$$N_2 \rightarrow N + N$$
$$O_2 \rightarrow O + O$$
$$O_2 + N \rightarrow NO + O$$
$$N_2 + O \rightarrow NO + N.$$

Fig. 5 shows the progress of methane oxidation after the first time step. It is apparent that the combustion process started at the combustion chamber border instead of the combustion chamber centre, hence in the place of numerical initation. Gradually the flame spreads into the combustion space. There is only little methane in the combustion space after the fourth time step. The process of oxygen concentration decrease corresponds to the process of methane decrease.



ICECNB3
Ch4 Mass Fraction
Lmax = 3.480E-02 Lmin = 0.000E-01 Time = 1.100E-03
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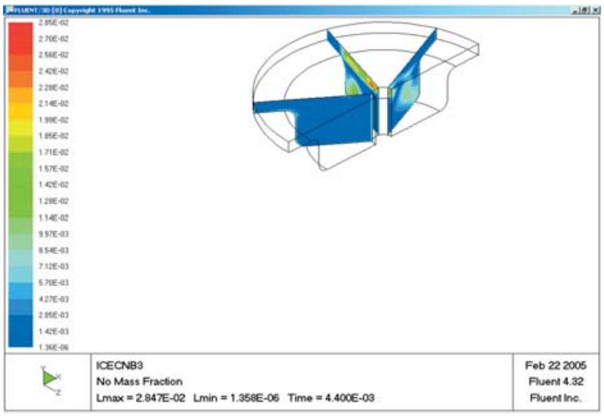
Fluent Inc.

Fig. 5 Mass fraction of CH_4 in the time t = 0.0011 s

Figs. 6, 7, 8 and 9 illustrate the progress of NO concentration through the simulation.



ICECNB3
No Mass Fraction
Lmax = 2.847E-02 Lmin = 1.358E-06 Time = 4.400E-03
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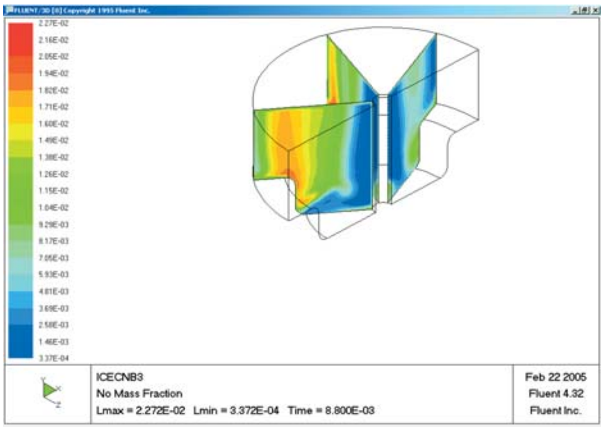
Fluent 4.32
Fluent Inc.

Fig. 6 Mass fraction of NO in the time t = 0.0044 s



ICECNB3
No Mass Fraction
Lmax = 2.272E-02 Lmin = 3.372E-04 Time = 8.800E-03
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Fluent 4.32
Fluent Inc.

Fig. 7 Mass fraction of NO in the time t = 0.0088 s

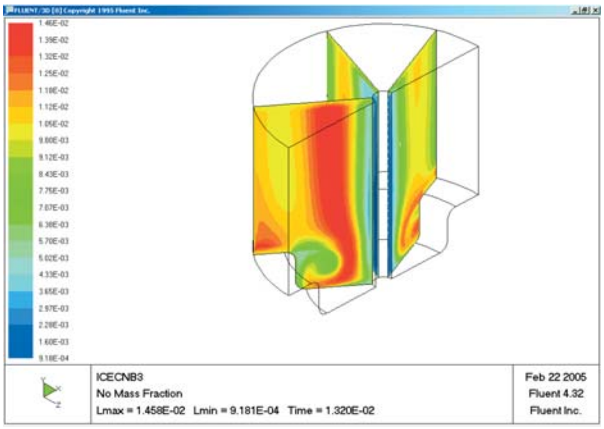

Fig. 8 Mass fraction of NO in the time t = 0.0132 s

Fig. 9 illustrates NO concentration in the last time step.

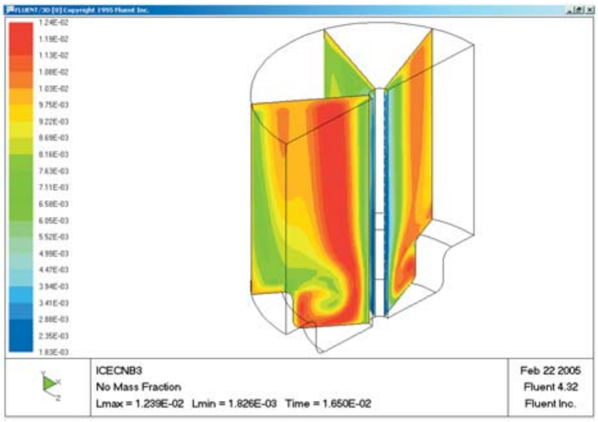

Fig. 9 Mass fraction of NO in the time t = 0.0165 s

Influence of the flow induced by the piston movement on the flow in the combustion chamber gradually increases. The highest values of flow velocity are obtained in the area of maximum change in the computational domain diameter.

The CO and NO concentrations differ from real values because of the inaccurate values used in the reactions definitions.

The experimentally found value of O_2 concentration in the exhaust gases for the main operational mode is 8.2 % vol., through the simulation found value is 3.9 % vol.

The experimentally found value of CO_2 concentration for the main operational mode is 7.3 % vol., through the simulation the calculated value is 11.7 % vol.

The value of calculated maximum combustion temperature is 2629 K.

A more accurate model can be obtained by the precision of boundary conditions, for example considering the influence of heat transfer into the combustion chamber walls, using more suitable reactions, more accurate definition of chemical reactions (activation energy, preexponential factor), the temperature dependent specific heat etc.

In relation to the differences between the simulation and experimental results it is to be noted that the calculated values are considered inside the combustion chamber for the value of 490° crankangle, i.e. the expansion stroke so far not finished (because of the capacity of used hardware) and the experimental values are evaluated by the probe placed after the exhaust exchanger.

3. Solutions proposal

For the decrease in NOx concentration being the most critical harmful pollutant, two ways were used and verified by a simulation:

1. the combustion temperature decrease through the intercooler of compressed air (decrease in the temperature mixture of about 20 °C),
2. the combustion temperature decrease through the intercooler of compressed air (decrease in the temperature mixture of about 20 °C) and simultaneously through the recirculation of 20 % of exhaust gases.

The combustion temperature decrease through the intercooler results in the maximal combustion temperature of 2484 K (about 145 K lower than in the previous calculation) achieved in the third time step similarly as in the previous calculation, i.e. in the time of 0.0033 s after the initiation. The assumption of the maximum combustion temperature decrease through the intercooler is verified. NO concentration for the whole combustion space is about 12.6 % lower than in the case without the intercooler.

The combustion temperature decrease through the intercooler and simultaneously the recirculation of 20 % of exhaust gases results in the maximum combustion temperature of 2485 K (about 1 K higher than in the previous calculation – with an intercooler) again achieved in the third time step similarly as in the previous calculation, i.e. in the time of 0.0033 s after the initiation. NO concentration for the whole combustion chamber is about 76.9 % lower than in the case without the intercooler.

4. Conclusion

For the cogeneration units operating as a part of advanced energy unit there is a need to adjust their current operational mode to the mode required by cooperated or superior devices. This can result in higher environment loads [5]. The used mathematical model of a harmful gaseous emissions formation has the potential to optimize the whole energetic unit from the ecological point of view.

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