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SONIC STIMULATION OF NATURAL GAS COMBUSTION

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Abstract. This paper describes the equipment intended for investigating the efficiency of sonic stimulation in natural gas combustion. Sonic stimulation has a definite influence on the combustion process, which allows for a decrease in the hazardous component (NO_x, CO) pollution. Convective heat transfer is enhanced due to the destruction of the laminar boundary layer. It is shown that the velocity of the flue gas flow estimated by the Laser-Doppler Anemometer, its rate of turbulence and the concentration of char particles are in good agreement with other independent measurements. In spite of the laminar velocity profile in the duct of exit flue gas, the heat transfer coefficient almost doubles with the acoustic stimulation of gas combustion.

Key words: combustion, sonic stimulation, heat transfer, Laser-Doppler Anemometer.

The sonic stimulation of gas combustion must serve two purposes: 1) to minimize the pollution by hazardous products (such as CO, NO_x and char) and 2) at the same time, to intensify heat transfer in the combustion chamber (to minimize heat losses from the flue gas). Sometimes those requirements contradict each other. For example, with the intensification of the combustion process, the NO_x pollution increases, and with the stoichiometric oxygen supply, the pollution with CO grows as well. Hence, the goal is to find optimal activities for the combustion stimulation. The investigations revealing the effect of sonic stimulation by natural gas combustion were carried out in two directions: 1) estimation of the sound generator regimes (frequency and intensity) for the minimum pollution level and 2) estimation of the distribution of heat absorption along the combustion chamber and convective heating surfaces at different regimes of sonic stimulation.

Experiments of the active sonic control of combustion were carried out on the equipment shown in Fig. 1. Several types of burners were used for burning natural gas (the calorific value of 37.3 MJ/nm^3). The test section was a chamber with the height of 1000 mm and diameter of 150 mm, where a quartz tube (the inner diameter of 40 mm) was located. The tube had a porous ceramic insulation of 400 mm height. The temperature field in the direction of the gas flame in the quartz tube was measured by eight thermocouples. The temperature field data were registered by the analogue-digital converter ADC-16 (PICO-Technology). The thermocouples were mounted with the space of 80 mm, allowing for information acquisition about the temperature distribution at the distance of 640 mm. The first thermocouple was located at the distance of 170 mm from the burner. For calorific measurements, the chamber had water-cooled walls, and at the exit from the chamber, a calorimetric surface was installed. The water flow rate through the chamber wall cooler and the calorimetric surface was measured. In addition, the water temperature drop was measured. On the basis of these data, added to the exit gas parameters, the heat balance of the equipment can be calculated.

The tests at different frequencies and amplitudes of the sonic field showed that around the resonance frequency of the chamber of 80 Hz, the acoustic efficiency of the generator increased significantly. It means that the tests performed at frequencies of 50–100 Hz have the strongest effect on the heat transfer and on the reduction of CO and NO_x emissions.

The first demonstration tests on the sonic stimulation of gas combustion showed that the free gas flame in the tube shortened almost twice in its length with the sonic generator switched on. This phenomenon can be explained by the enhancement of the diffusion of oxygen and combustible components. It is known that the height of the luminous flame L_f is inversely proportional to the oxygen diffusion coefficient D [1]:

$$L_f = \frac{\beta \cdot G}{4 \cdot \pi \cdot D \cdot c}, \tag{1}$$

where β is the stoichiometric coefficient; G is the gas flow rate, kg/s; D is the coefficient of oxygen diffusion, m^2/s; c is the oxygen concentration, kg/m^3.

The probability of particle oscillation Z is estimated by the sound frequency f:

$$Z = \frac{1}{\sqrt{1 + \left(\frac{4 \cdot \pi \cdot \rho \cdot r^2 \cdot f}{9 \cdot \mu} \right)^2}}, \tag{2}$$

where μ is the dynamic viscosity of the gas medium, Pa·s; ρ is the density of a particle, kg/m^3; f is the sound frequency, Hz; r is the particle size, m.

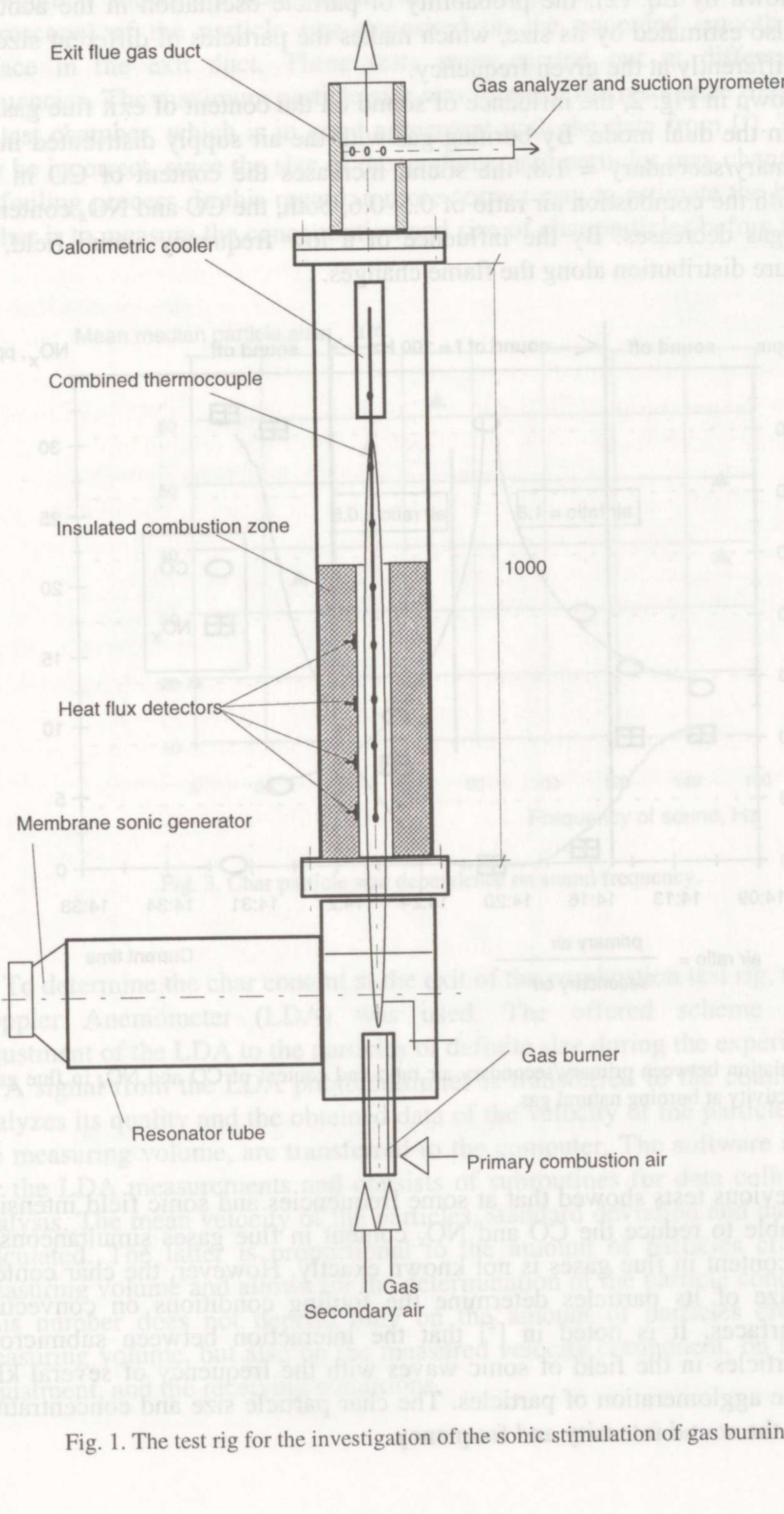

Fig. 1. The test rig for the investigation of the sonic stimulation of gas burning.

As shown by Eq. (2), the probability of particle oscillation in the acoustic field is also estimated by its size, which makes the particles of different sizes to behave differently at the given frequency.

As shown in Fig. 2, the influence of sound on the content of exit flue gas can be seen in the dual mode. By burning gas with the air supply distributed in the ratio primary/secondary = 1.8, the sound increases the content of CO in flue gases. With the combustion air ratio of 0.5–0.6, both, the CO and NO_x content in the flue gas decreases. By the influence of a low frequency sound field, the temperature distribution along the flame changes.

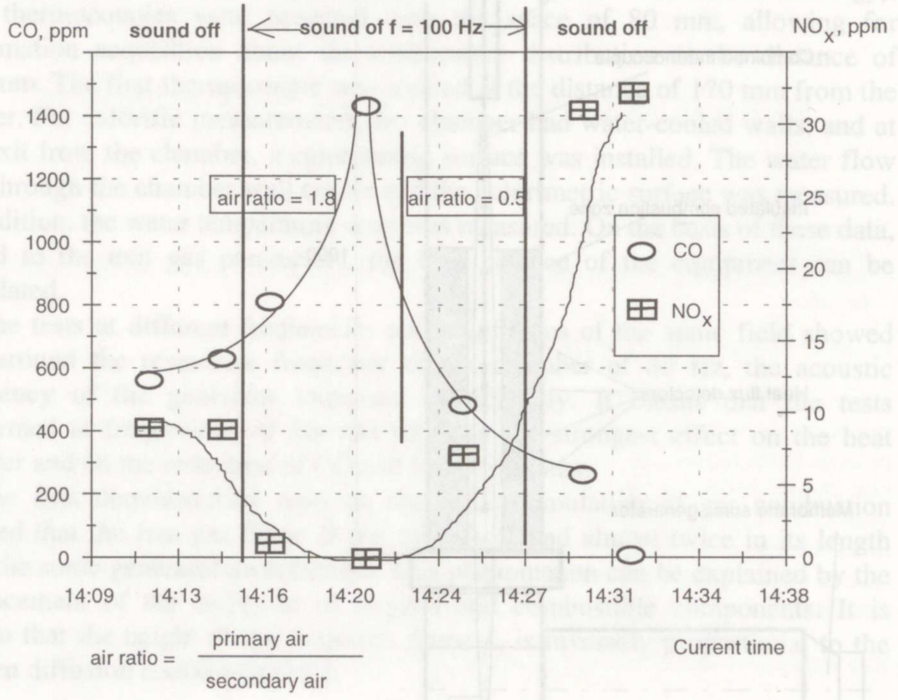

Fig. 2. Correlation between primary/secondary air ratio and content of CO and NO_x in flue gases with sonic activity at burning natural gas.

Our previous tests showed that at some frequencies and sonic field intensity, we were able to reduce the CO and NO_x content in flue gases simultaneously. The char content in flue gases is not known exactly. However, the char content and the size of its particles determine the fouling conditions on convective heating surfaces. It is noted in [2] that the interaction between submicrone aerosol particles in the field of sonic waves with the frequency of several kHz leads to the agglomeration of particles. The char particle size and concentration depend on the sound intensity and frequency.

Figure 3 shows the data on the direct measurements (by counting under microscope) of the particle size deposited on the uncooled smooth metallic surface in the exit duct. These tests were carried out at different sound frequencies. The maximum particle size was found at the resonance frequency of the test chamber, which is in good agreement with the data from [2]. This data may be incorrect, since the size of the agglomerated particles may change during the fouling process. In this regard, a more correct way to estimate the behaviour of char is to measure the concentration and size of char particles before fouling.

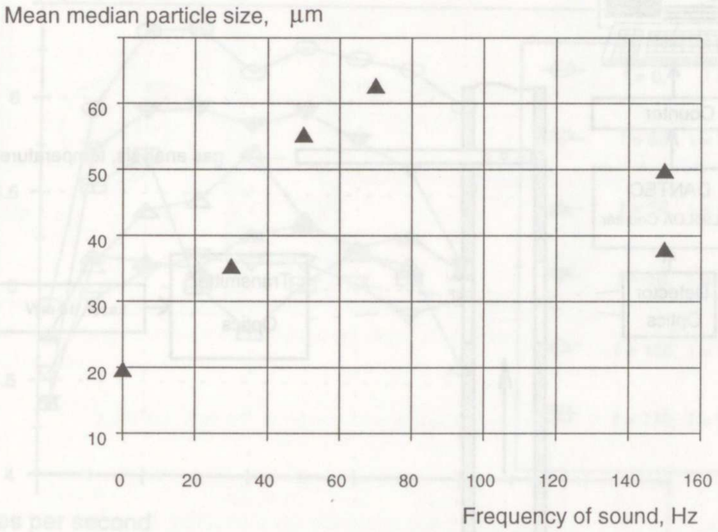

Fig. 3. Char particle size dependence on sound frequency.

To determine the char content at the exit of the combustion test rig, the Laser-Doppler Anemometer (LDA) was used. The offered scheme facilitates adjustment of the LDA to the particles of definite size during the experiment.

A signal from the LDA photomultiplier is transferred to the counter, which analyzes its quality and the obtained data of the velocity of the particle, crossing the measuring volume, are transferred to the computer. The software is specific for the LDA measurements and consists of subroutines for data collection and analysis. The mean velocity of the particles, standard deviation and data rate are calculated. The latter is proportional to the amount of particles crossing the measuring volume and allows for the determination of the particle concentration. This number does not depend only on the amount of particles crossing the measuring volume, but also on the measured velocity component, on the system adjustment, and the receiving conditions.

For these experiments, the LDA system was tuned to record signals from the particles of 20–40 μm and 50–70 μm. As shown in Fig. 3, the diameters of the captured char particles were in good agreement with these ranges. The LDA equipment was mounted at the outlet of the chamber as shown in Fig. 4.

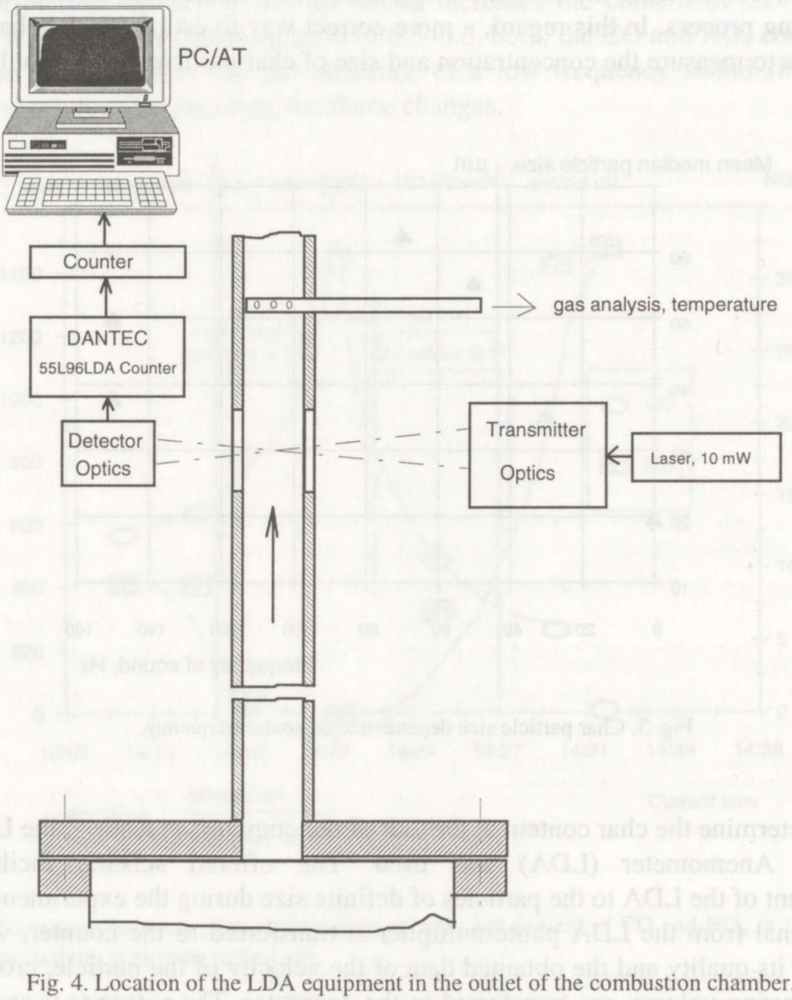

Fig. 4. Location of the LDA equipment in the outlet of the combustion chamber.

Laser beams from the LDA Transmitter System were sent to the outlet channel with the square cross-sectional inner size of 30 × 30 mm through the windows, while the inner surfaces of the windows were levelled to the inner surface of the channel. The axis of the windows was located at the level of 250 mm from the outlet of the chamber. Close to the LDA measuring volume (with the size of 0.3 × 0.3 × 0.6 mm), the flue gas content and temperature were checked. The LDA equipment allows for scanning the whole cross-section of the channel.

Figure 5 shows some gas velocity distributions in the cross-section of the gas duct outlet for different sonic field levels. The sound intensity is given here as the amplitude of pressure in the test chamber measured by a pressure transducer and recorded by a computer through a special interface with the sampling rate of 200 Hz.

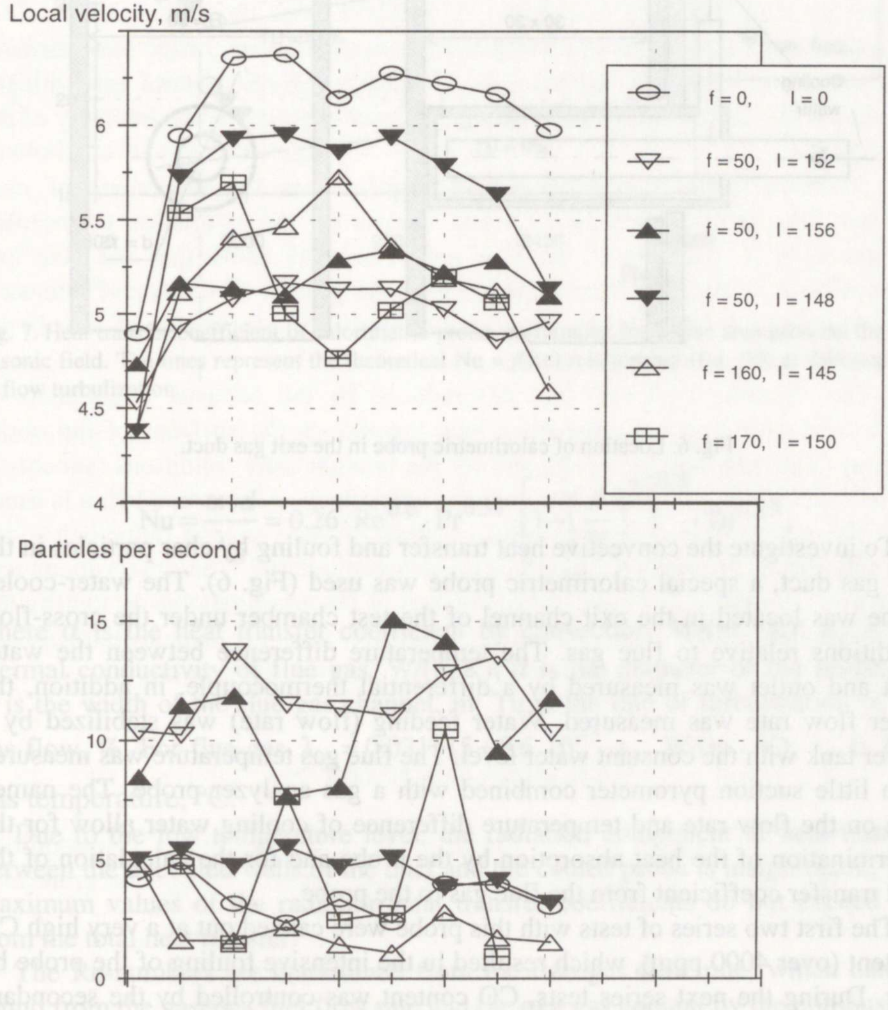

Fig. 5. The local velocity and particle distribution in the channel cross-section at the different levels of sound frequency (*f*, Hz) and intensity (*I*, dB).

In spite of the low values of Re numbers at the measuring point (by the flue gas Re = 2400–3000), the velocity profiles look like those of the turbulent flow, in particular, for the high level of sound intensity. Moreover, the concentration of particles is less uniform through the cross-section of the channel with the growth of the sound field intensity.

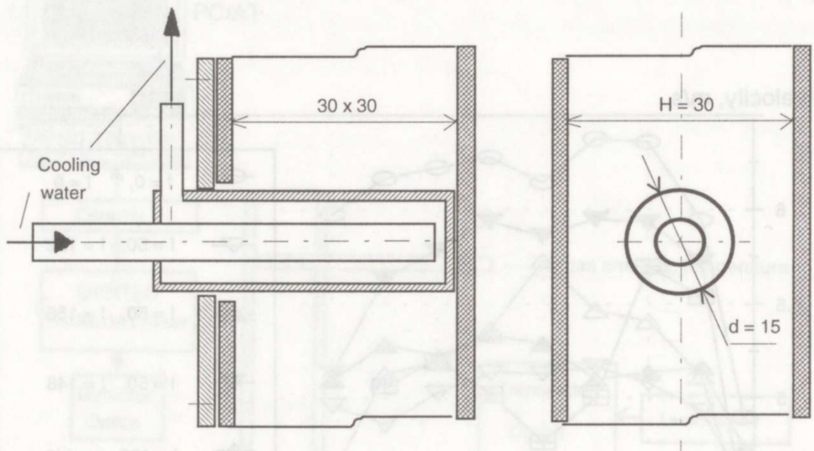

Fig. 6. Location of calorimetric probe in the exit gas duct.

To investigate the convective heat transfer and fouling by char particles in the exit gas duct, a special calorimetric probe was used (Fig. 6). The water-cooled probe was located in the exit channel of the test chamber under the cross-flow conditions relative to flue gas. The temperature difference between the water inlet and outlet was measured by a differential thermocouple, in addition, the water flow rate was measured. Water feeding (flow rate) was stabilized by a buffer tank with the constant water level. The flue gas temperature was measured by a little suction pyrometer combined with a gas analyzer probe. The named data on the flow rate and temperature difference of cooling water allow for the determination of the heat absorption by the probe and for the calculation of the heat transfer coefficient from the flue gas to the probe.

The first two series of tests with this probe were carried out at a very high CO content (over 4000 ppm), which resulted in the intensive fouling of the probe by char. During the next series tests, CO content was controlled by the secondary air supply, and the probe stayed clean. Figure 7 shows some data on the heat transfer coefficient by convection.

The lines in Fig. 7 represent a well-known theoretical Nu = *f*(Re) relationship (Nu is heat transfer coefficient) at different rates of flow turbulization ($1000 < Re < 2 \cdot 10^5$) for the cross-flow of a single cylinder in the channel:

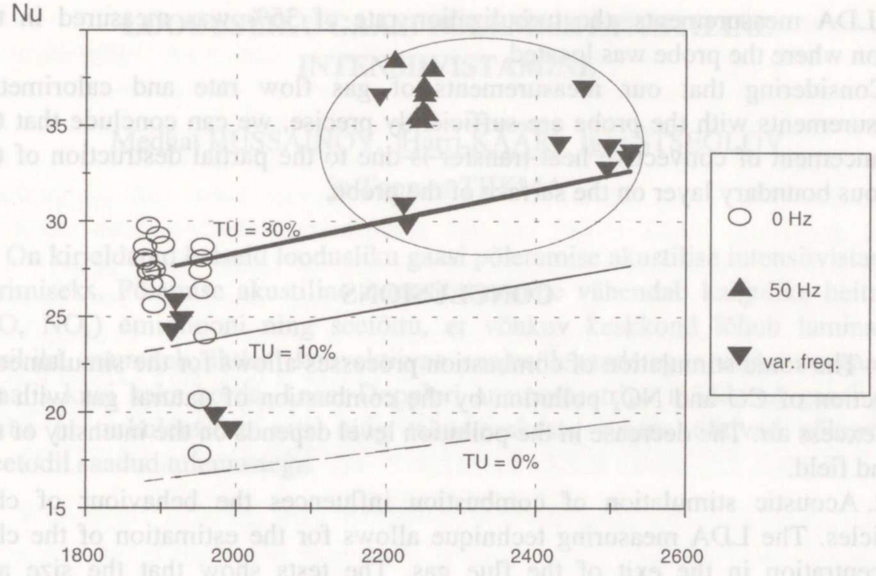

Fig. 7. Heat transfer coefficient of calorimetric probe, surrounded by ellipse area presents the data at sonic field. The lines represent the theoretical Nu = *f*(Re) relationship (Eq. (1)) at different rate of flow turbulization.

$$\mathrm{Nu} = \frac{\alpha \cdot d}{\lambda_g} = 0.26 \cdot \mathrm{Re}^{0.6} \cdot \mathrm{Pr}^{0.37} \cdot \left[1 - \left(\frac{d}{H}\right)^2\right]^{0.8} \cdot \mathrm{Tu}^{0.15}, \tag{3}$$

where α is the heat transfer coefficient by convection, W/(m^2·K); λ_g is the thermal conductivity of flue gas, W/(m·K); d is the diameter of the probe, m; H is the width of the flue gas channel, m; Tu is the rate of turbulization of the gas flow, %. For flue gas $\lambda_g = 0.031115 + 8.6 \cdot 10^{-5} \cdot t_g$, W/(m · K); t_g is flue gas temperature, °C.

Due to the low temperature level, the radiation component of heat transfer between the uncooled walls of the duct and the cooled probe is insignificant. The maximum values of the radiation heat transfer coefficients do not exceed 5% from the total heat transfer.

The Re-numbers are determined from the flue gas flow rate, which can be found from the gaseous fuel flow rate and the exit gas content by the combustion equations. The flue gas velocity, determined by the flow rate and measured by the LDA, is in good agreement. The intensity of the sonic field in our experiments was 130 dB.

As shown in Fig. 7, the experimental values of the heat transfer coefficients Nu exceed almost twice the theoretical values at the turbulization rate of 0%. By the LDA measurements, the turbulization rate of 35% was measured in the region where the probe was located.

Considering that our measurements of gas flow rate and calorimetric measurements with the probe are sufficiently precise, we can conclude that the enhancement of convective heat transfer is due to the partial destruction of the viscous boundary layer on the surface of the probe.

CONCLUSIONS

1. The sonic stimulation of combustion processes allows for the simultaneous reduction of CO and NO_x pollution by the combustion of natural gas with the low excess air. The decrease in the pollution level depends on the intensity of the sound field.

2. Acoustic stimulation of combustion influences the behaviour of char particles. The LDA measuring technique allows for the estimation of the char concentration in the exit of the flue gas. The tests show that the size and concentration of char particles increase with the growth of the sound intensity. Special investigations must be carried out to explain the formation of char in the combustion process stimulated by the acoustic field.

3. The oscillation of exit flue gas induced by the acoustic stimulation of combustion increases the convective heat transfer on the surfaces of the outlet gas duct. The heat transfer coefficient for the laminar flow conditions (according to Re-numbers) may increase almost twice when the acoustic stimulation is used.

4. The radiative heat transfer in the combustion zone and the flame behaviour under the sonic stimulation requires special investigations. The observations and some measurements of the total heat balance of the equipment show that by the sonic stimulation, the emissivity and the location of the maximum temperature zone differ to some extent as compared to the conventional burning.

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LOODUSLIKU GAASI PÕLEMISE AKUSTILINE INTENSIIVISTAMINE

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On kirjeldatud katseid loodusliku gaasi põletamise akustilise intensiivistamise uurimiseks. Põlemise akustiline intensiivistamine vähendab kahjulike heitmete (CO, NO_x) emissiooni ning seetõttu, et võnkuv keskkond lõhub laminaarse piirikihi, suureneb ühtlasi konvektiivne soojusülekandetegur väljuvate gaaside kanalis kuni kaks korda. Laser-Doppleri anemomeetriga mõõdetud gaasivoolu kiirus ja turbulentsuse aste ning tahmaosakeste suurus ühtivad sõltumatul meetodil saadud tulemustega.