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THE IMPORTANCE OF MIXTURE PREPARATION FOR INDUSTRIAL HEAT AND POWER GAS ENGINES

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Abstract

The main task of a gas mixer is to mix the fuel (gas) with air in such a way that in the gas engine optimal combustion takes place. A high efficiency of the whole combustion process and low emissions are the decisive optimization parameters. An industrial gas engine operates mostly with a lean air-gas combustion mixture with an air excess coefficient ratio of → $\lambda=1.6$. Most often heat and power industrial gas engines operate with biogas. The biogas is produced by anaerobic digestion, where biodegradable materials in the absence of oxygen are fermented. That is why the biogas fuel consists mostly of methane → CH_4 (up to 70 [%]), carbon dioxide → CO_2 and traces of other contaminant gases. It is well known, that the performance of industrial gas engines strongly depends on the quality of air and fuel mixing and therefore homogeneity of the mixture. Improper air-gas mixture can lead to unstable operation of the entire gas engine and excessive emissions beyond the applicable environmental standards. Therefore, in this article numerical investigations were performed using the open source computational fluid dynamics software OpenFOAM to show the importance of mixture preparation for industrial heat and power gas engines by describing in detail the mixing behaviour in a Venturi gas mixer model.

Keywords: *gas engine, environmental friendly power generation, combustion processes, mixture preparation*

1. Introduction

Nowadays industrial gas engines are increasingly powered by Biogas. The Biogas fuel is a renewable energy source produced by anaerobic digestion, where biodegradable materials in the absence of oxygen are fermented. That is why Biogas engines not only improve waste management, but also generate an economical energy supply. However, there is a large variety of gases resulting from specific fermentation processes dependent on various organic waste like the household waste, wastewater treatment plants sludge, agricultural waste or waste of agrifood industry. The Biogas fuel consists mostly of methane → CH_4 (up to 70%), carbon dioxide → CO_2 and traces of other contaminant gases whose share may be variable. Various gas compositions require specific mixture properties between air and fuel to get an environment friendly power generation [1]. It is well known, that the performance of industrial gas engines strongly depends on the quality of air and fuel mixing, in other words homogeneity of the mixture. Improper air-gas mixture can lead to unstable operation of the entire gas engine and excessive emissions, which are going beyond the applicable environmental standards [2]. On how the complete combustion process develops, has a great impact the mixture proportion of air and fuel [3]. When the air-fuel mixture is optimally prepared, there will occur an optimal combustion process that complies with the European Union environmental standards [4]. This situation changes immediately when the air-fuel mixture becomes too lean, what results in consequence with misfire or a slow combustion process. On the other hand, when the air-fuel mixture becomes too rich, this can result with pre-ignition, glow-ignition and in the worst case with knock combustion, which consequently may lead to the complete destruction of the entire industrial gas engine. To provide an efficiency combustion process in an industrial gas engine the mixer device should be designed to allow the best possible mixing of the two components, air and fuel. Additionally it should be compact, with minimum of pressure loss, and moreover good suction pressure in the throat due to the Venturi principle. Many analyses have been performed to improve the efficiency of the whole mixing process in a Venturi gas mixer [5-8]. However, the influence of some geometrical parameters have not been analysed so far, what is important especially for the manufacturers of such gas mixing devices. Most often industrial gas engines are equipped with Venturi gas mixer devices, which are able to prepare mixtures with an appropriate air-fuel concentration depending on the demand of the gas engine, from no load conditions during its start-up to full load conditions during its constant operation [8]. The main task of a gas mixer is to mix the fuel (gas) with air in such a way that in the gas engine optimal combustion takes place. In the case of biogas-fuelled gas engines, special attention should be paid to the knocking and misfiring limits (see Fig. 1.b). High efficiency and low emissions are the decisive optimization parameters, according to the applicable environmental regulations in the European Union.

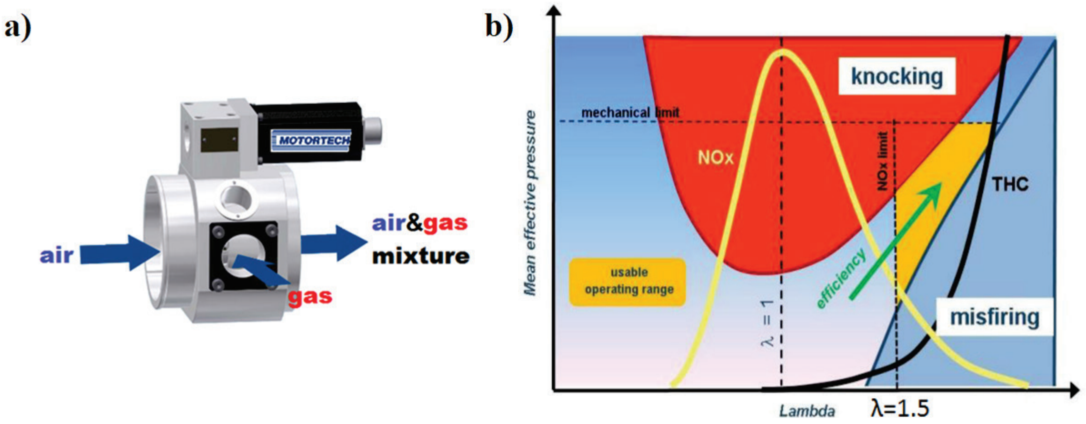

Fig. 2. Venturi gas mixer VariFuel2 [9] – a), knocking and misfiring limits [1] – b)

The figure above presents the VariFuel2 gas mixer manufactured by MOTORTECH GmbH, where gas and air are mixed based on the Venturi principle (see Fig. 1a). The air is sucked in through the air inlet by the suction pressure of the engine into the Venturi nozzle. This creates an under pressure at the most narrow place (Throat), which causes the gas to be sucked in through the gas inlet. In this way, both the gas and the air are mixed and released at the mixture outlet. As mentioned earlier, Venturi gas mixer devices should be theoretically able to prepare mixtures with an appropriate air-fuel concentration depending on the demand of the gas engine. However, at that point the question arose whether the air-fuel mixture leaving the Venturi gas mixer really homogenously mixed? To answer this question, research has been undertaken in cooperation with the company MOTORTECH GmbH from Germany, where one of the tasks was to analyse Air-Fuel Ratio characteristics given by different mixing devices. The article presents a preliminary research using the open source Computational Fluid Dynamics software OpenFOAM, where the main aim will be to analyse flow field characteristics and mixing behaviour of air and fuel in a Venturi gas mixer model to show the interplay of individual flow parameters on each other, like the interactions between AFR distribution, Turbulence Kinetic Energy (TKE), velocity changes and pressure loss [Pa] by the flow through the Venturi gas mixer.

2. Geometry and the solution procedure

The Venturi gas mixer was designed using the software Autodesk Inventor. Such a Venturi tube consists of a confuser and diffuser section, which are characterized by specific inflow and outflow angles. The dimensions of the simulated Venturi gas mixer were set as follows (see Fig. 2). The air inlet was equipped with a diameter of 50[mm] and a length of 100[mm], the Venturi throat as well as the gas inlet (CH_4) were provided with a diameter of 25 [mm]. The gas is sucked into the Venturi gas mixer circumferentially through six fuel injection holes (see Fig. 3).

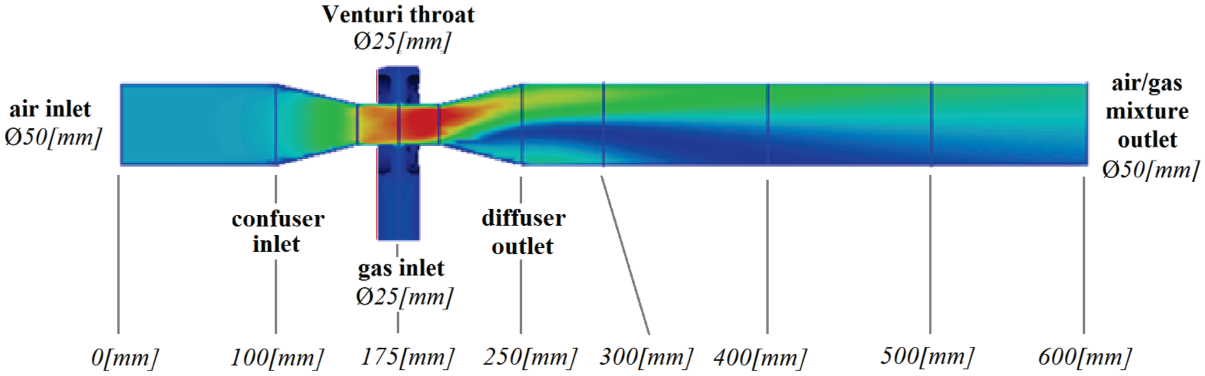

Fig. 2. Venturi gas mixer design with dimensions

The throat point was centered on a length of 175 [mm] beyond the air inlet, while the air/gas mixing pipe after the Venturi throat was set on 350 [mm] in length to achieve an appropriative convergence of the whole mixing simulation. In a way the total length of the analysed Venturi gas mixer were set on 600 [mm]. Numerical calculations were performed for a lean air/gas combustion mixture, in which the most common industrial gas engines operates, with an air excess coefficient of → $\lambda = 1.6$. In this numerical analysis OpenFOAM, software was used. OpenFOAM (Open Field Operation and Manipulation) is an open source CFD software with a package for solving a wide range of engineering tasks, from complex CFD calculations, including chemical reactions and also turbulence flows. In order to analyse the efficiency of the air-gas mixing process, the modified OpenFOAM solver *reactingFoam* was used. This model is based on the VOF (Volume of Fluid) methodology, which allows analysing different mixing reactions. In this article was analysed the mixing of methane → CH_4 with air. During numerical calculations, the composition of air was adopted in 21% of oxygen → O_2 and 79% of nitrogen → N_2.

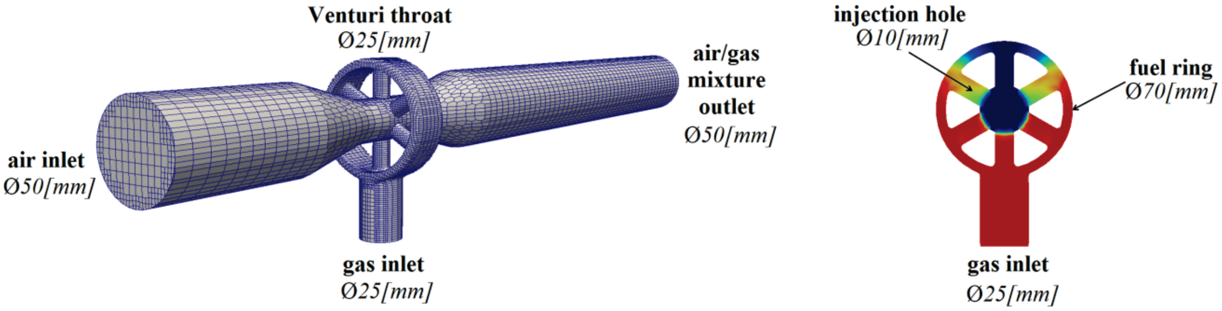

Fig. 3. Geometry of the simulated Venturi gas mixer with cross sectional view of gas inlet

The boundary conditions are required anywhere fluid enters the system and can be set as pressure, mass flow, volume flow or velocity. Because the flow through a Venturi gas mixer was studied in this article, air inlet velocity was set up on 12[m/s] as well as the gas inlet velocity on five [m/s]. For the outlet, pressure was taken a value of 101325[Pa], which means that the fluid exits the Venturi gas mixer model at atmospheric pressure. The walls of this numerical domain were considered as wall boundary conditions. The mesh was generated using the programs integrated into the OpenFOAM software, such as *BlockMeshDict* and *SnappyHexMesh*. Therefore, three meshes were compared according to the mesh quality. There were limited highly skewed and large aspect ratio elements. The final mesh (see Fig. 3) consists therefore of 24099 cells of which 18267 are hexahedras, 2801 are prisms, 2732 are polyhedras, 295 are tetwedges and last 4 cells are tetrahedras. By using the commend *checkMesh* automatically was checked the topology of the generated mesh by checking the boundary conditions or multiple connected surfaces.

3. Simulation of mixing process in a Venturi gas mixer

In this chapter were presented the results of numerical calculations of mixing behaviour in a Venturi gas mixer. Particular attention has been paid to the Air-Fuel Ratio changes (AFR) by analysing the concentrations of methane mass fraction → CH_4 through the Venturi gas mixer.

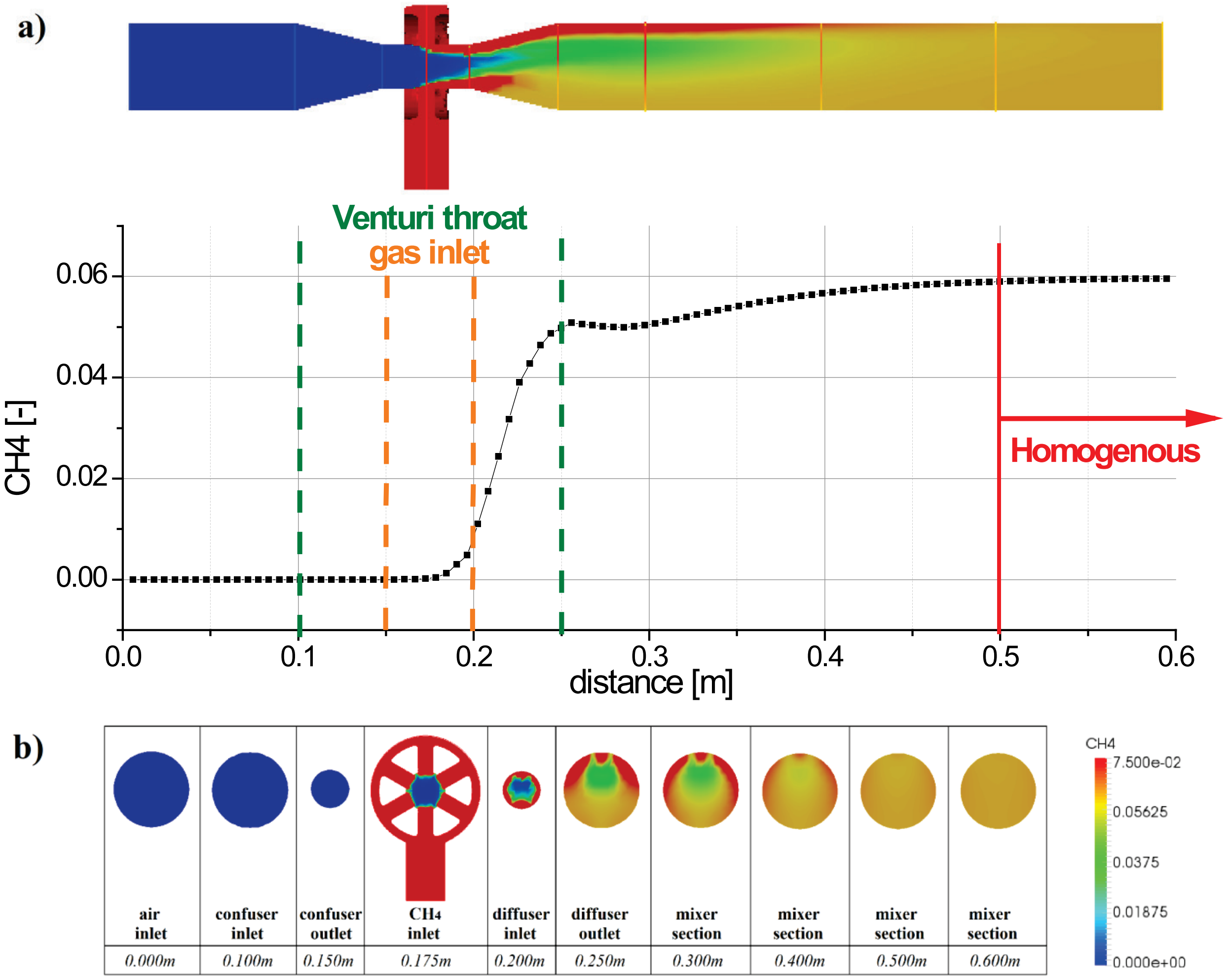

Fig. 4. Distribution of methane mass fraction in average – a) and cross sectional view – b) at different distances by the flow through the Venturi gas mixer model

Analysing the distributions of methane mass fraction in average and cross-sectional view (see Fig. 4a and b) it can be note how the methane → CH_4 is sucked into the Venturi gas mixer through six fuel injection holes and how is the distribution of it in the whole mixer section. As can be noted, after passing the diffuser outlet at a distance of 0.250 [m] the concentration is forming rapidly in an aerodynamic trace attached to the top wall due to the turbulent flow through the Venturi gas mixer. This mixture is unhomogenous until 0.500 [m] where it becomes stable. Here could be observed Air-Fuel Ratio (AFR) changes, which arise especially in Venturi gas mixer devices. This contour analysis in Fig. 4.b. gave a view on the distributions of methane mass fraction in cross-sectional view, but for a more detailed analysis, how the average concentration changes through the whole mixer section, it was necessary to analyse the average numerical data of the concentration distribution through the Venturi gas mixer. Such a more detailed analysis was shown in Fig. 4a., where it could be noted that after passing the gas inlet location (marked with orange dashed lines) there is a rapid increase of the concentration in the Venturi throat, while after passing the throat at distance 0.250 [m] occurs a drastically drop in this concentration. What is important to note, that at a distance of 0.500 [m] there occurs a stabilization of the whole distribution of methane concentration. This means, that at a distance of 0.500 [m] we have a homogenous mixture which does not change its concentration anymore. As it was mentioned before, the flow through the Venturi gas mixer is a turbulent flow, so it was especially important to analyse the Turbulent Kinetic Energy (TKE) along the flow through the Venturi gas mixer.

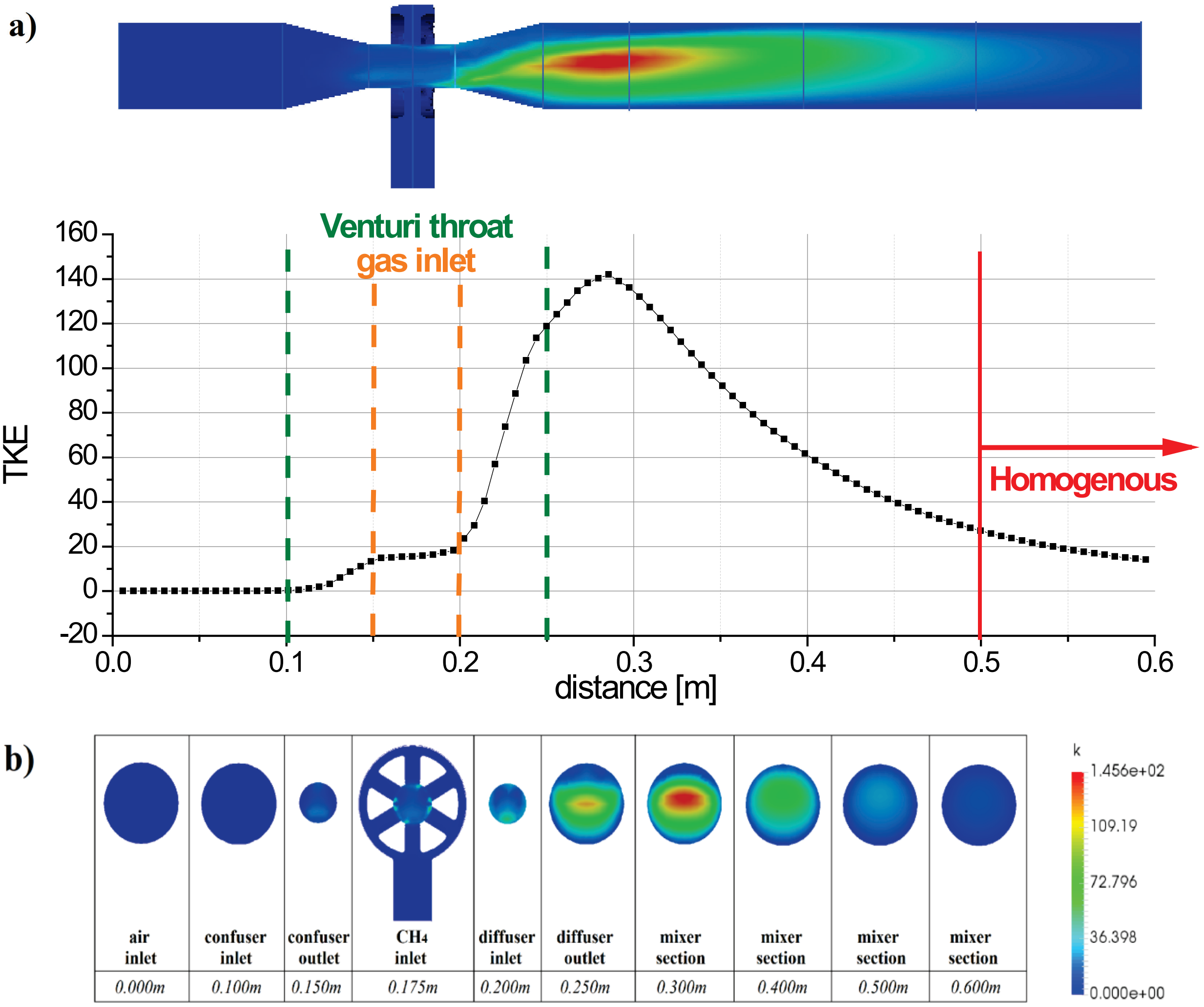

Fig. 5. Turbulent Kinetic Energy (TKE) in average – a) and cross sectional view – b) at different distances by the flow through the Venturi gas mixer model

Figure 5 shows the distribution of Turbulent Kinetic Energy (TKE) by the flow through the Venturi gas mixer. In fluid dynamics, the Turbulent Kinetic Energy is defined as the mean kinetic energy per unit mass of the turbulent fluctuations u_i' in a turbulent flow. Physically, TKE is characterized by measured root-mean square (RMS), therefore velocity fluctuations. There is a drastically grow up of the turbulent fluctuations as long as the flow rate increases. The biggest whirls are affecting and drawing energy from the main flow. In this case, the forces of inertia dominate, while the viscosity forces are negligible. In Reynolds-averaged Navier Stokes equations (RANS), the turbulence kinetic energy (TKE) can be calculated based on the closure method, i.e.

a turbulence model. In numerical calculations, the turbulence model k-ε was applied. Turbulence kinetic energy (TKE) can be generated by fluid shear, friction or buoyancy [10]. Analysing in Fig. 5 the distributions of the Turbulent Kinetic Energy (TKE) through the Venturi gas Mixer it could be seen how the TKE is growing up by flowing through the Venturi throat. It rapidly increases in this place, while after passing the Venturi throat is followed a drastic decrease of this parameter. It is known, that at a distance of 0.5 [m] we deal with a homogenous mixture (analysing the methane distribution earlier in Fig. 4), while the TKE after a distance of 0.5 [m] becomes almost stable in cross sectional view and equals $TKE < 30$. Due to the fact that the flow through a Venturi gas mixer is turbulent there could be expected a drastic increase of the velocity in the Venturi throat of this gas mixer.

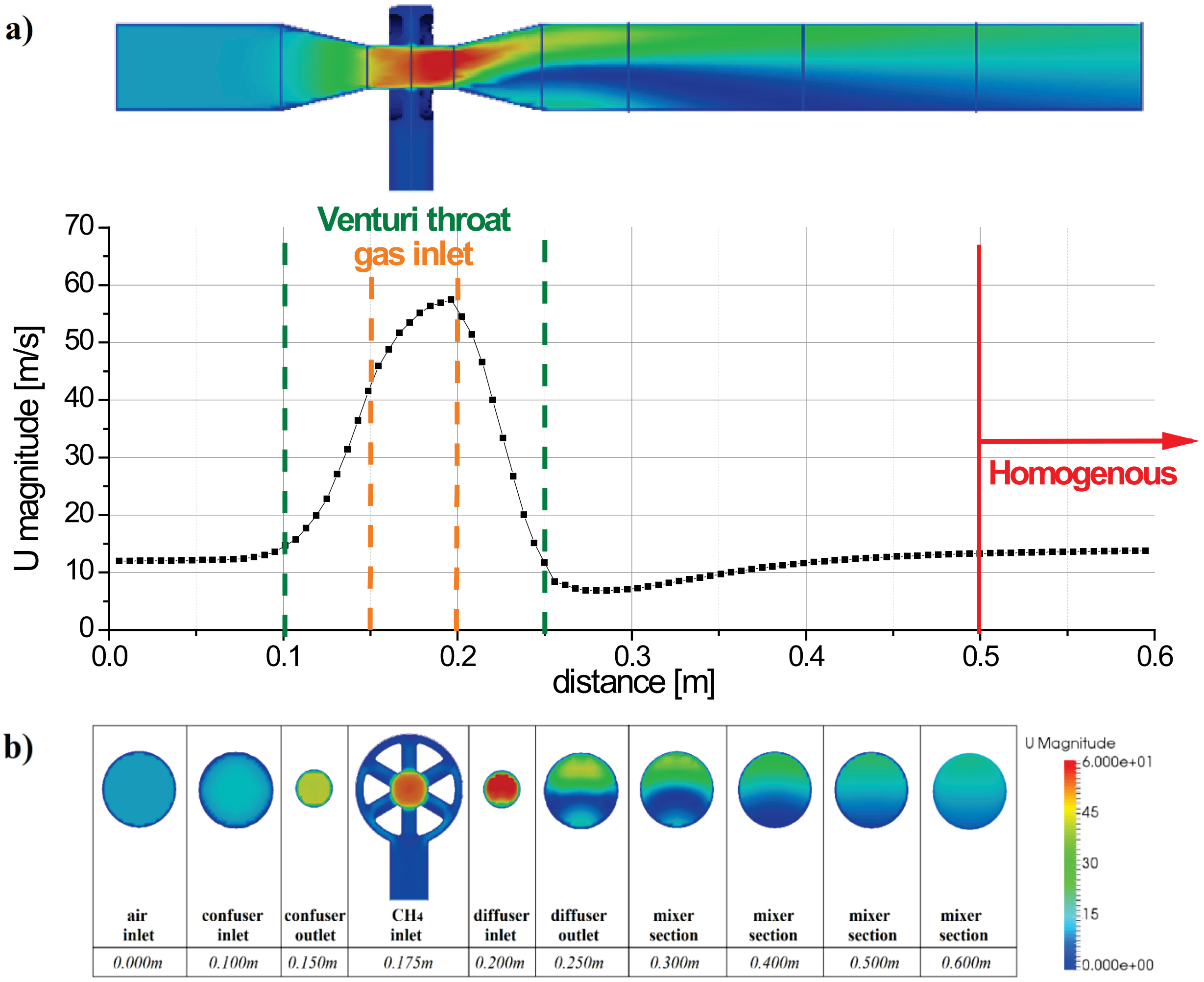

Fig. 6. Velocity changes in average – a) and cross sectional view – b) at different distances by the flow through the Venturi gas mixer model

For a reminder, in fluid dynamics, a fluid's velocity increases as it passes through a throat in accordance with the principle of mass continuity, while its static pressure decreases in accordance with the principle of conservation of mechanical energy. The initialized velocity at the air inlet was set on 12 [m/s] (see Fig. 6a) in the numerical calculations, which causes the gas being sucked into the Venturi gas mixer by an under-pressure generated in the throat point of the Venturi gas mixer. As expected, the velocity was increasing up to 60[m/s] over the flow through the Venturi throat. The flow stream was forming rapidly in an aerodynamic trace attached to the top wall due to the turbulent flow through the Venturi gas mixer (the same like in Fig. 4). This velocity changes are huge by the flow through the Venturi gas mixer until 0.5 [m] where it becomes stable. During the flow through a Venturi gas mixer, there are strong turbulences, which also has a positive effect on the overall mixing process. Finally, one of the most important parameters of a Venturi gas mixer, the pressure loss, was analysed. This is one of the most qualitative parameters to describe the quality and efficiency of a gas mixer.

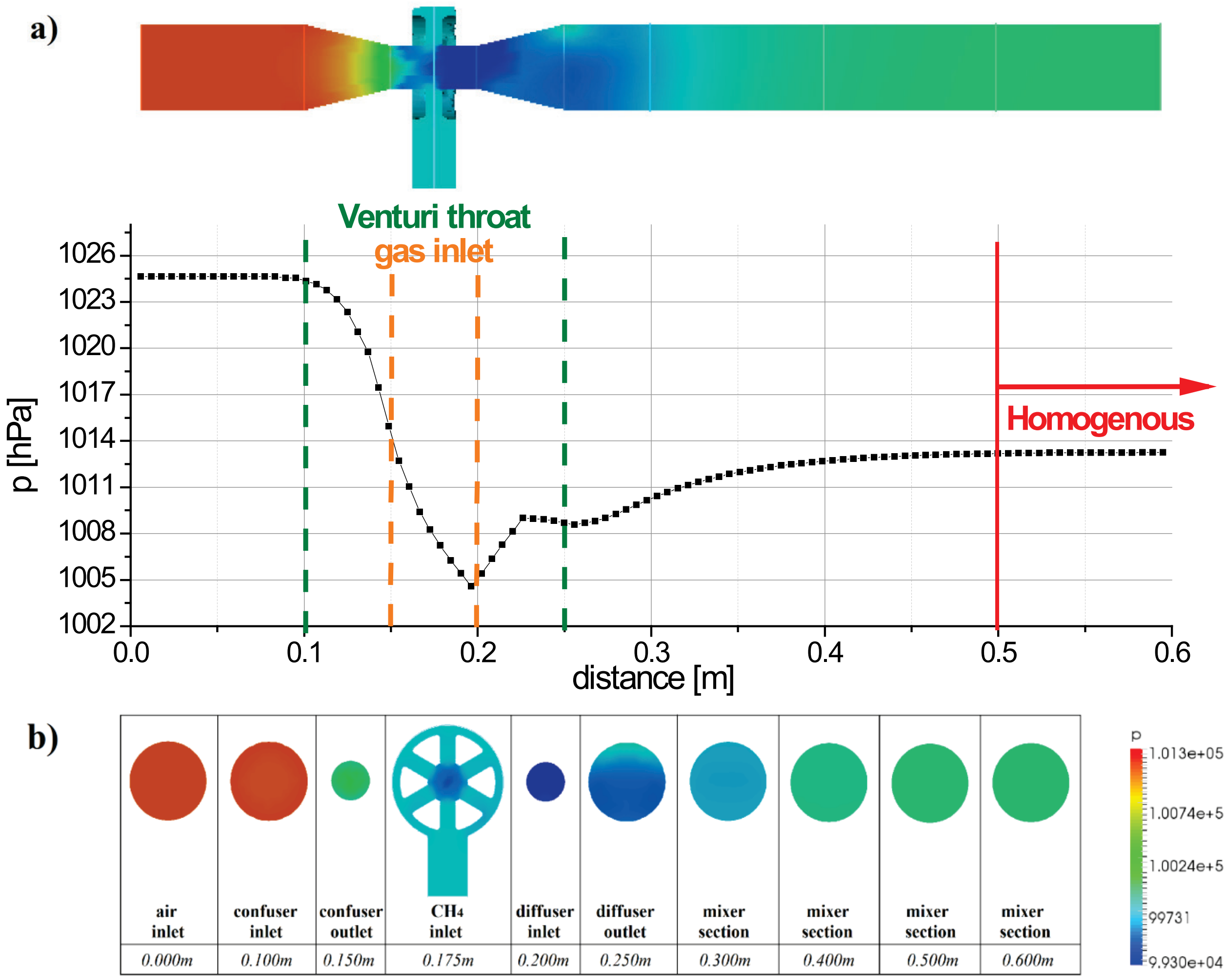

Fig. 7. Pressure loss [hPa] in average – a) and cross sectional view – b) at different distances by the flow through the Venturi gas mixer model

Analysing the pressure loss [hPa] through the Venturi gas mixer it could be note that the whole pressure loss occurs in the Venturi throat of the gas mixer, and after that it is growing slowly again until the distance of 0.5 [m] where it stabilizes and keeps at a constant level.

4. Conclusions

The article has presented a preliminary research using the open source Computational Fluid Dynamics software OpenFOAM, where the main aim was to analyse flow field characteristics and mixing behaviour of air and fuel in a Venturi gas mixer model to show the interplay of individual flow parameters on each other. To provide an efficiency combustion process in an industrial gas engine, the Venturi gas mixer should be designed to allow the best possible mixing of the two components, air and fuel. Additionally it should be compact, with minimum of pressure loss, and moreover good suction pressure in the throat due to the Venturi principle. Many analyses have been performed to improve the efficiency of the whole mixing process in a Venturi gas mixer. However, the influence of some geometrical parameters have not been analysed so far, what is important especially for the manufacturers of such gas mixing devices. What could be noted by analysing all four figures (Fig. 4-7) that the flow parameters have a huge impact not only on the homogeneity of the mixture, but also on of the mixture formation in the Venturi throat. Additionally, it can be stated that the homogeneity of the mixture largely depends on the flow parameters of the mixer, such as Turbulent Kinetic Energy (TKE) or Pressure loss. Furthermore, it should be taken into account that each mixer geometry gives different mixture formations. Therefore, minor geometrical changes require re-analysis of this mixing phenomenon. It is worth paying attention to the fact, that the distance of the mixing trace 0.5 [m] before it gets homogenous is a quite good distance in this numerical investigations, because most often the intake manifold from the gas mixer to the gas engine has a length less than 1.0 [m] depending on the mixer used and of course the gas engine. In the real world of gas mixers, it looks a bit different. Stabilization of the mixture is very dependent on flow conditions, often at a distance of about 0.5 [m] after the gas mixer the mixture is still unhomogeneous, which is associated with strong turbulence. The first experimental results gave the view that depending on the flow conditions, a fully homogeneous mixture is obtained until 1.5 [m] after the gas mixer which is not a good result. Further cooperation will be established with the company MOTORTECH GmbH from Germany to analyse Air-Fuel Ratio characteristics given by different mixing devices not only by the numerical way, but also experimentally. The experimental investigations will be done using a new constructed Air-Fuel Ratio Measurement station. The main aim will be to determinate the optimal geometrical parameters of mixer device which will be able to prepare homogenous mixtures with appropriate air-fuel concentrations depending on the demand of the industrial gas engine in a short distance behind the gas mixer.

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