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Influence of gas inlet angle on the mixing process in a Venturi mixer

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Abstract. In this paper numerical analysis were performed to investigate the influence of gas inlet angle on mixing process in a Venturi mixer. Performance of an industrial gas engine depends significantly on the quality of mixing air and fuel; therefore, on the homogeneity of the mixture. In addition, there must be a suitable, adapted to the current load of fuel, air ratio. Responsible for this fact, among others, is the mixer located before entering the combustion chamber of the engine. Incorrect mixture proportion can lead to unstable operation of the engine, as well as higher emissions going beyond current environmental standards in the European Union. To validate the simulation the Air-Fuel Ratio (AFR) was mathematically calculated for the air-fuel mixture of lean combustion gas engine. In this study, an open source three-dimensional computational fluid dynamics (CFD) modelling software OpenFOAM has been used, to investigate and analyse the influence of different gas inlet angles on mixer characteristics and their performances. Attention was focused on the air-fuel ratio changes, pressure loss, as well as improvement of the mixing quality in the Venturi mixer.

1 Introduction

The performance of industrial gas engines strongly depends on the quality of mixing air and fuel, and therefore homogeneity of the mixture. Rapid variations between the concentration of fuel and air called "Air-Fuel Ratio (AFR) changes" have a very negative impact not only on environmental emissions, but also on the fuel consumption in industrial gas engines. With increasing the requirements in line with European Union environmental standards for high efficiency combustion process in the gas engine, the need for a precise, homogeneously mixed air-fuel mixture, become more and more essential for better engine performance [5]. Therefore, an ideal Venturi mixer prepares a mixture with an appropriate air-fuel concentration, depending on the demand of the gas engine, both from no load during its start-up, to full load conditions during its constant operation [3]. 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. It is worth noting that for industrial gas engines, the anomalies of combustion processes are very different from those of conventional combustion processes. These processes can negatively affect the operation of the entire gas engine, which is associated with the occurrence of many kinds of undesirable phenomena [6]. The mixture proportion of air and fuel has a great impact on how the complete combustion process develops. When the air-fuel mixture is optimally prepared, there occurs an optimal combustion process. This situation changes when the air-fuel mixture is too lean (i.e. it has more air than necessary), then this can lead to a non-ignition mixture that results with misfire. As a result, there are unburned gas-fuel fractions in the exhaust duct. An additional undesirable phenomenon can also be a slow combustion process. This involves high CO emissions and consequently high instability of the entire combustion process. On the other hand, when the air-fuel mixture is too rich (i.e. it has more fuel than necessary) there may occur sudden, violent undesirable processes such as pre-ignition and glow-ignition. Most often, they occur during engine operation at maximum performance. Glow-ignition causes a strong instability of the entire combustion process, higher exhausts emissions and is, additionally, very dangerous for the gas engine itself. Various reasons for pre-ignition and glow-ignition have been analysed and investigated over the past few years, but the most common cause of self-ignition has been stated as the inadequate proportion of the air-fuel mixture [4]. Another symptom of a too rich air-fuel mixture is the knocking phenomenon. This is the most undesirable phenomenon, because it affects not only very badly on exhaust emissions, but primarily on the life of the entire gas engine. Consequently, it can lead to complete destruction of the whole industrial gas engine. To provide an efficiency combustion process in an industrial gas engine, the Venturi mixer should be designed to allow the best possible mixing of the two components. Additionally, it should be compact, with minimum of pressure loss, and moreover, should have a good suction pressure in the throat due to the Venturi principle. Different analyses were

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performed to improve the efficiency of the whole mixing process in the Venturi mixer. The effectiveness of the mixing process in the Venturi mixer depends on many factors, such as the Venturi throat diameter and its position, gas inlet area, as well as the gas inlet position. As was shown by Danardono et al. [2], by decreasing the throat diameter in the Venturi mixer, the mixture is richer in the end, and the Air-Fuel Ratio decreases significantly. Additionally, they showed that by increasing the size of the gas inlet area, the air-gas mixture is richer, there would be a better mixing process and a lower pressure loss. The influence of gas inlet position was investigated by Romańczyk and Elsner [8]. They showed that the optimal gas inlet position is located at an angle of inclination directly into the flow stream of air, where the mixing process takes place without much resistance from the air itself, what leads to a better mixing process and in addition to a lower pressure loss. They also paid attention to the gas inlet located indirectly into the flow stream of air (i.e. in the opposite direction to the flow), which results in a poorer mixing process and automatically – a bigger pressure loss through the Venturi mixer. To show how the whole mixing process depended on the gas inlet location, it was decided, by using the computational fluid dynamics simulation software OpenFOAM, to investigate the influence of different gas inlet angles in 5° intervals, which were located directly into the flow stream of air.

2 Mixer design and numerical modelling software OpenFOAM

In modern industrial gas engines, the manufactures more often try to design mixers based on the Venturi principle. The Venturi principle describes the drop in fluid pressure that occurs when a fluid flows through a throat in a pipe. 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. By decreasing in some points, the cross-sectional area of the air supply (see Figure 1), in accordance with Bernoulli's law and the continuity condition, creates a vacuum resulting in gas being sucked into the Venturi mixer. In this way, gas is being mixed with air.

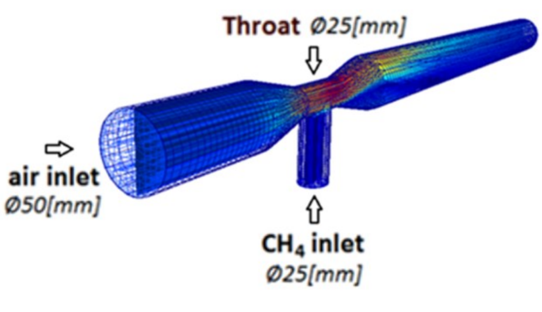

Fig. 1. Venturi mixer design with dimensions [mm].

In previous paper the optimal localisation of gas inlet position was investigated. It was shown that the optimal gas inlet position was located at an angle of inclination, directly into the flow stream of air, where the mixing process was taking place without much resistance from the air itself. Therefore, resulting in better mixing process and lower pressure loss. To demonstrate how the whole mixing process depends on the gas inlet location, it was decided to investigate the influence of different gas inlet angles located directly into the flow stream of air, by using the computational fluid dynamics simulation software OpenFOAM. As a result, seven gas inlets were analysed at different angles from 0°-30° with 5° intervals.

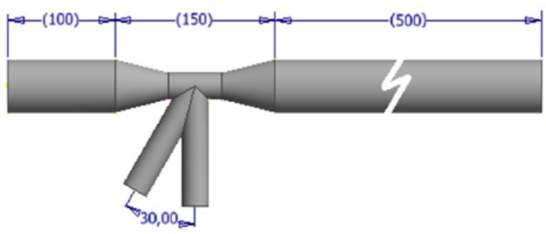

Fig. 2. Analysed cases (0°-30°) with the dimensions [mm].

The Venturi mixer models were designed with software Autodesk Inventor. The dimensions of the Venturi mixer were adopted in all analysed cases at the same level (see Figure 1 and Figure 2). Differences were in the gas inlet angles, only. The air inlet was equipped with a diameter of → 50 [mm], and length of 100 [mm]. The throat point, as well as the gas inlet (CH_4), were provided with a diameter of → 25 [mm]. The throat point was centred on a length of the next 150 [mm] beyond the air inlet, while the gas-air mixing pipe after the Venturi throat was set on 500 [mm] in length to achieve an appropriative convergence of the whole simulation. For this reason, the total length of the analysed Venturi mixers was set on 750 [mm]. Numerical calculations were performed for a lean combustion mixture, in which the most common industrial gas engines operate, with an air excess coefficient of $\lambda = 1.6$. In numerical analysis, OpenFOAM software was used. OpenFOAM (Open Field Operation and Manipulation) is open source CFD software with a package for solving a wide range of engineering issues, from complex CFD calculations, including chemical reactions and turbulence flows. The flow through the Venturi mixer is a turbulent flow, so it was necessary to use a turbulence model in numerical calculations. For this purpose, a two-equation turbulence model k-ε was used to analyse the Turbulence Kinetic Energy (TKE), along with the flow through the Venturi mixer. That turbulence model was selected, because it is one of the most widely used, good validated model in terms of consistency and reliability. It also consumes less computer time [9]. To analyse the efficiency of the gas-air mixing process, the standard OpenFOAM solver *reactingFoam* was used. This model is based on the VOF (Volume of Fluid) methodology, which allows to analyse different mixing reactions. In this paper, the mixing of methane → CH_4 with air was analysed. During numerical calculations, the composition of air was

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adopted as standard in 21% of oxygen → O_2 and 79% of nitrogen → N_2. The next chapter in this paper discusses results of numerical calculations of the analysed cases with different gas inlet angles. Particular attention has been paid to the Air-Fuel Ratio changes (AFR), by analysing the concentrations of methane mass fraction → CH_4 and air through the Venturi mixer. In addition, the distribution of the Turbulence Kinetic Energy (TKE) through the Venturi mixer, and the velocity changes with the pressure loss (which is one of the most qualitative parameters to describe the quality and efficiency of a gas mixer) were analysed.

3 Results and discussion

The results presented in this paper show a comparison between seven different gas inlet angles, located directly into the flow stream of air from 0°-30° with 5° of intervals. Analysing the whole mixing process in a Venturi gas mixer, it is very important to know, how the concentrations of methane mass fraction → CH_4 and air changes through the whole mixer section. Therefore, the mixing characteristics in the cross-sectional view of the Venturi mixer were firstly analysed in the Figure 3 after passing the Venturi throat, and in the Figure 4 at the outlet of the Venturi mixer.

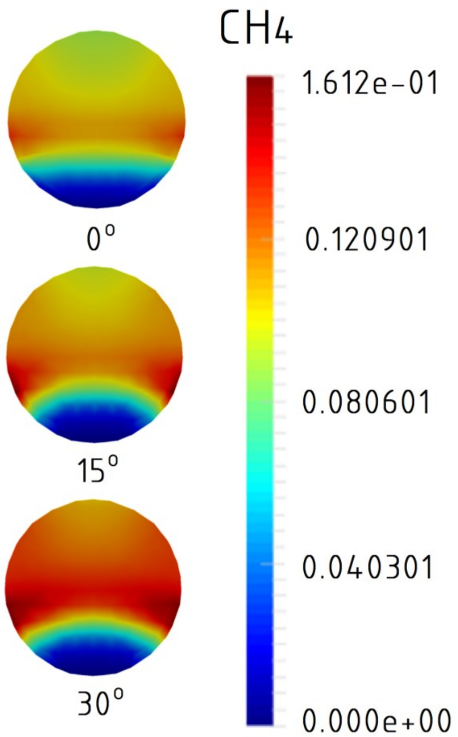

Fig. 3. Distribution of methane mass fraction in the cross-sectional view between analysed cases – 0°,15, 30° after passing the Venturi throat at 0.25 [m] from the inlet.

Analysing contours of distributions of methane mass fraction in the cross-sectional view, after passing the Venturi throat in the Figure 3, following assumption can be made: the greater the inclination of the gas inlet, the more methane → CH_4 is sucked into the Venturi mixer.

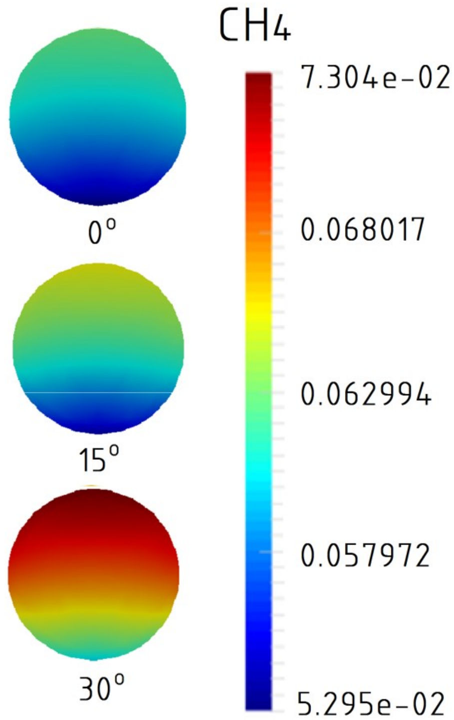

Fig. 4. Distribution of methane mass fraction in the cross-sectional view between analysed cases – 0°,15, 30° at the outlet of the Venturi mixer at 0.74 [m] from the inlet.

As a result, there would be a richer air-gas mixture at the outlet of the Venturi gas mixer, as presented in the Figure 4, that for 0° gas inlet angle the methane content is much lower than the methane content for a 30° angle. Analysing Figure 4, it could be seen that the greater the angle of inclination of the gas inlet, the higher is the concentration of methane mass fraction at the outlet of the Venturi mixer. These contours of methane mass fraction in the cross-sectional view, presented above, are very important, but unfortunately, they cannot fully describe the phenomenon occurring in the whole Venturi mixer section. Therefore, detailed analysis between the different gas inlet angles with average numerical results from the whole Venturi mixer were performed. Each numerical modelling analysis should be validated in the form of experimental data or mathematical calculations, using book definitions. For this reason, in the paper mathematical calculations, according to the book definition, were made to verify the correctness of this numerical calculations. The Air-Fuel Ratio (AFR) was calculated for a lean air-gas combustion mixture for which the most common industrial gas engines operate, with an air excess coefficient ratio of → λ=1.6, where the stoichiometric (i.e. λ=1.0) Air-Fuel Ratio AFR_{stoich} for methane CH_4 equals → 9.52 $\frac{m^3 air}{m^3 CH_4}$ [7]. The mathematical calculation was presented below:

$$AFR = \frac{m_{air}}{m_{fuel}} \tag{1}$$

$$AFR_{stoich} = 9.52\ \frac{m^3 air}{m^3 CH_4} \tag{2}$$

where the air excess coefficient ratio → λ:

$$\lambda = \frac{AFR}{AFR_{stoich}} \tag{3}$$

for $\rightarrow \lambda = 1.6$:

$$1.6 = \frac{AFR}{9.52} \Rightarrow AFR = 15.232 \frac{m^3 air}{m^3 CH_4}$$

and as a result:

$$for\ \ AFR = 15.232 \frac{m^3 air}{m^3 CH_4} \Rightarrow \frac{0.9384\, m_{air}\ [-]}{0.0616\, m_{CH_4} [-]}$$

The mathematical calculations gave the following results. For an air excess coefficient ratio of $\rightarrow \lambda = 1.6$, in which the most common industrial gas engines operate, the concentration of methane equals $CH_4 \Rightarrow 0.0616\, m_{CH_4}$ while the concentration of $air \Rightarrow 0.9384\, m_{air}$. In the next step, detailed analysis between different gas inlet angles were made, with average numerical data, to show if numerical results match the mathematical calculations.

Table 1. Comparison between mathematical and numerical calculations with specified Approximation error at the outlet of the Venturi mixer.

	Gas inlet angle	Concentration of air	Concentration of CH_4	Air excess coefficient $\rightarrow \lambda$	Approx. error
Units	[°]	[-]	[-]	[-]	[%]
Math. calculations	0°	0,93840	0,06160	1,60000	0,00
Numerical calculations	0°	0,93835	0,06165	1,59888	0,07
	5°	0,93790	0,06210	1,58635	0,86
	10°	0,93747	0,06253	1,57481	1,60
	15°	0,93708	0,06292	1,56446	2,27
	20°	0,93679	0,06321	1,55675	2,78
	25°	0,93485	0,06515	1,50727	6,15
	30°	0,93177	0,06823	1,43449	11,54

Accordingly to data in the Table 1, describing the concentrations of air and methane mass fraction → CH_4 through the Venturi mixer, the results calculated with theoretical mathematical formulas show full compatibility with the numerical calculations performed using OpenFOAM software. The approximation error for 0° of gas inlet angle is only 0.07 [%], so it can be concluded that the numerical calculations were performed correctly for these analysed cases. The greater the gas inlet angle, the higher is the approximation error, because more methane → CH_4 is sucked into the Venturi mixer which causes a richer mixture proportion at the outlet of the Venturi mixer as evidenced by a smaller air excess coefficient ratio → λ, from λ = 1.6 up to λ ≈ 1.44. In the Figure 5 were presented the concentrations of methane mass fraction changing through the Venturi mixers for different gas inlet angles.

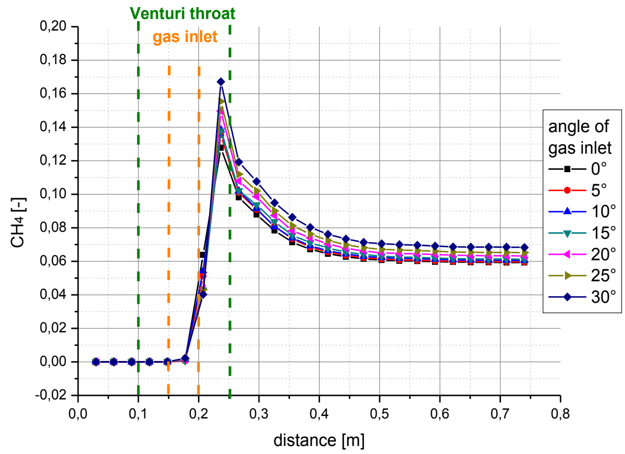

Fig. 5. Concentration of methane mass fraction CH_4 through the Venturi mixer for different gas inlet angles.

Analysing the concentration of methane mass fraction CH_4 through the Venturi mixer in the Figure 5, it could be seen that for mixers equipped with a greater gas inlet angle than > 20° the suction of methane appears a little bit later and initially is slower, but in the end more methane CH_4 is sucked into the mixer, which results in a better mixing process of the two components – air and gas. 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 0.25 [m] a drastic drop in the concentration can be observed. However, at 0.6 [m] there occurs a stabilisation of the whole distribution of methane concentration. If more methane CH_4 is sucked in, better and intensified mixing process of two components, air and gas, can occur. Automatically, there is a richer mixture proportion at the outlet of the Venturi mixer. Here, we could observe the Air-Fuel Ratio (AFR) changes, which could be explained with the angle of the gas inlet flow, which causes more suction of gas into the flow stream of the Venturi mixer, at identical inlet conditions in the simulations for all analysed cases.

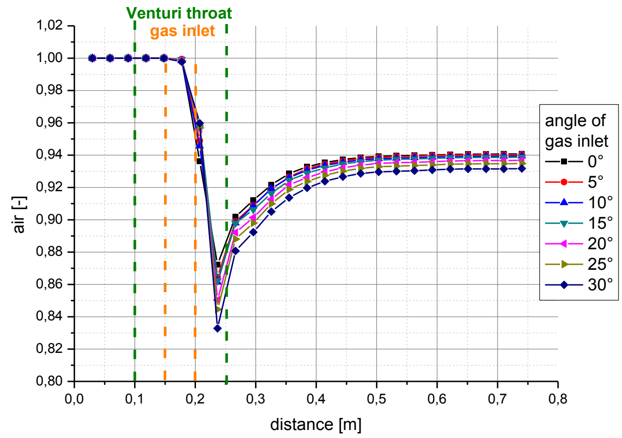

Fig. 6. Concentration of air through the Venturi mixer for different gas inlet angles.

These drops in concentration changes are also seen in the Figure 6, while analysing the concentration of air through the Venturi mixer, because in the total flow volume there is always a 100 [%] air-gas mixture totalling → 1. Thus, the distribution of air concentration is the mirror image of the distribution of methane concentration. As was shown previously, the result of numerical calculations matches very well with the theoretical mathematical calculations. By analysing the concentration changes of methane CH_4 (Figure 5) and air (Figure 6) along the flow, it can be observed that the greater the gas inlet angle, more methane $\rightarrow CH_4$ is sucked into the Venturi mixer which causes a richer mixture proportion at the outlet of the Venturi mixer. This results with a smaller air excess coefficient ratio → λ, changing from λ = 1.6 up to λ ≈ 1.44. Having the simulated concentration changes (m_{air}, m_{fuel}), in the next step, additional mathematical calculations for the air excess coefficient → λ were made, to show how the Air-Fuel Ratio changes for the different analysed cases in the flow through the whole Venturi mixer. For example, calculation is presented below for $\rightarrow \lambda = 1{,}6$:

Knowing that:

$$AFR = \frac{m_{air}}{m_{fuel}} \Rightarrow \frac{0{,}9384\, m_{air}}{0.0616\, m_{fuel}}$$

$$AFR_{stoich} = 9.52\, \frac{m^3 air}{m^3 CH_4},$$

It can be calculated the air excess coefficient $\rightarrow \lambda$:

$$\lambda = \frac{AFR}{AFR_{stoich}} \Rightarrow \frac{\frac{m_{air}}{m_{fuel}}}{9.52} \Rightarrow \frac{\frac{0{,}9384\, m_{air}}{0.0616\, m_{fuel}}}{9.52} = 1.6$$

The calculated distributions of the air excess coefficient $\rightarrow \lambda$ for these analysed cases is presented in the Figure 7.

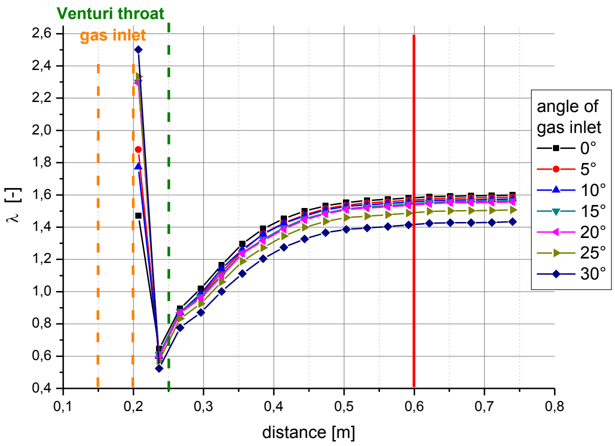

Fig. 7. Distribution of air excess coefficient → λ, through the Venturi mixer for different gas inlet angles.

Analysing the distributions of the air excess coefficient ratio it could be seen that after passing the Venturi throat of the mixer, the coefficient rapidly increases and stabilises at about 0.6 [m] for all analysed cases. The greater the gas inlet angle, the faster is the drop after passing the gas inlet, while the grow up in the Venturi throat is faster. More methane $\rightarrow CH_4$ is sucked into the Venturi mixer which causes a richer mixture proportion at the outlet. This results with a smaller air excess coefficient ratio → λ, changing from λ = 1.6 for a standard gas inlet at 0° up to λ ≈ 1.44 for a gas inlet located with an angle of 30°. As it was mentioned before, the flow through the Venturi mixer is a turbulent flow, so it was necessary to analyse the Turbulent Kinetic Energy (TKE) along the flow through the Venturi mixer. Figure 8 shows the distribution of Turbulent Kinetic Energy (TKE). In fluid dynamics, the Turbulent Kinetic Energy is defined as the mean kinetic energy per unit mass, associated with eddies in the 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 if 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. As it was mentioned before, in the numerical calculations the turbulence model k-ε was applied. Turbulence kinetic energy (TKE) can be generated by fluid shear, friction or buoyancy, or through an external force at low-frequency eddy scales [1].

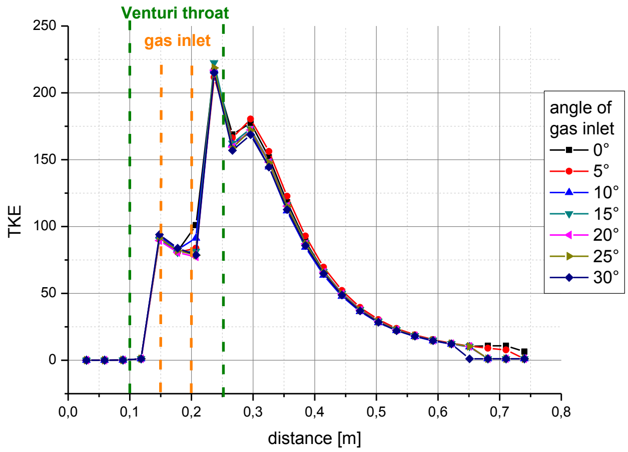

Fig. 8. Distribution of Turbulent Kinetic Energy (TKE) through the Venturi mixer for different gas inlet angles.

Analysing in Figure 8 the distributions of Turbulent Kinetic Energy (TKE) through the Venturi mixer for different gas inlet angles it could be seen how the TKE is growing up through the Venturi throat. It rapidly increases in this place, while after passing the Venturi throat is followed a drastic decrease of this parameter. There are very small changes between the analysed cases, so it could be concluded that for the changing of gas inlet angles, the Turbulent Kinetic Energy (TKE) is almost constant. In the next step were analysed in detail velocity changes in the flow through the Venturi mixer. As was mentioned before, the flow through a Venturi mixer is a turbulent flow, so there could be expected drastic increases of the velocity after passing the Venturi throat of this mixer. 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 initialised velocity at the air inlet was set on 12 [m/s] in the numerical calculations, which caused the gas being sucked into the Venturi mixer by an

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under-pressure generated in the throat point of the Venturi mixer. Therefore, firstly the contours of velocity magnitude between the analysed cases for three different gas inlet angles → 0°, 15° and 30°, were analysed in the Figure 9.

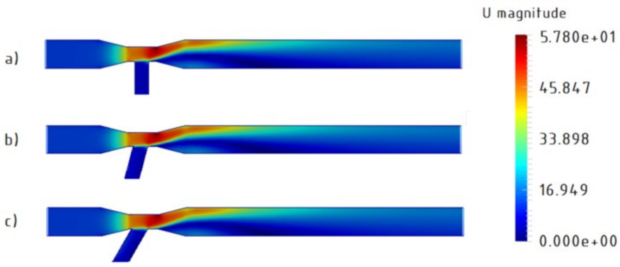

Fig. 9. Contours of velocity magnitude between analysed cases – a) 0°, b) 15° and c) 30° [m/s].

The expected velocity was increasing nearly to 58 [m/s] during the flow through the Venturi throat. During the flow through the Venturi mixer, there are strong turbulences, which also have a positive effect on the overall mixing process. Analysing the contours of velocity magnitude (Figure 9), it could be seen that the differences between them are so minor, that it cannot be described correctly by only analysing these contours. Therefore, better view of the flow rate will give the analysis of the average distribution of velocity magnitude [m/s] through the Venturi mixer for different gas inlet angles presented in the Figure 10.

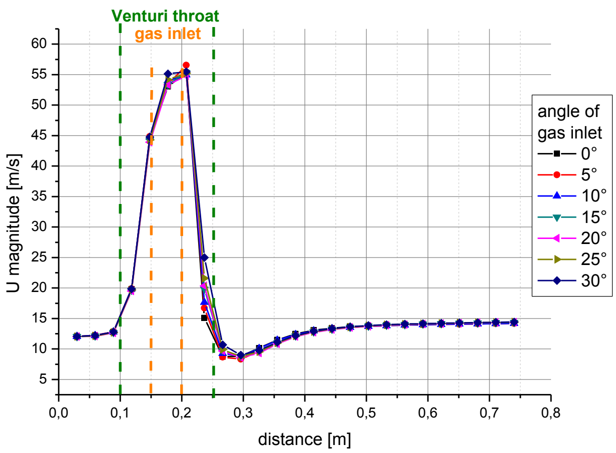

Fig. 10. Distribution of velocity magnitude [m/s] through the Venturi mixer for different gas inlet angles.

Analysing the average distribution of velocity magnitude [m/s] through the Venturi mixer (presented in the Figure 10) for different gas inlet angles, it could be seen that the biggest changes happened in the Venturi throat section of the gas mixer. Initially, in the Venturi throat inlet the velocity was drastically growing up nearly to 58 [m/s], while after passing the gas inlet section it started to fall to a smaller velocity, as set in the inlet of the Venturi mixer. The greater the gas inlet angle, the lower is the velocity drop after passing the gas inlet section. But it is worth noting, that the differences in drops of velocity between the analysed cases with different gas inlet angles are very small. Finally, the most significant parameter of the Venturi mixer – the pressure loss was analysed. This is one of the most qualitative parameters to describe the quality and efficiency of a gas mixer. Firstly, the contours of pressure loss were analysed in the Figure 11, between three analysed cases for a gas inlet angle of 0°, 15° and 30°.

Fig. 11. Contours of pressure loss between analysed cases – a) 0°, b) 15° and c) 30° [Pa].

Analysing the contours of pressure loss between these three cases, it could be noticed which of the following Venturi gas mixer has a lower pressure loss, by analysing the colour scale bar of the pressure contour located at the right-hand side in the Figure 11. Here, the differences are much greater than in the previous analysis of the velocity magnitude contours. Supposing, the brightest red colour at the Venturi gas inlet angle of 30° should provide the lowest pressure loss. In addition, after passing the Venturi gas inlet the largest vacuum zone (marked in blue) is in the mixer with the greatest gas inlet angle for 30°. This results in bigger under-pressure which causes more gas being sucked into the Venturi mixer. Therefore, in the end there would be a richer air-fuel mixture proportion which results with a smaller air excess coefficient ratio $\rightarrow \lambda$. This contour analysis shows a good comparison between the three analysed cases. On the other hand, here too, for a more detailed analysis, it was necessary to analyse the average numerical data of the pressure loss through the Venturi mixer for different gas inlet angles. This analysis was shown in the Figure 12.

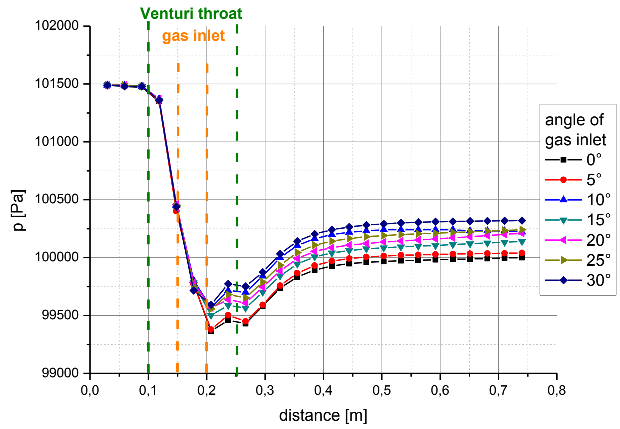

Fig. 12. Pressure loss [Pa] through the Venturi mixer for different gas inlet angles.

Analysing the pressure loss [Pa] through the Venturi gas mixer for different gas inlet angles (Figure 12), it could be noticed that the greater the gas inlet angle, the smaller the pressure loss through the whole Venturi mixer was. It could be also seen that the whole pressure loss occurs in the Venturi throat of the gas mixer, and after that it was growing slowly again until the distance of 0.6 [m] from the

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Venturi mixer inlet where it stabilises and keeps at a constant level for each analysed case.

4 Conclusions

The detailed analysis presented in this paper showed that the greater the inclination of the gas inlet, the more methane $\rightarrow CH_4$ is sucked into the Venturi gas mixer. As a result, there would be a richer air-gas mixture at the outlet of the Venturi mixer. This also significantly affects the increase of the efficiency of the whole mixing process. Moreover, smaller pressure loss occurs through the whole Venturi mixer. In this paper, detailed analysis between seven different gas inlet angles was made, with average numerical result from the whole Venturi mixer performed with the numerical OpenFOAM software. As it is commonly known, each numerical modelling analysis should be validated in the form with experimental data or mathematical calculations. In this paper mathematical calculations were made accordingly to the book definition, to verify the correctness of this numerical calculations. As was shown previously, the result of numerical calculations matches very well with the theoretical mathematical calculations.

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References

1. R. Absi, J. Appl. Mech., **75**, 1 (2008)
2. *D.* Danardono, K. S. Kim, S. Y. Lee, J. H. Lee, J. MECH. SCI. TECHNOL. **25** (9), 2285 (2011)
3. R. Devarajan, Comparative Evaluation of a Two Stroke Compressed Natural Gas Mixer Design using Simulation and Experimental Techniques. *International Conference on Association of Science and Technology for Development, Power and Energy Systems*, Langkawi: 359 (2008)
4. M. Günther, Y. Uygun, F. Kremer, S. Pischinger, *MTZ Worldw*, **74**, 46 (2013)
5. M. Gorjibandpy, M. K. Sangsereki, World Academy of Science, Engineering and Technology. International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, **4** (2010)
6. K. M. Han, *Lichtleiterbasierte Methoden zur optischen Analyse von räumlichen Verbrennungsprozessen und Verbrennungsanomalien in Ottomotoren*. Technische Universität Karlsruhe, Dissertation (2010)
7. K. Ražniewić, *Tablice cieplne z wykresami* (Warszawa WNT 1966)
8. M. Romańczyk, W. Elsner, *23rd International Conference Engineering Mechanics 2017*, *Book of full texts: ISBN 978-80-2014-5497-2*, Svratka, Czech Republic, 15 (2017)
9. S. Sundararaj, V. Selladurai, International Journal of Applied Engineering Research, **7,** 891 (2008)