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MIXING OF BIOMASS AND COAL IN A STATIC MIXER AS AN EXAMPLE OF TECHNOLOGICAL SOLUTIONS INVOLVING IMPLEMENTATION OF RENEWABLE ENERGY SOURCES

MIESZANIE BIOMASY Z WĘGLEM W MIESZALNIKU STATYCZNYM JAKO PRZYKŁAD ROZWIĄZAŃ TECHNOLOGICZNYCH WDRAŻANIA ODNAWIALNYCH ŹRÓDEŁ ENERGII

Abstract: The purpose of this article is to demonstrate possibilities of mixing coal with biomass using static mixers. The paper present simple and inexpensive methods for producing fuel mixes for heat-generating plants equipped with stoker-fired boilers of power ranging from 3 up to 50 MW. Static mixer proposed in this article may constitute an alternative for currently used solutions in production facility. Based on statistical analysis, the article demonstrates that five mixing elements of the mixer is optimal number to ensure best biomass (chips and pellets) concentration distribution in a mixture with fine hard coal.

Keywords: renewable energy sources, biomass, black coal, co-combustion, solids mixing processes, static mixer

Introduction

Increasing energy demand with simultaneous depletion of non-renewable resources and growing pollution of natural environment due to the consumption of fuels cause greater interest in the use of energy derived from renewable sources. Renewable energy is considered an important resource in many countries around the world [1-8]. Renewable energy sources constitute crucial component of energy balances in European countries and will play increasing role in actions aimed to reduce emissions of greenhouse gases, support social and economic development, and improve energy security (diversification of delivery sources, dispersed energy production based on locally available raw materials) [9]. Global energy consumption is growing [10, 11], however the year 2012 saw a slowdown, partly as a result of the economic slowdown but also because businesses and individuals have responded to high prices by becoming more efficient in their use of energy [10]. The

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world's energy market is flexible, continuously changing, adapt, innovate and evolve which may be visible in an increasing diversity of sources of energy [10]. In 2012 renewable energy in power generation reached record shares of global primary energy consumption at level 8.6% (hydroelectric output 6.7% and other renewables 1.9%) [10].

Activities related to growing importance of renewable energy sources result from legal regulations of the European Union Member States, which specify general and detailed objectives for reaching established energy share rates. In Poland, a strategic goal of state policy is to increase the use of renewable energy resources, so as to ensure that the share of this energy type in final gross energy consumption in a sustainable way reaches 15.5% in 2020 [12]. 'Sustainable way' should be highlighted here, as a result of the fundamental goal of the EU strategy for sustainable development - to improve the quality of life on earth of both present and future generations including targets for renewable energies, reduction in energy consumption, cleaner production, support for climate targets for 2020 and (indirectly) for 2050, and the strategy for biomass [13-17]. Poland is expected to exceed their 2020 binding targets [18].

Biomass is the plant material derived from the reaction between CO_2 in the air, water and sunlight, through photosynthesis, to produce carbohydrates that form the building blocks of biomass [9]. Biomass is an important contributor to the world economy. Agriculture and forest products industries provide not only food, feed, fiber, a wide range of other products, but biomass is also a source of a large variety of chemicals and materials, and of electricity and fuels [19].

In Poland, energy from renewable sources includes energy from: solar radiation, water, wind, geothermal resources, and energy generated from solid biofuels, biogas and liquid biofuels, and ambient energy acquired by heat pumps [20]. In Polish conditions, we are able to use renewable energy sources in a limited scope, thus in document [12] it has been assumed that the pillar for increasing the share of energy derived from renewable sources will be using to a larger extent biomass and electric energy generated from wind. In years 2007-2011 the share of energy from renewable sources in total primary energy increased in the EU-27 from 15.6 to 20.3%, and in Poland - from 6.7 to 10.9%. At the same time, the rate of primary energy generated from renewable sources increased in the EU-27 by 21% and in Poland by 54% [20]. The structure of energy production from different renewable sources is diversified for the EU countries. Energy production from solid biofuels, which include firewood, forestry waste, wood and paper industry waste, fuels from plantations for energy production purposes, charcoal and organic waste from agriculture and gardening reached 50.2% in 2007 and 48.1% in 2011 in the UE, while in Poland: 91.1% in 2007 and 85.3% in 2011, respectively [20]. Biomass is planned to represent 17.2% of the planned EU heating and cooling mix and 6.5% of electricity consumption in 2020 [21]. Moreover Poland will be one of the main bioenergy markets in 2020 [18].

Energy production from renewable energy sources is considered more natural environment-friendly than in case of production from conventional sources (fossil) due to the reduction of harmful impact of the power industry on natural environment, primarily through limited emission of noxious substances, in particular greenhouse gases. However, the issue of renewable energy production is highly controversial and is criticised, also as regards sustainable development, both on an international and local (national) scale [21, 22]. Cao and Pawłowski [22] showed that the production of biofuels from agricultural crops is, in many cases, unsustainable due to the fact that it reduces the access to food by devoting cultivatable land to crops designated for the production of biofuels and it has also negative influence on the environment, by reduces biodiversity, pollute water. Authors also highlighted that not in all cases the use of biofuels leads to the reduction of CO_2 emission [22]. Critics around the world point at high investment costs, the need to support wind and solar power stations by conventional power plants, ecological and health hazards, and doubtful effect on total CO_2 emission [22-24]. Nevertheless, the CBA (cost-benefit analyses) indicate many benefits (environmental, economic and other, non-conventional), which surpass the costs of initial support for renewable energy sources development (being gradually reduced per generated energy unit) if appropriate policy steps are taken [25, 26], and further technological improvements, especially technologies of converting the transportation sector and the introduction of flexible energy system technologies are crucial [27].

Co-firing of coal and biomass in power boilers is one of technological solutions not requiring considerable financial outlays for implementing renewable energy sources, which may bring about ecological, energy-related and economic effect. In recent years, it is one of development trends in professional energy production sector. Co-firing of shredded biomass in a mixture with coal may be also effectively executed in low-power boilers in individual heating, and in stoker-fired boilers, fluidised-bed boilers and pulverised-fuel boilers in industrial power industry provided that optimal share of biomass in the mixture is maintained. This guarantees effective combustion process execution from ecological and energy production point of view, with reduced emission of organic pollution (TOC), including WWA and volatile organic compounds (VOCs), SO_2 and NO_x in flue gas, reduction of combustible fraction volume in ash (slag) and reduced CO_2 emission. Numerously studies have shown that burning biomass with fossil fuels has a positive impact both on the environment and the economics of power generation [28-32]. The emissions of SO_2 and NO_x were reduced in most co-firing of biomass and coal techniques. There are also other ecological effects of biomass and coal co-firing, that is the reduction of advancing environment deterioration caused by fossil fuels mining and disposal of waste from mining industry in the environment, as well as reduction of soil erosion processes, water management regulation and air pollution assimilation resulting from cultivation of biomass for energy production purposes. Introduction of biomass and coal co-firing constitutes an additional economic benefit for larger Polish heat-generating plants with installed power exceeding 10 MW, that is zero CO_2 emission in CO_2 emission trading system in case of using biomass [33].

The purpose of this article is to demonstrate possibilities of mixing coal with biomass using static mixers, which involves the need to solve the problem of using simple and inexpensive methods for producing fuel mixes for heat-generating plants equipped with stoker-fired boilers (power ranging from 3 up to 50 MW).

Materials and methods

The experiment have been carried out in an industrial model of static mixer equipped with internal elements - roofs (Fig. 1), which has been designed to replace mechanical mixer currently used in industrial conditions (Fig. 2), supplying fuel mixture (coal with biomass) to stoker-fired boilers of the MWD-2 line. In industrial conditions static mixer will be located between upper edge of belt conveyor supplying the existing mechanical mixer and charging hopper of belt conveyor delivering coal to boiler house.

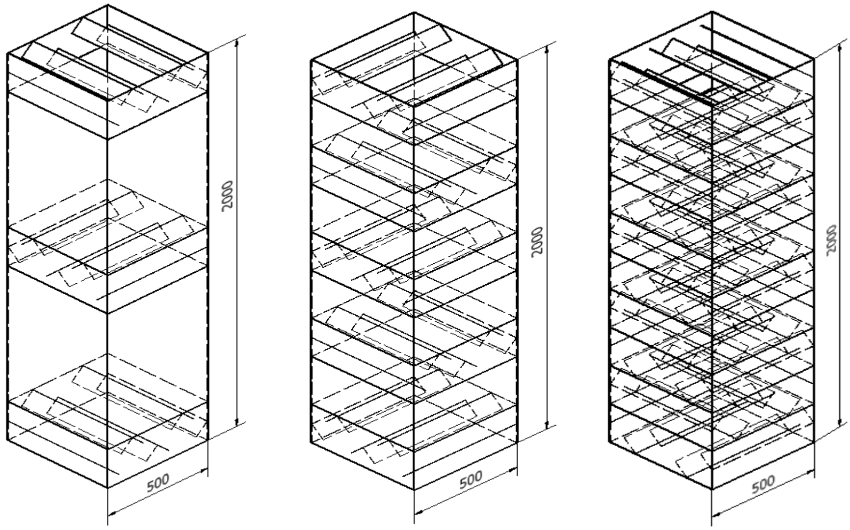

Fig. 1. Static mixer with 3, 5 and 10 mixing elements

Static mixer dimensions result from the design of MWD-2 mixing station, so as to allow static mixer replace the mixing station. Static mixer total height reached 3500 mm. Mixing elements consisted of three, five and ten parts, fitted alternately - at the angle of 90° relative to each other. Besides mixing elements shown in photographs, feeding box sized 500 x 500 x 500 mm was provided above the mixer, and receiving box sized 360 x 350 x 520 mm below it. The height of each receiving frame was 40 mm.

Fig. 2. The MWD-2 station in heat-generating plant equipped with stoker-fired boilers

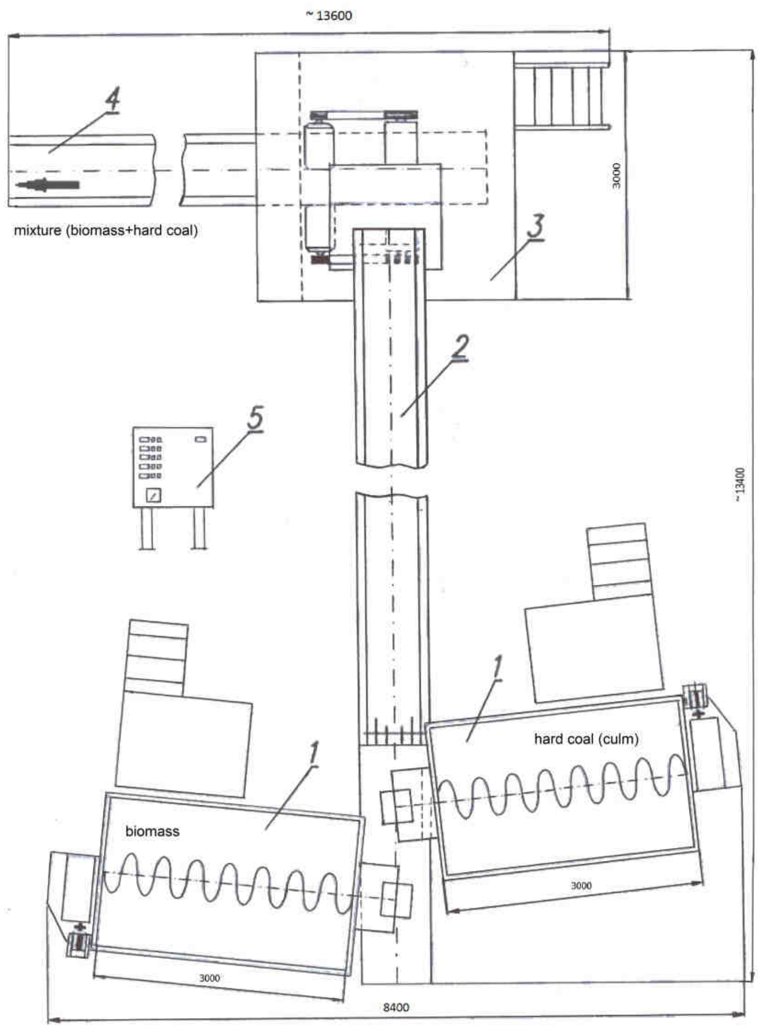

Fig. 3. Diagram of mixing line for biomass and fine coal: 1 - preliminary mixing basket, 2 - belt conveyor flight I, 3 - mixer, 4 - belt conveyor flight II, 5 - control cabinet (based on 34)

Biomass and coal mix may be obtained in specially designed mixing stations (Fig. 3), which are used to mix and shred biofuels in fuel storage yards located at boiler houses. Ingredients are mixed in a mixer.

Static mixer proposed in this article may constitute an alternative for currently used solutions, including: separate coal and biomass feeding during coal delivery and their mixing in pulverised-fuel boilers, bucket loaders, mixture production out of the plant, or using specially designed for biomass in form of dust. In the proposed static mixer, mixing process is executed by gravity-generated motion of grains of materials being mixed, which run into mixing elements on their way. Grainy material stream is divided by mixing elements several times, and then it is merged. Mixed ingredients are homogenised due to the crossing of smaller material streams.

Considering the technology of mixing process in the MWD-2 station, that is filling of charging hoppers, feeding the mixture ingredients onto the shared belt conveyor, mixing and shredding in a mixer, receiving ready mixture from the mixer and its transport to the storage yard, mixing in the static mixer may be include single flow only, that is one mixing step. Process configuration at the MWD-2 station excludes the mixture circulation. In real conditions, the mixing process will be additionally supported by grainy material transport by belt conveyor.

The following materials were used for tests: hard coal with grain size from 0 to 25 mm and wood biomass: pellets 6 mm in diameter and length from 5 up to 30 mm, and softwood chips sized up to 50 mm. Raw material for chip production included waste from forest production, wood industry of energy crops, while in case of pellets these were unprocessed wastes, namely wood dust, fine sawdust or straw. Parameters of the ingredients being mixed are shown in Table 1.

Table 1

The parameters of applied granular materials

<table>
<tr><th>Parameter/ material</th><th>Bulk density ρ [kg/m^3]</th><th colspan="2">Bulk density ratio</th><th>Diameter d_z [mm]</th><th colspan="2">Diameter ratio</th></tr>
<tr><td>Hard coal</td><td>$\rho_1 = 700$</td><td rowspan="2">$\rho_1/\rho_2 = 3.89$</td><td>-</td><td>$d_{z1} = 8.25$</td><td rowspan="2">$d_{z1}/ d_{z2} = 0.61$</td><td></td></tr>
<tr><td>Chips</td><td>$\rho_2 = 180$</td><td rowspan="2">$\rho_1/\rho_3 = 1.21$</td><td>$d_{z2} = 13.44$</td><td rowspan="2">$d_{z1}/ d_{z2} = 0.80$</td></tr>
<tr><td>Pellets</td><td>$\rho_3 = 580$</td><td></td><td>$d_{z3} = 10.35$</td><td></td></tr>
</table>

Ingredients were mixed at weight ratio 1:10 (biomass : coal). A 10% biomass share was imposed by general application of this ratio in energy production industry for firing boilers unfitted for biomass combustion.

The tests involved using computer image analysis with PATAN application for observation of quantitative portion [%] of tracer that is biomass on the surface of individual receiving box sections. More information about computer image analysis is shown in a different paper of the author [35]. After completion of decimal-to-binary conversion, biomass (tracer) received value 1 and coal - value 0. Ten images of biomass concentration on individual receiving box surfaces were received for each research experiment.

During preliminary tests it has been determined that location of coal in upper part of feeding box, and biomass in its lower part will contribute to improvement of the mixing effect. Mixing effect depends on many parameters, not just the parameters of the components, but also on the technology and process conditions [36]. From practical point of view, this configuration of ingredients on belt conveyor feeding the mixer (biomass covered by coal) prevents blowing off of relatively light biomass from the conveyor by strong wind. Moreover, in the proposed configuration we deal with negative segregation potential, when denser ingredient is on top, an extra mixing effect takes place.

The research experiment involved observation of mixing process for coal/chips and coal/pellets configuration for three, five and ten mixing elements (Fig. 1). The purpose of the experiment was to determine optimal number of mixing elements in order to ensure proper mixing of ingredients, which will be the basis for specifying guidelines for static mixer design.

Results and discussion

Figure 4 shows graphically test results for chips concentration in four test series for 10 mixing elements. It is visible that concentration of chips in lower segments of receiving box is lower than in upper ones. The data can be described by third degree power function, which represents empirical data variability trajectory very well. This is proven by high value of the fit coefficient (R = 0.90).

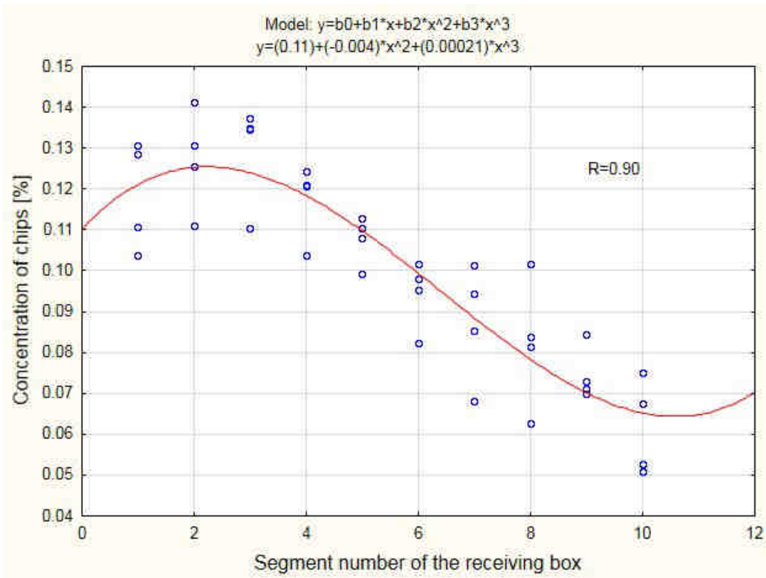

Fig. 4. Concentration of chips in successive segments of receiving box for 10 mixing elements in four test series, including function model

Due to significance level value (p = 0.07) obtained for ‘b1’ coefficient of regression function, this coefficient was not taken into account in the model. Therefore, the model has the following form:

$$y = 0.11 - 0.004x^2 + 0.00021x^3 \qquad (1)$$

Figure 5 shows pellet concentration for 5 mixing elements in four test series. It is visible that in upper segment of the receiving box pellet concentration is by far lower than in successive segments.

High value of the regression coefficient (R = 0.92) proves very good representation of empirical data variability by this model. Due to the significance level value (p = 0.13) obtained for ‘b0’ coefficient of regression function, this coefficient wasn’t taken into account in the model. Therefore, the proposed model may be used for predicting changes in biomass concentration during mixing in a static mixer. Obtained results of experimental research allow concluding that satisfactory biomass concentration is observed in central segments of receiving box, while starting and end segments contain biomass with concentration different from average. The progress of feed mixing process was described by a polynomial also in another paper of the authors [37] for a 2-ton mixer working in industrial conditions; other statistical methods (analysis of concentrations) were also applied to describe variability of this process [38].

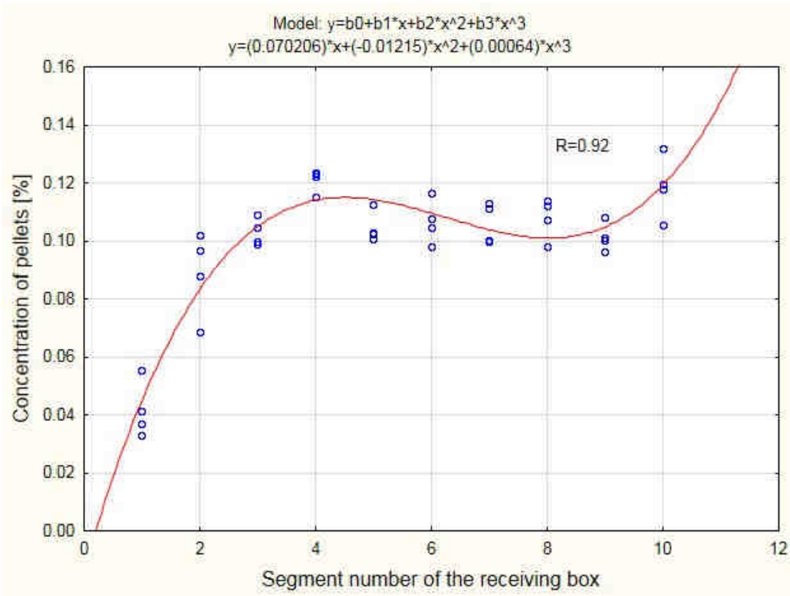

Fig. 5. Concentration of pellets in successive segments of receiving box for 5 mixing elements in four test series, including function model

Also in this case variability trajectory of empirical values is described by the following function:

$$y = 0.07x - 0.012x^2 + 0.00064x^3 \tag{2}$$

High value of the regression coefficient (R = 0.92) proves very good representation of empirical data variability by this model. Due to the significance level value (p = 0.13) obtained for ‘b0’ coefficient of regression function, this coefficient wasn’t taken into account in the model. Therefore, the proposed model may be used for predicting changes in biomass concentration during mixing in a static mixer. Obtained results of experimental research allow concluding that satisfactory biomass concentration is observed in central segments of receiving box, while starting and end segments contain biomass with concentration different from average. The progress of feed mixing process was described by a polynomial also in another paper of the authors [37] for a 2-ton mixer working in industrial conditions; other statistical methods (analysis of concentrations) were also applied to describe variability of this process [38].

Basic statistics for coal/chips and coal/pellets configuration were compared in order to determine optimal number of mixing elements in static mixer. Figure 6 presents obtained results graphically.

Statistical analysis of research results also involved proving whether there are any statistically significant differences in biomass concentration for 3, 5 and 10 mixing elements. The nonparametric Kruskal-Wallis test was applied for the analysis. It was checked whether there are any significant differences in the concentration for 3, 5 and 10 mixing elements of static mixer. In case if no statistically significant differences are found, it can be assumed that the number of mixing elements inside the mixer has no impact on biomass concentration. For this purpose, the zero hypothesis has been formulated as follows:

$$H_0: \mu_1 = \mu_2 = \mu_3$$

Expected values of concentration for a given coal/biomass configuration for 3, 5 and 10 mixing elements are equal.

Therefore, the alternative hypothesis is as follows:

$$H_1: \neg(\mu_1=\mu_2=\mu_3)$$

There is at least one mixing configuration characterised by an expected value of concentration different from other expected values in another mixing configurations.

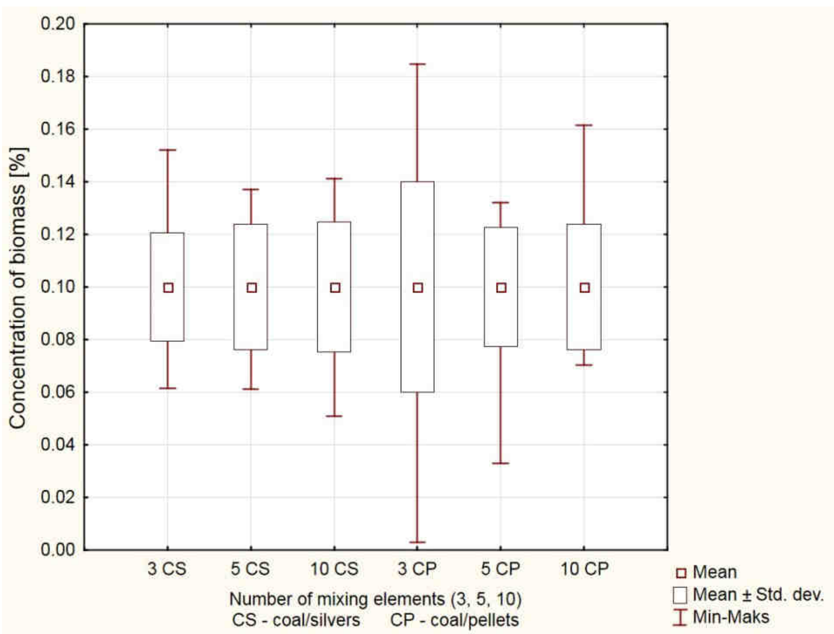

Fig. 6. Comparison of basic statistics of various number of mixing elements for coal/chips and coal/pellets arrangements

Since $p > 0.05$ ($p = 0.97$ for coal/chips configuration and $p = 0.4625$ for coal/pellets configuration), there are no grounds for rejecting the zero hypothesis, and thus concentrations are equal independently of the number of mixing configurations. The Kruskal-Wallis test results and analysis of standard deviation values provided the grounds for selecting the number of mixing elements. The lowest value of standard deviation for coal/chips configuration was obtained for 3 mixing elements, whereas in case of the coal/pellets configuration the lowest value was received for 5 mixing elements. From operating point of view, the number of five mixing elements seems to be the most advantageous due to obtained results and versatility of the mixer for pellets and chips.

Conclusions

Using static mixer for mixing of coal and biomass is a simple and inexpensive method for the production of fuel mixes for heat-generating plants equipped with stoker-fired boilers (power ranging from 3 up to 50 MW). Mixer design and mixing method presented in the article may be used as the guidelines for building other static mixers, which will be used in industrial applications, therefore the proposed mixer may constitute an alternative for currently used solutions, including separate coal and biomass feeding during coal delivery and their mixing in pulverised-fuel boilers, bucket loaders, mixture production out of the plant, or using specially designed burners for biomass in form of dust. Satisfactory biomass concentration is observed in central segments of receiving box, while starting and end segments contain biomass with concentration different from average. On the basis of Kruskal-Wallis test results and analysis of standard deviation values, five mixing elements are deemed to be the optimal number in order to obtain best distribution of biomass concentration in a mixture with fine hard coal. In conditions of mixing on an industrial scale in the static mixer, the goal should be to ensure that the mixed ingredients do not differ too much in their size. For fine coal, maximum size of biomass grains should not exceed 20 mm.

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MIESZANIE BIOMASY Z WĘGLEM W MIESZALNIKU STATYCZNYM JAKO PRZYKŁAD ROZWIĄZAŃ TECHNOLOGICZNYCH WDRAŻANIA ODNAWIALNYCH ŹRÓDEŁ ENERGII

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Abstrakt: Celem artykułu jest przedstawienie możliwości mieszania węgla z biomasą z użyciem mieszalnika statycznego. Zaprezentowano prostą i tanią metodę produkcji mieszanek paliw dla ciepłowni wyposażonych w kotły rusztowe o mocach od 3 do 50 MW. Zaproponowany mieszalnik statyczny do mieszania węgla z biomasą może stanowić alternatywę dla rozwiązań obecnie stosowanych w warunkach przemysłowych. W artykule wskazano, na podstawie analizy statystycznej, iż liczba pięciu elementów mieszających mieszalnika jest optymalna, aby zapewnić najlepszy rozkład koncentracji biomasy (zrębki oraz pellety) w mieszance z miałem węgla kamiennego.

Słowa kluczowe: odnawialne źródła energii, biomasa, węgiel kamienny, współspalanie, mieszanie materiałów ziarnistych, mieszalnik statyczny