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Modeling of a Primary Air Distribution in a Plenum Chamber of the 700 MWth Circulating Fluidized Bed Boiler

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ABSTRACT

The windbox is a compressed air chamber installed directly beneath the fluidized bed boiler grid and is designed to evenly distribute the primary air across the entire cross-section of the air distributor. Due to the large volume of the plenum chambers, it is very difficult to experimentally determine the flow conditions within them. Therefore, the analysis of airflow in these devices is usually performed using computational fluid dynamics tools. The article presents the results of modeling primary air distribution in the plenum chamber of the 700 MWth circulating fluidized bed boiler operating in PGE GiEK S.A. Turów Power Plant Division. Based on the results of calculations performed using the ANSYS Fluent software, the basic problems of the design windbox geometry were identified and a method for improving the uniformity of the gas flow under the grid was proposed. As can be seen from the results obtained, the design geometry of the windbox does not provide the required uniformity of air distribution under the grid.

Keywords: windbox, circulating fluidized bed boiler, fluidization, primary air.

INTRODUCTION

Circulating Fluidized Bed (CFB) boilers have several advantages that can be considered from two points of view: environmental and process. These devices are capable of burning a diverse range of difficult low-grade fuels of varying quality with low emissions of nitrogen oxides, CO, and C_xH_y as well as low-cost sulfur capture during combustion in the furnace itself. An additional advantage of CFB boilers is the possibility of using relatively simple solutions to reduce the emission of nitrogen oxides. In this case, the key role is played by the low combustion temperature (approx. 850°C) and the staging of the air supplied to the combustion chamber. From the process point of view, the main advantages of fluidized bed boilers are among others: high bed-to-surface heat transfer coefficients (100–400 W/m^{2}K), the possibility of multi-fuel firing, stable operation conditions and good turn-down ratio, and no need for fuel preparation.

Due to the specifically organized combustion process, a special role in fluidized bed boilers is played by the air supply and distribution system, the integral part of which is a primary air windbox. This device is built in the form of a chamber installed directly below the air distributor. Due to the significant volume, in some boiler configurations, the windbox is splitted into smaller compartments that are supplied with independent air streams. When the ratio of the pressure drop across the loose material bed to the pressure drop across the air distributor is sufficiently large, the shape of the plenum chamber does not play a significant role in the formation of flow conditions in the furnace [1, 2]. In practice, a large number of CFB boilers in operation today operate at a low value of this ratio. In such cases, the flow conditions in the combustion chamber result not only from the design of the air distributor itself but also from the construction of the plenum chamber cooperating with it. Modeling the airflow in the combustion chamber of a boiler, therefore, involves a complex analysis of the flow conditions in the boiler windbox on the one hand and the operating conditions of the air grid on the other. Concerning the windbox, the optimization task is to search for a design that will ensure uniform air pressure distribution under the grid of the furnace.

Tasks for the primary air plenum chamber

The main task for the primary air windboxes of CFB boilers is to ensure a uniform air velocity distribution under the air distributor at a sufficiently high static pressure value [3]. The fulfillment of this task is of particular importance due to:

- the need to achieve homogeneous fluidization and the resulting homogeneous oxygen concentration in the cross-section of the boiler combustion chamber [4],
- the necessity to obtain good mixing and heat transfer, which results in a uniform temperature distribution along with the height of the combustion chamber, reduction of pollutant emissions, as well as the possibility of sinter formation,
- reduction of the backflow of the loose material into the windbox volume caused by the horizontal pressure gradient, which occurs in the case of low-pressure drop grids under conditions of non-uniform air velocity field under the air distributor [5],
- limitation of the backflow of the loose material into the plenum chamber volume caused by the inverted vertical pressure gradient, which arises in the case of grids with a low-pressure drop under conditions of variable boiler load [4, 5].

The windbox is inextricably coupled with the air distributor of the fluidized bed boiler. Careless design of both devices can significantly affect the fluidization quality, combustion efficiency and cause many operational problems. Therefore, research on windboxes of fluidized bed boilers is carried out in a two-pronged approach and includes analysis of pressure fluctuations of the gas filling the plenum volume and the flow conditions within them.

The interest in studying pressure fluctuations stems from the existence of a strong correlation between changes of this parameter in the fluidized bed and the windbox, especially in boilers equipped with a low resistance air distributor [6]. Under conditions of well-developed bubbling fluidization, alternate compression and expansion of gas occur in the plenum [7], and the frequency of this phenomenon, called the natural frequency of the windbox, is lower the larger the volume of the windbox is [8]. As demonstrated by Moritomi et al. [9] the fluctuations of gas pressure in the windbox are additionally influenced by the air-feed system. Thus, the pressure pulsations in the windbox constitute a superposition of periodic phenomena occurring in the combustion chamber and the primary air supply system. Kage et al. found that the application of advanced frequency analysis to the study of the plenum static pressure time courses additionally allows the determination of bubble eruption and generation frequency [10, 11]. Similar conclusions were made by Vakhshouri and Grace [12], Bonniol et al. [13], and Sasi et al. [14] showing that there is a strong relationship between the air-plenum conditions and the bed dynamics for low-pressure drop distributors.

Compared to the analysis of pressure oscillations, much less attention has been paid in the voluminous fluidization literature to the study of flow conditions existing in the plenum chambers. To date, most work in this area has been done using Computational Fluid dynamics (CFD) tools, which are also used in other areas of a flow investigation [15, 16]. Bhasker et al. [17] analyzed airflow in an isobaric windbox with a depth of 7.21 m and a height of 12.24 m. It was found, that in the near-grid zone where intensive turbulence and high-pressure effects are concentrated, low-velocity regions responsible for non-uniform airflow inside the windbox are formed. Depypere et al. [18] analyzed the uniformity of air distribution inside the plenum chamber of a laboratory-scale Glatt GPCG-1 type fluidized bed-coating unit. CFD simulations revealed that the current geometry of the windbox causes a non-homogeneous airflow towards the distributor and the relocation of the plenum air inlet is a simple solution to this problem. Most of the research on the flow conditions prevailing in the air box concerns working devices. A slightly different approach was used in the work of Yan et al. [19]. Authors verified velocity profiles in the windboxes of the various depth of a 600 MW CFB boiler and found that velocity and viscosity have no obvious influence on the mal-distribution.

Types of windboxes used in Polish CFB boilers

When designing the geometry of the air box, the method of air supply should be taken into account. If the gas is supplied to the box from below, the air box must be of sufficient depth to prevent the gas from preferentially flowing in the middle of the device [20]. If the gas is supplied from the side, the outlet of the supply line should be in the center of the plenum and not on its wall [20]. Figure 1 shows various configurations of the windbox designs used in Polish CFB boilers. As can be seen, the fulfillment of above mentioned recommendations is not always taken into account when designing the windbox. Moreover as can be seen, in most cases air is supplied to the plenum chamber from the side along or across the combustion chamber. The exception is the windbox shown in Figure 1b, where the air is supplied from the bottom.

In the windbox shown in Figure 1a, to obtain a uniform static pressure distribution under the grid, the air supply is provided by a diffuser and a system of vanes. In the windbox shown in Figure 1b, the role of the diffuser is fulfilled by the windbox itself. In the case of the plenum chamber shown in Figure 1c, the volume is splitted into three equal chambers and independent air flows are supplied to each one of them. Typically, CFB boiler windboxes do not have any built-in equipment. An exception is a design shown in Figure 1f, in which lighting-up burners are installed and the walls are lined with refractory concrete. Most CFB boiler plenum chambers currently being designed have a design similar to that shown in Figure 1e [5, 17, 19]. This type of construction is intended to provide proportional airflow distribution along the entire length of the combustion chamber with minimal losses due to the turbulence of the incoming airflow.

Since the plenum chambers have a significant impact on the hydrodynamics of a fluidized bed boiler investigation into the primary air distribution is essential for better improvement of the boiler performance. Unfortunately, due to the fact that in large-scale CFB boilers plenum chambers are devices of considerable volume, experimental studies of the flow conditions within them are very difficult and in some cases even impossible to carry out. In such a situation, it is convenient to analyze the distribution of air inside the windbox by using CFD tools. As mentioned above, the purpose of such an analysis is first of all to investigate the uniformity of air distribution under the grid and also to identify areas where the so-called "dead zones" occur due to turbulence. This term is used to describe places where the air velocity is close to zero.

This paper presents an analysis of the flow conditions occurring in the windbox of the 700 MW_{th} Compact CFB boiler operating in PGE GiEK SA – Turow Power Plant division. The geometry of the plenum chamber was designed as a constant discharge duct, in which the stream of supplied air is splitted into two parts. Based on simulation calculations the uniformity of air distribution for the windbox reference design and the influence of the applied baffle have been examined. Additionally, alternative designs to improve the uniformity of air distribution in the cross-section of the windbox are proposed. The uniformity index was used instead of the standard deviation to assess the homogeneity of air distribution in the windbox. This index has been shown to provide a better measure of the degree of heterogeneity in air distribution in some cases.

REFERENCE FACILITY

The reference facility for the tests is the windbox of the 700 MW_{th} Compact CFB boiler operating in PGE GiEK SA – Turow Power Plant division, shown in Figure 2.

Basic boiler design and operating data are shown in Table 1.

The boiler's primary air distributor is supplied through the 12 × 5.6 × 5.2 m^3 plenum chamber. Due to the asymmetrical gas supply, the device has a duct design with a variable cross-section. Figure 3 shows a cross-section of the boiler's windbox with a vertical symmetry plane, indicating the location of the air supply cross-section.

As can be seen, the geometry of the windbox is designed as a constant discharge duct, whose purpose is to evenly distribute the gas just under the air distributor. Due to the very large volume of the plenum chamber (about 546 m^3) this task can be very difficult to achieve. For this reason, the designers of the device decided to place an additional baffle splitting the stream of the supplied air. Thanks to this, the inner area of the windbox is divided into two independent sections, which prevents the formation of macro-vortexes favoring the creation of dead zones in the distributor area. Table 2 shows the design parameters of the air flowing through the windbox at the maximum boiler's load.

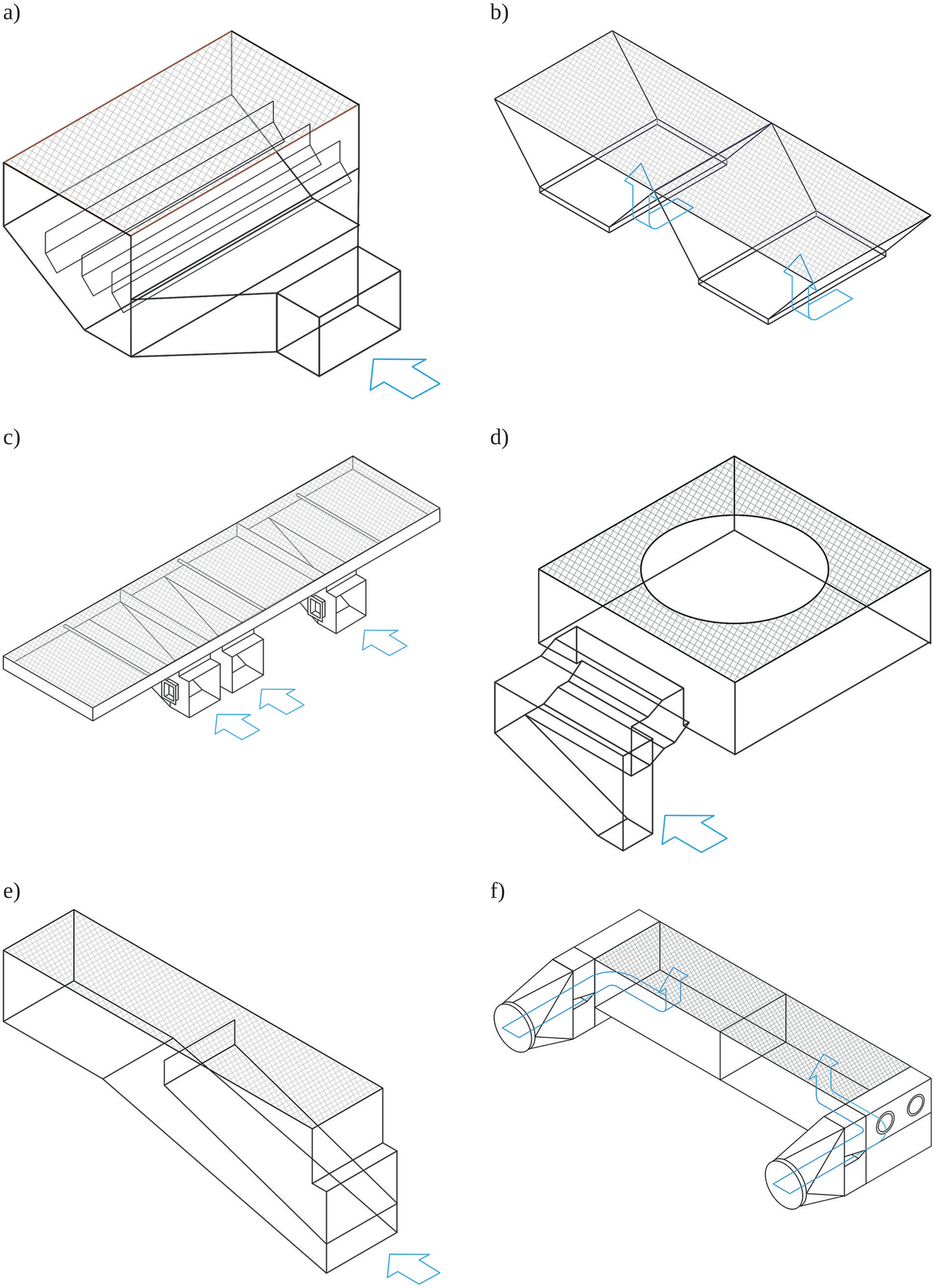

Figure 1. Designs of primary air plenum chambers applied in Polish CFB boilers: (a) EC Żerań SA, (b) EC Chorzów „ELCHO" Sp. z o.o., (c) PGE GiEK SA – Turow Power Plant division, (d) EC Tychy SA, (e) PGE GiEK SA – Turow Power Plant division, (f) Tauron Wytwarzanie SA – EC Katowice division [5]

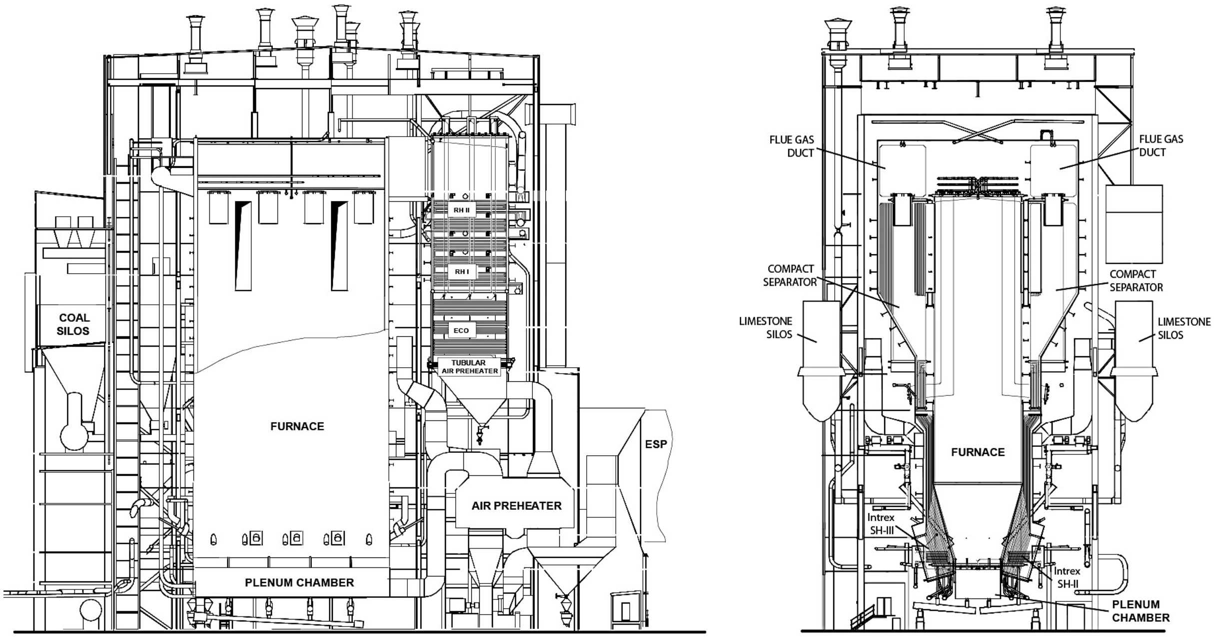

Figure 2. Schematic diagram of the 700 MW_{th} Compact CFB boiler working in PGE GiEK SA – Turow Power Plant division

SIMULATION CALCULATION

The purpose of the simulation calculations is to investigate the flow conditions in the plenum chamber of the 700 MW_{th} Compact CFB boiler concerning the uniformity of the gas distribution under the boiler's air distributor. The analysis is performed for four cases involving four different internal designs of the windbox (Figure 4). In the first case (Figure 4a), the flow conditions in the windbox without a baffle separating the airflow at the inlet are studied. In case two (Figure 4b), the air distribution in the windbox splitted by a flat baffle is analyzed. In case three (Figure 4c), the effect of a pre-distributor (made in the form of a perforated plate) on the uniformity of airflow under the grid is studied. Finally, in case four (Figure 4d) the flow conditions in the windbox equipped with both the baffle splitting the airflow at the inlet and the pre-distributor equalizing the static pressure located under the grid area are studied. It should be noted, that the use of a pre-distributor is not a new concept and is an alternative solution wherever it is not possible to modify the air inlet to the windbox [18]. Unfortunately, this solution requires modification of the operating characteristics of the primary air fan and an increase in energy consumption. Computational simulations of the airflow in the internal volume of the plenum chamber are performed using ANSYS CFD software and Fluent solver. The discretization of the windbox geometry is performed using the MultiZone method, in which a Hexa/Prism combination was used as the mapped mesh type. The increase in the resolution of the computational mesh was done through local settings tools at the locations of expected higher gas velocity gradients. The final mesh size after the

Table 1. Boiler construction and operational data

Quantity	Unit	Value
Electrical power	MW	260
Primary/superheated steam mass flow	kg/s	195.5/180.7
Primary/superheated steam pressure	MPa	16.65/3.85
Primary/superheated steam temperature	K	838/833
Combustion chamber height	m	42.1
Cross-sectional area of combustion chamber at the grid level	m^2	21.9 × 5.2
Cross sectional area of the combustion chamber above the furnace lining	m^2	21.9 × 10.1
Fuel		Brown coal
Fuel flow	kg/s	73.7

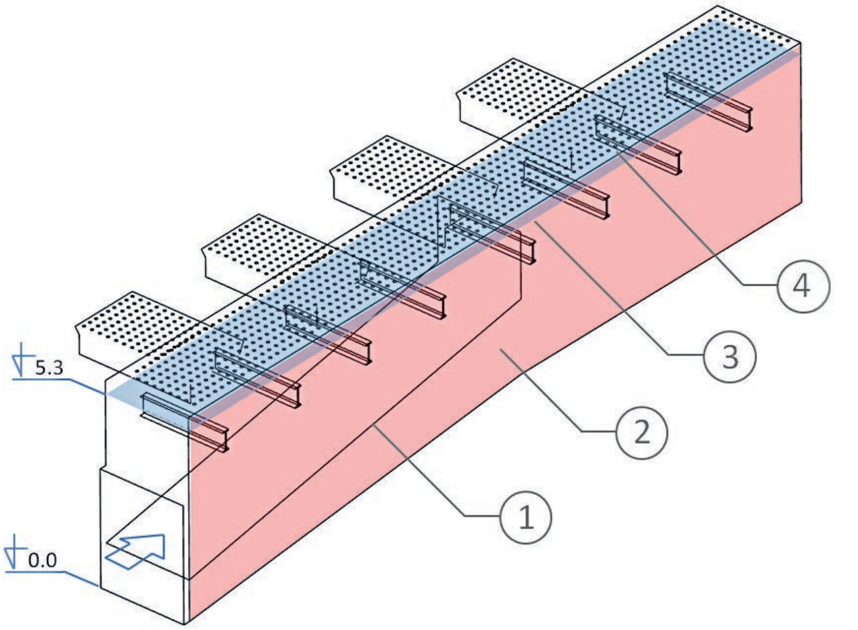

Figure 3. Cross-section of the 700 MW_{th} Compact CFB boiler windbox showing the air supply cross-section, 1 – baffle dividing the primary airflow, 2 – symmetry plane (red), 3 – control plane, 4 – air distributor

Table 2. Input parameters for the windbox calculation at maximum boiler load

Quantity	Unit	Value
Static pressure	Pa	114 405
Air mass flow rate	kg/s	100.95
Air density	kg/m^3	0.660
Air viscosity	Pa s	27.98e-6

sensitivity test is 1 751 116. Simulation calculations were performed using models and boundary conditions shown in Table 3.

The control planes for the obtained calculation results are two cross-sections: the vertical plane of the windbox symmetry and the horizontal one, located under the grid at the height of 5.3m from the bottom edge of the inlet (Figure 3). The following surface integrals of static pressure and velocity are studied in the horizontal plane:

- Area-weighted average
- Standard deviation
- Facet min and max
- Uniformity index – area weighted
- Uniformity index – mass weighted

The degree of uniformity of air distribution in the plenum chamber is determined based on the standard deviation of the quantity under investigation. Alternatively, another surface integral characteristic is used for this purpose – the uniformity index, which may be related to both the surface area and the mass flow rate. The area-weighted average of a quantity θ is calculated based on the following equation [21]:

$$\frac{1}{A}\int \theta dA = \frac{1}{A}\sum_{i=1}^{n} \theta_i |A_i| \tag{1}$$

where: A – surface area, m^2,
i – the facet index of a surface with n facets.

The uniformity index represents how a specified field variable varies over a surface, where a value of 1 indicates the highest uniformity and 0 the lowest. There are two expression of this parameter: area weighted and mass weighted. The first one captures the variation of the quantity and is expressed by the following equation [21]:

$$\vartheta_a = 1 - \frac{\sum_{i=1}^{n}\left[\left(\left|\theta_i - \bar{\theta}_a\right|\right)A_i\right]}{2\left|\bar{\theta}_a\right|\sum_{i=1}^{n} A_i} \tag{2}$$

where: $\bar{\theta}_a$ – represents the average value of the field variable over the surface according to the following equation [21]:

$$\bar{\theta}_a = \frac{\sum_{i=1}^{n} \theta_i A_i}{\sum_{i=1}^{n} A_i} \tag{3}$$

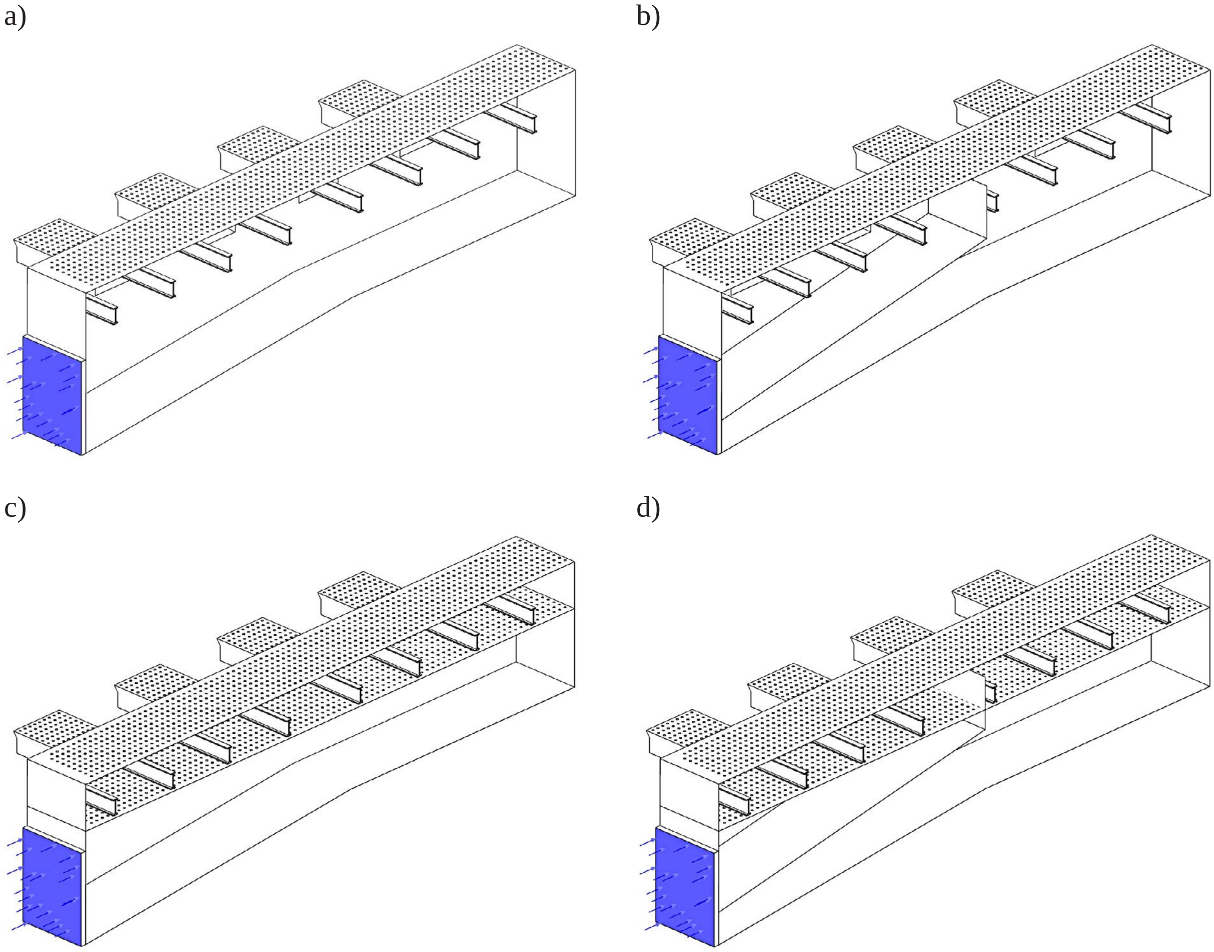

Figure 4. Analyzed windbox designs: (a) without the baffle dividing the gas stream at the inlet, (b) with the baffle dividing the gas stream at the inlet, (c) with a pre-distributor under the grid, (d) with the baffle dividing the gas stream at the inlet and with the pre-distributor under the grid

The latter one captures the variation of the flux and is calculated based on the following equation [21]:

$$\vartheta_m = 1 - \frac{\sum_{i=1}^{n}\left[\left(\left|\theta_i - \bar{\theta}_m\right|\right)\left(\left|\rho_i \vec{v}_i A_i\right|\right)\right]}{2\left|\bar{\theta}_m\right| \sum_{i=1}^{n}\left[\left|\rho_i \vec{v}_i A_i\right|\right]} \quad (4)$$

where: ρ – represents the fluid density,
$\vec{v}$ – velocity vector and the average flux of the field variable through the surface is expressed by the following equation [21]

$$\bar{\theta}_m = \frac{\sum_{i=1}^{n}\left[\theta_i\left(\left|\rho_i \vec{v}_i A_i\right|\right)\right]}{\sum_{i=1}^{n}\left[\left|\rho_i \vec{v}_i A_i\right|\right]} \quad (5)$$

Table 3. Models and boundary conditions for numerical calculations of the windbox geometry for maximum boiler load

Model and boundary conditions	Setting
Space	3D
Time	Steady
Viscous	Transition SST
Wall treatment	Standard Wall Functions
Spatial discretization	Gradient: G-G Cell Based, Pressure, Momentum, Turbulent Kinetic Energy, Specific Dissipation Rate, Intermittency, Momentum Thickness Re: 2nd Ordered Upwind
Heat transfer	Enabled
Mass flow specification method	Mass Flow Rate: 100.95 kg/s
Temperature	535 K
Pressure	114.4 kPa
Gas viscosity	27.98e-6

RESULTS AND DISCUSSION

Figures from 5 to 8 show the contour velocity fields of the primary air in the windbox of the 700 MW_{th} Compact CFB boiler for all analyzed windbox designs. From the point of view of uniformity of air distribution in the cross-section of the boiler combustion chamber, cases A and B turned out to be the least favorable cases of the internal windbox design.

In these cases, due to the one-sided air supply, there is a visible decrease in the airflow in the areas of aerodynamic shadows occurring behind the constructional beams. As a result, the dead zones occur under the grid of the boiler, where the supplied air stream reaches a value close to zero. The presence of dead zones can be significantly reduced by placing a pre-distributor just under the construction beams, allowing the direction of the incoming air from the inlet to be changed. For this type of windbox design (cases C and D), the most uniform velocity fields are obtained in the horizontal control section. However, due to the high qualitative similarity of the obtained velocity distributions, the identification of the most effective design is only possible based on the analysis of additional surface integral characteristics.

Table 4 compares the values of the area and mass uniformity index calculated for the control cross-section located under the grid of the analyzed windbox designs. It is noteworthy that among all studied windbox designs, the lowest degree of velocity field uniformity occurs for the reference design of the windbox (case B). Thus, from the point of view of ensuring homogeneous air distribution under the grid, the splitting of the box volume by a separating baffle has no sense whatsoever.

The highest uniformity index values are observed for case C, in which the velocity uniformity under the grid is achieved solely through the pre-distributor. The use of such a solution also made it possible to uniform the airflow in the windbox analyzed by Depypere et al. [18]. However, since the authors did not provide any uniformity characteristics it is difficult to make a measurable assessment of the effectiveness of this solution. It is noteworthy that in the very sparse literature devoted to the study of flow conditions in the plenum chambers, the assessment of the degree of heterogeneity of air distribution is usually subjectively based on the visual assessment of contour velocity fields [17, 18]. Exceptions are the study of Yan et al. [19], where the degree of homogeneity of the airflow was evaluated based on the non-uniformity coefficient, and own work [5], where the measure of the degree of homogeneity was the standard deviation of the velocity in

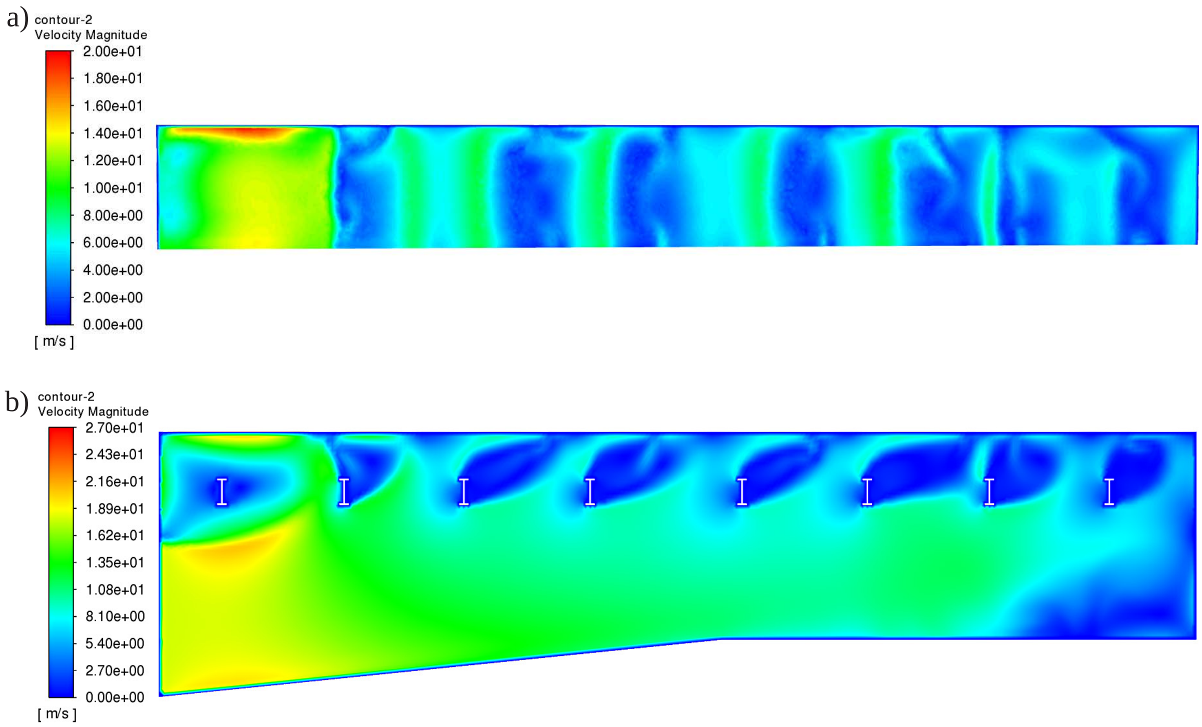

Figure 5. Contour velocity fields of the primary air in the control planes of the windbox of the 700 MW_{th} Compact CFB boiler – Case A

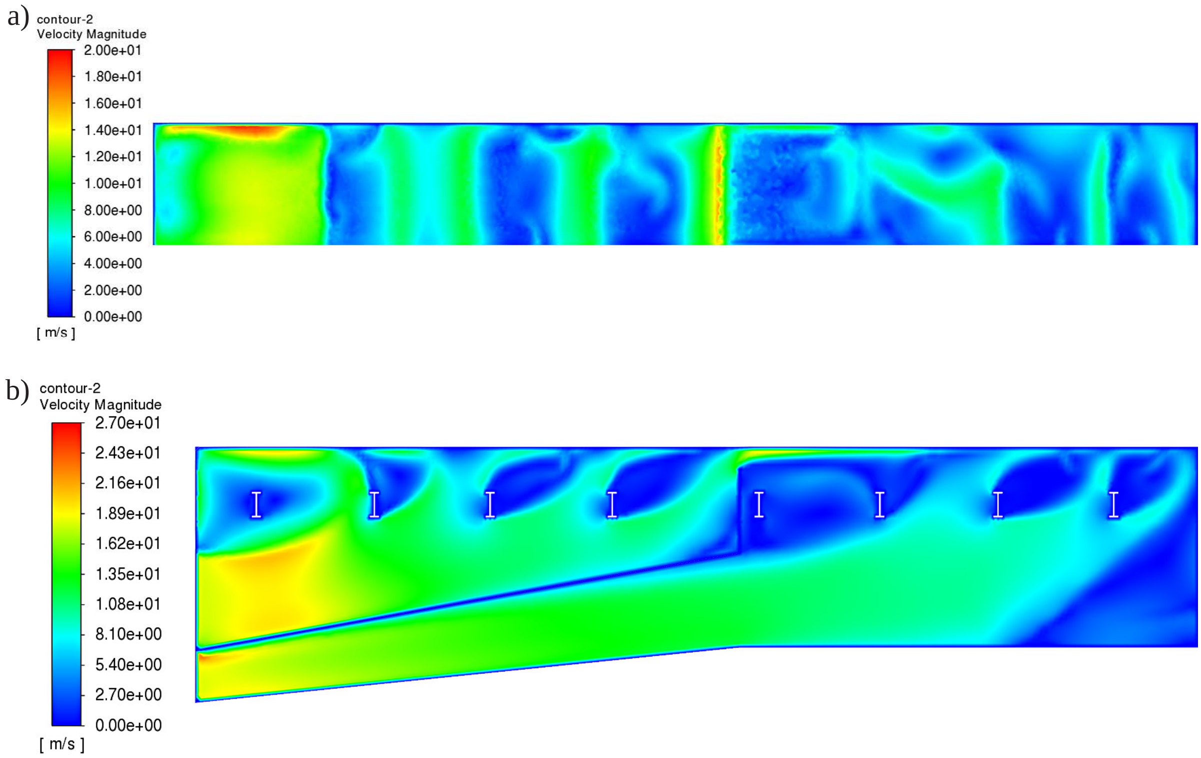

Figure 6. Contour velocity fields of the primary air in the control planes of the windbox of the 700 MW_{th} Compact CFB boiler – Case B

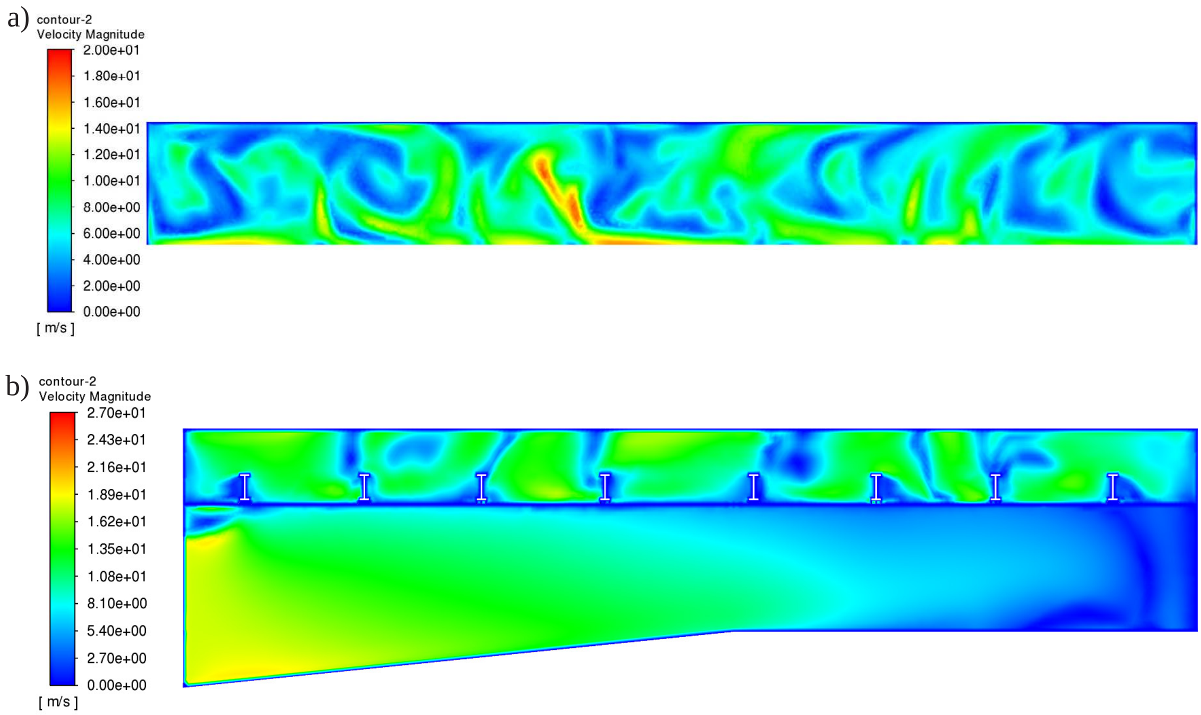

Figure 7. Contour velocity fields of the primary air in the control planes of the windbox of the 700 MW_{th} Compact CFB boiler – Case C

the control plane. Figure 9 shows the gas velocity surface integral characteristics determined for the control plane for all analyzed cases of the windbox design. When comparing the data shown in the figure, it is important to note first the values of the standard deviation, which can be an alternative indicator of the uniformity of the surface distribution of a given quantity.

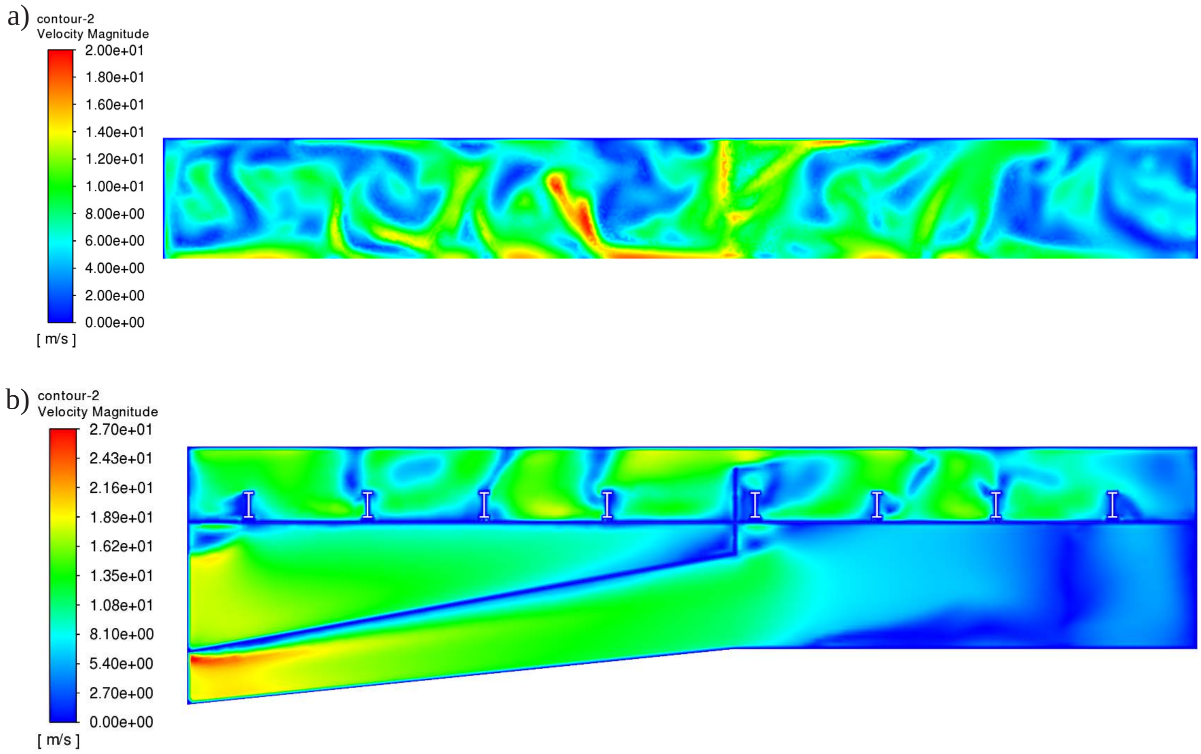

Figure 8. Contour velocity fields of the primary air in the control planes of the windbox of the 700 MW_{th} Compact CFB boiler – Case D

As can be seen, the determined standard deviation values correlate well with values of the uniformity index. The highest values of standard deviation occur for case B of the windbox design (3.70 m/s) and the lowest for case C (2.89 m/s).

The analysis of the uniformity of the velocity field under the grid of the boiler was supplemented by the study of static pressure distributions in this area. The results of this analysis are presented in Figures from 10 to 13. As can be seen from the presented distributions, the highest pressure gradients occur for the windbox designs A and B, with the most unfavorable case for design B, where the local pressure differences reach values close to 150 Pa. Thus, neither the initial design of the windbox (A) nor the reference one (B) allows for a uniform pressure distribution under the air distributor.

Equalization of static pressure in the air distributor area is possible with the use of a pre-distributor which, as shown in Figures 12 and 13, provides an effective boundary between the high and low-pressure zones located on the inlet and grid sides of the windbox, respectively.

The highest degree of homogeneity of the static pressure field in the horizontal control section can be observed for the case with the pre-distributor. In this case, the highest values of uniformity index (area: 0.9987; mass: 0.9986) and, at the same time, the lowest value of static pressure standard deviation (20.99 Pa) are obtained (Figure 14).

It should be noted that the maximum value of standard deviation equal to 47.25 Pa is not determined for the most unfavorable windbox design,

Table 4. Summary of the surface uniformity indexes determined for the control plane of the analyzed windbox designs located under the grid of the boiler

Case	Uniformity index			
	Area	Mass	Area	Mass
	Velocity		Static pressure	
A	0.767	0.834	0.9972	0.9975
B	0.747	0.822	0.9967	0.9967
C	0.818	0.848	0.9987	0.9986
D	0.804	0.840	0.9975	0.9975

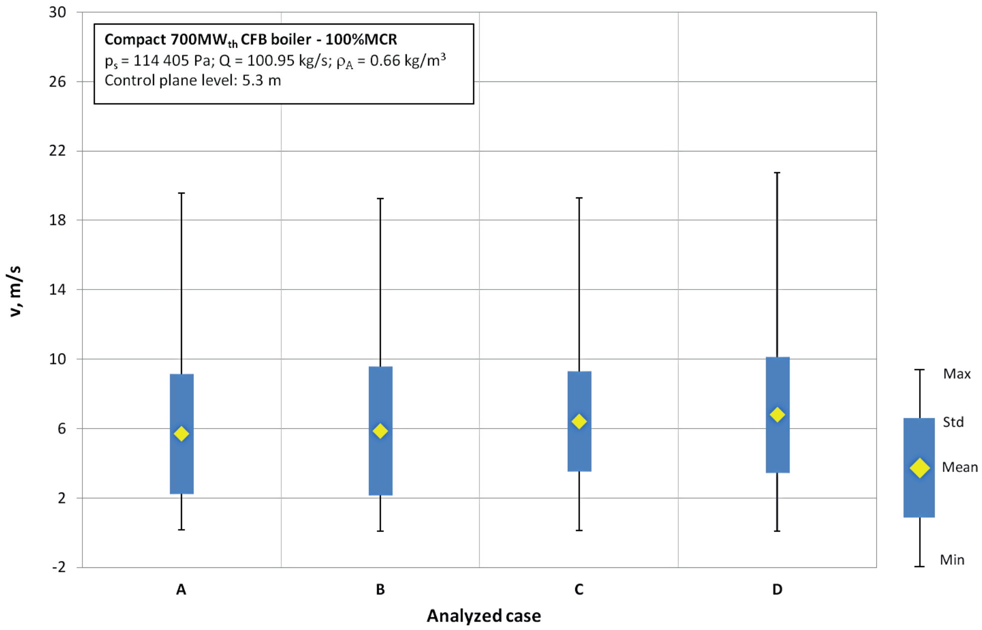

Figure 9. Surface integral characteristics determined for the velocity in the control plane under the grid for all analyzed windbox designs

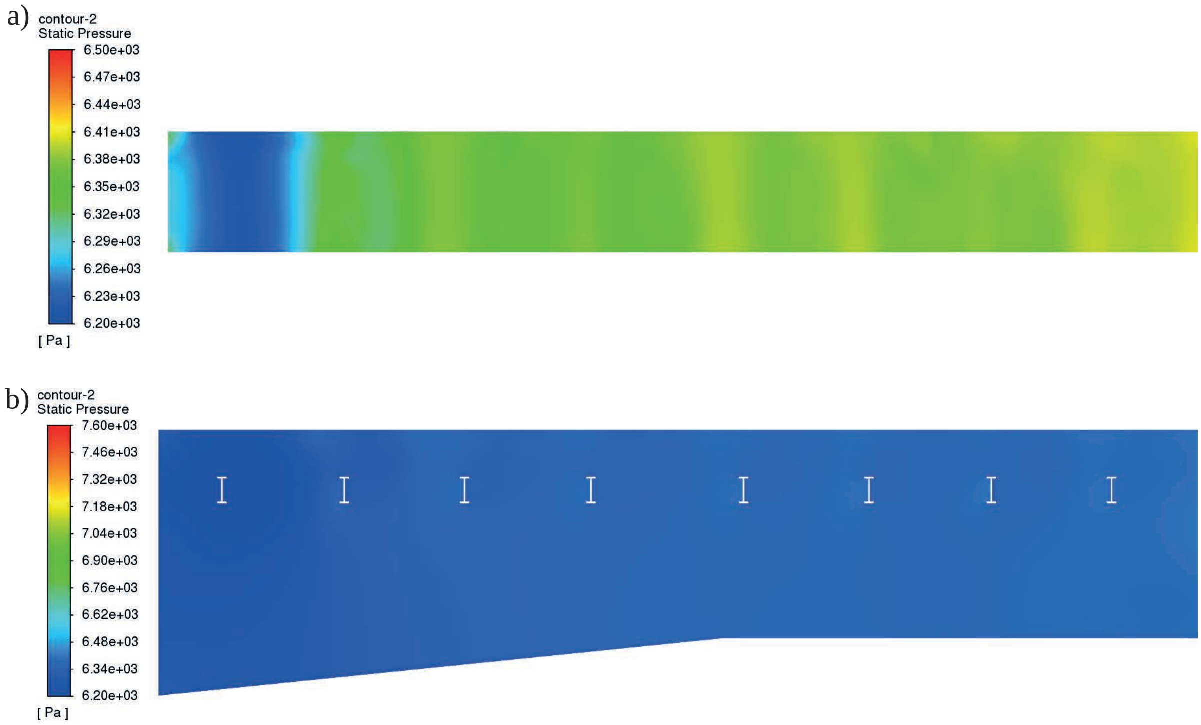

Figure 10. Contour static pressure fields of the primary air in the control planes of the windbox of the 700 MW_{th} Compact CFB boiler – Case A

i.e. (B) (in this case Std = 47.15 Pa), but only for the design (A). This means that in some cases the uniformity index is a more reliable parameter for evaluating the degree of homogeneity of the distribution of the quantity under study, and the standard deviation is a characteristic that should be used with special caution.

CONCLUSIONS

One of the most important components of a CFB boiler is the primary air supply system, which consists, among other things, of the windbox. Since flow conditions in this element affect the hydrodynamics of the fluidized bed and

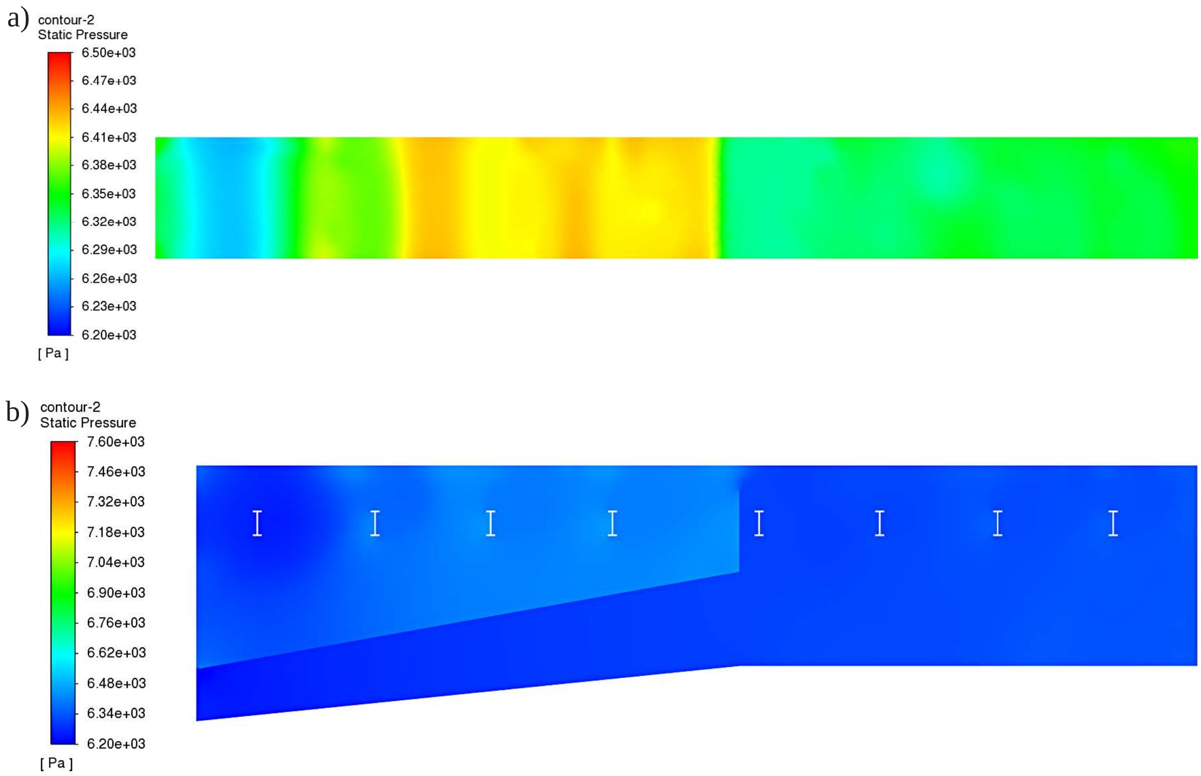

Figure 11. Contour static pressure fields of the primary air in the control planes of the windbox of the 700 MW_{th} Compact CFB boiler – Case B

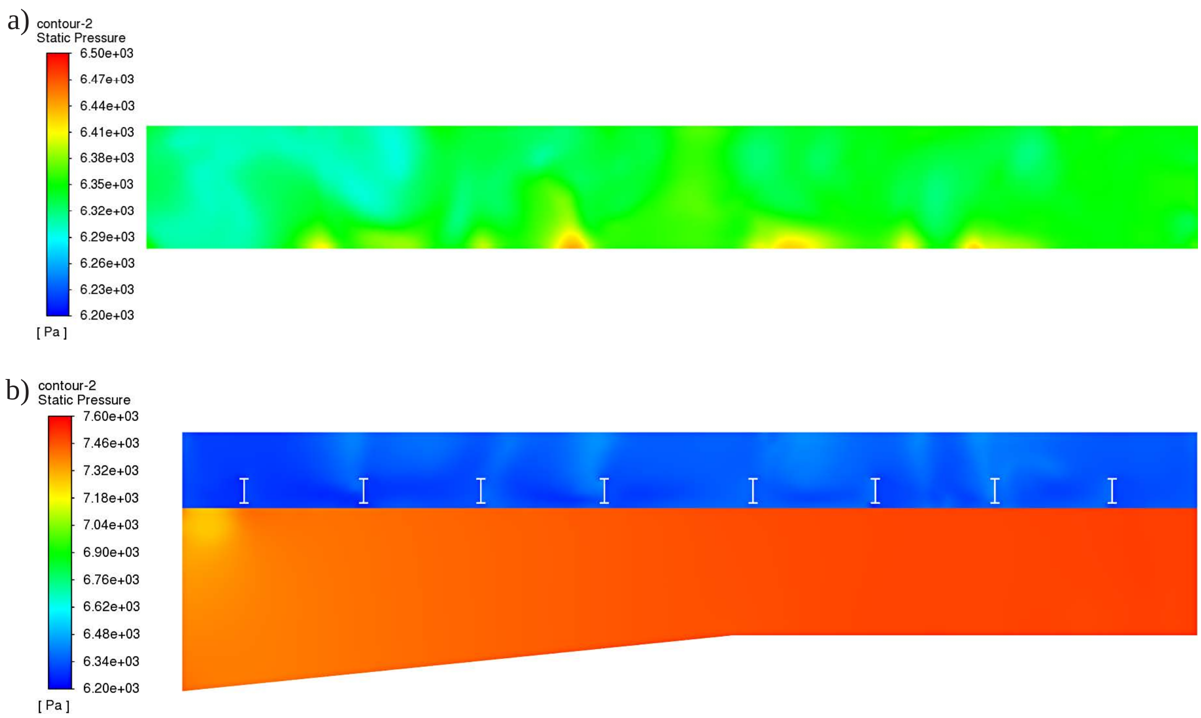

Figure 12. Contour static pressure fields of the primary air in the control planes of the windbox of the 700 MW_{th} Compact CFB boiler – Case C

determine the efficiency of the combustion process, the key issue is to assess the operation of this device by determining the degree of uniformity of air distribution in the near-grid zone.

The conducted simulation calculations and the analysis of the obtained results allowed to formulate the following conclusions. Design of the windbox of the 700 MW_{th} Compact CFB boiler

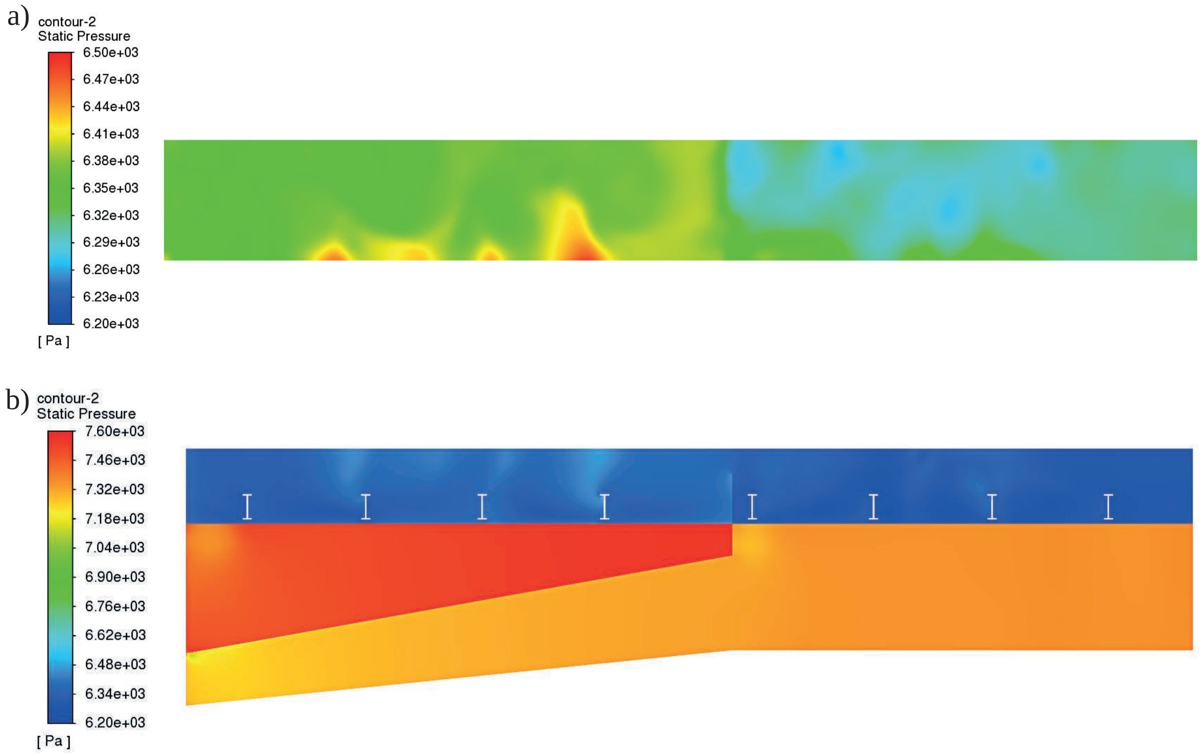

Figure 13. Contour static pressure fields of the primary air in the control planes of the windbox of the 700 MW_{th} Compact CFB boiler – Case D

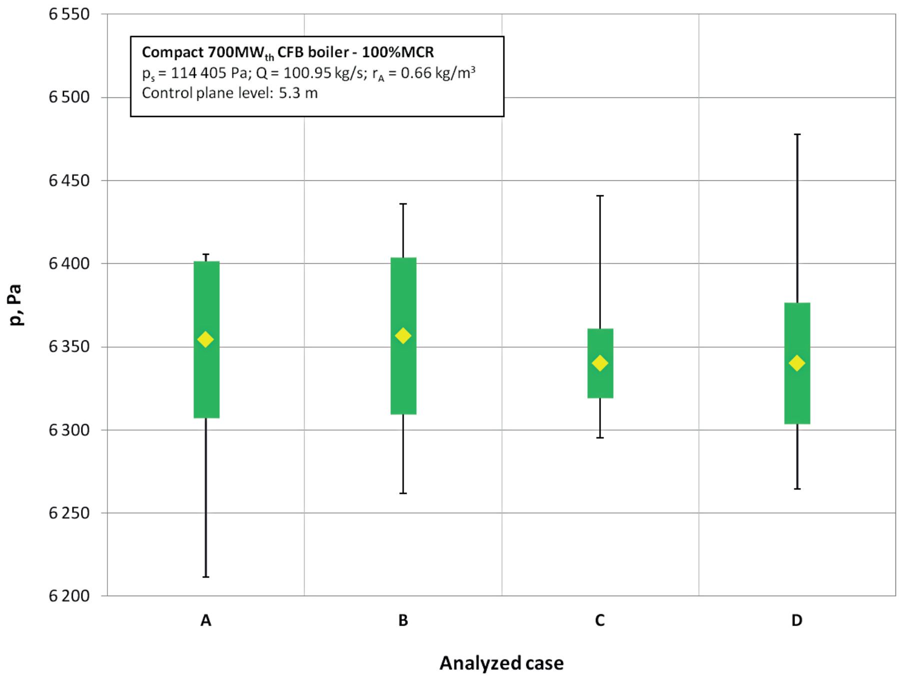

Figure 14. Surface integral characteristics determined for the static pressure in the control plane under the grid for all analyzed windbox designs

made in the form of a constant discharge duct is not able to ensure uniform air distribution in the area near the boiler grid. Splitting of the incoming airflow reduces the degree of uniformity of gas distribution under the air distributor. Thus, the use of a flow splitter is not reasonable from the point of view of the purpose of the plenum chamber. The best characteristics of the uniformity of air distribution can be obtained for the windbox design equipped with the pre-distributor located under the construction beams of the air distributor. The uniformity index is a reliable measure of the uniformity of the surface distribution of the quantity under test. The standard deviation may not always provide an alternative characteristic of the degree of uniformity of distribution of the test quantity compared to the uniformity index.

Acknowledgments

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REFERENCES

1. Reddy Karri S.B., Werther J. Gas distributor and plenum design in fluidized beds. Chapter 6 in: Wen-Ching Yang Handbook of Fluidization and Fluid-Particle Systems, Siemens Westinghouse Power Corporation, Pittsburgh, Pennsylvania, USA, Marcel Dekker Inc., 2003.
2. Passos M.L., Barrozo M.A.S., Mujumdar A.S. Fluidization Engineering – practice, 2nd expanded edition, Laval, Canada, 2014.
3. Basu P. Combustion and Gasification in Fluidized Beds, Butterworth Heinemann, Taylor and Francis Group, LLC, 2006.
4. Mirek P., Jabłoński J., Nowak W. Numerical optimization of air flow in the plenum chamber of an industrial CFB boiler. Task Quarterly. 2008; 12(3): 237–244.
5. Mirek P. Air flow optimization and gas-solid flow similitude in circulating fluidized bed boilers, Publishing House of the Czestochowa University of Technology. 2012; 240.
6. Lirag R.C.Jr., Littman H. Statistical study of the pressure fluctuations in a fluidized bed. American Institute of Chemical Engineers Symposium Series. 1971; 67: 11–22.
7. Geldart D., Baeyens J. The design of distributors for gas-fluidized beds. Powder Technology. 1985; 42: 67–78.
8. Baird M.H.I., Klein A.J. Spontaneous oscillation of a gas-fluidized bed. Chemical Engineering Science. 1973; 28: 1039–1048.
9. Moritomi H., Mori S., Araki K., Moriyama A. Periodic pressure fluctuations in a gaseous fluidized bed. Kagaku Kogaku Ronbushu. 1980; 6: 392–396.
10. Kage H., Iwasaki N., Matsuno Y. Frequency analysis of pressure fluctuation in plenum as a diagnostic method for fluidized beds. American Institute of Chemical Engineers Symposium Series. 1993; 89: 184–190.
11. Kage H., Agari M., Ogura H., Matsuno Y. Frequency analysis of pressure fluctuation in fluidized bed plenum and its confidence limit for detection of various modes of fluidization. Advanced Powder Technology. 2000; 11: 459–475.
12. Vakhshouri K., Grace J.R. Effects of the plenum chamber volume and distributor geometry on fluidized bed hydrodynamics. Particuology. 2010; 8: 2–12.
13. Bonniol F., Sierra C., Occelli R., Tadrist L. Experimental study of the interaction of a dense gas–solid fluidized bed with its air-plenum. Powder Technology. 2010; 202: 118–129.
14. Sasic S., Leckner B., Johnsson F. Fluctuations and waves in fluidized bed systems: the influence of the air-supply system. Powder Technology. 2005; 153: 176–195.
15. Kamiński Z., Czyż Z., Wendeker M. Wind turbine operation parameter characteristics at a given speed. Advances in Science and Technology Research Journal. 2014; 8(22): 75–82.
16. Czyż Z., Karpiński P., Koçak S. Numerical analysis of the influence of particular parts of the high efficient electric vehicle on the aerodynamic forces. Advances in Science and Technology Research Journal. 2019; 13(4): 1–7.
17. Bhasker C. Simulation of air flow in the typical boiler windbox segments. Advances in Engineering Software. 2002; 33: 793–804.
18. Depypere F., Pieters J.G., Dewettinck K. CFD analysis of air distribution in fluidised bed equipment. Powder Technology. 2004; 145: 176–189.
19. Yan J., Lu X., Wang Q., Kang Y., Li J., Zhou J., Zhang Y., Lv Z., Sun S. Experimental and numerical study on air flow uniformity in the isobaric windbox of a 600 MW supercritical CFB boiler. Applied Thermal Engineering. 2017; 122: 311–321.
20. Reddy Karri S.B., Knowlton T. Gas distributor and plenum design in fluidized beds. Chapter 4 in Wen-Ching Yang Fluidization, Solids Handling, and Processing. Industrial Applications, 1st Edition William Andrew, 1998.
21. Ansys Fluent Theory Guide, ANSYS, Inc., Release 2021 R1.