NUMERICAL OPTIMIZATION OF AIR FLOW IN THE PLENUM CHAMBER OF AN INDUSTRIAL CFB BOILER

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Abstract: The article presents the results of experimental and numerical studies on windboxes operating in a 235 MW_e Circulating Fluidized Bed (CFB) boiler. The main problems of windbox designs have been identified and a modified internal geometry has been proposed which causes a more uniform flow under the grid and prevents the velocity field from formation of dead zones.

Keywords: windbox, air distributor, Circulating Fluidized Bed

1. Introduction

The air distributor is one of the most important elements of a fluidized-bed boiler. Its purpose is to provide a uniform distribution of primary air in the cross-section of the lower combustion chamber part. This is of particular importance because of the necessity of obtaining homogeneous fluidization with a resultant homogeneous oxygen concentration in the chamber cross-section [1]. The provision of a uniform air distribution allows also a good mixing and heat exchange to be achieved, which, as a result, leads to the formation of a uniform temperature distribution within the combustion chamber volume. In contrast, an inhomogeneous air distribution causes some regions of the boiler to become poorly fluidized, whereby the heat exchange and mixing processes progress in those regions less effectively. A temperature increase is observed in these regions, which is due to the mixing being hampered by the heat take-up from the fuel being combusted. This contributes to the formation of a non-uniform temperature distribution within the boiler chamber and an increase in emissions, as well as to a possible formation of sinters [1].

The air distributor together with the system of channels and the compressed air box constitute a primary air supply system in a CFB boiler. For this reason, in order to obtain the desired homogeneity of air distribution within the combustion chamber, this system should be treated as a system of connected vessels, in which each element needs to be correctly designed. For the air channels, this means an equalized lateral velocity profile, while for the windbox – a uniform velocity field under the grid. A non-uniformity of the velocity profile under the air distributor results in the formation of a vertical and horizontal pressure gradients, as a consequence of which a pouring over of the inert material to the inner box volume occurs [2].

In the relevant literature, a number of relationships can be found, which enable a CFB boiler air distributor to be correctly designed [3–6]. However, there are no reports on the method of determining the geometry of compressed air boxes. Whereas, in the large-power CFB boiler operation practice, the primary air supply system constitutes a major source of operational problems, while a particular role in this respect is believed to be played by the incorrect method of air distributor design, with a lesser role being attributed to the air supply channels. As has been demonstrated [1, 2, 7], considering the incorrect air distributor operation cannot take place in isolation from the flow phenomena occurring in the windboxes. Therefore, it is proposed first to make attempts to improve the air distribution in the windboxes, and then to carry out the optimization of air distributor operation.

The present article shows possibilities for improving the distribution of air in the air boxes of a 670 MW_{th} power CFB boiler. To achieve the objective of the study, numerical computation was, for which the GAMBIT 2.2.30 and FLUENT 6.2.16 programs were employed.

2. Formulation of the problem

The basis for carrying out the numerical analysis of air distribution has been the verification of the geometry of windboxes operating with the 670 MW_{th} power CFB boiler. Primary air is supplied to the combustion chamber through the system of three windboxes, as shown in Figure 1.

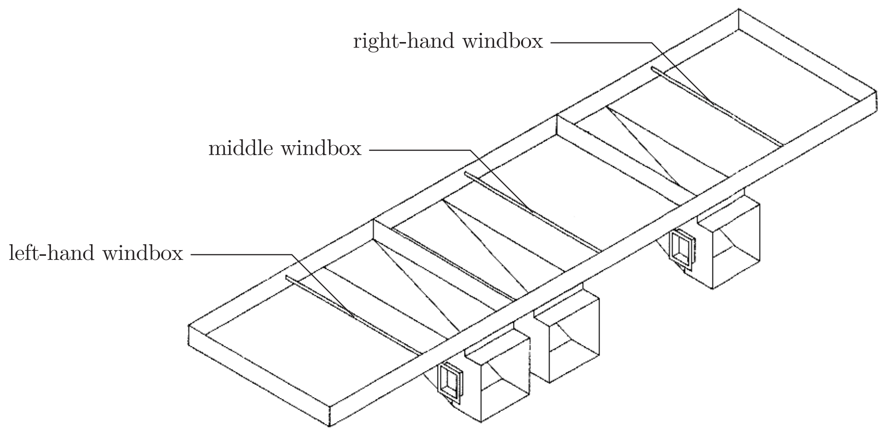

Figure 1. Arrangement of windboxes in the 670 MW_{th} power CFB boiler

As follows from Figure 1, the mode of air supply to each of the windboxes is asymmetrical. This favours the inhomogeneous velocity profile in the grid zone and the generation of dead zones. Moreover, as has been shown by a detailed inventory of the windbox geometry, additional obstacles have been installed in their inlet spaces, as shown in Figure 2, which impair the air distribution uniformity.

(a) (b)

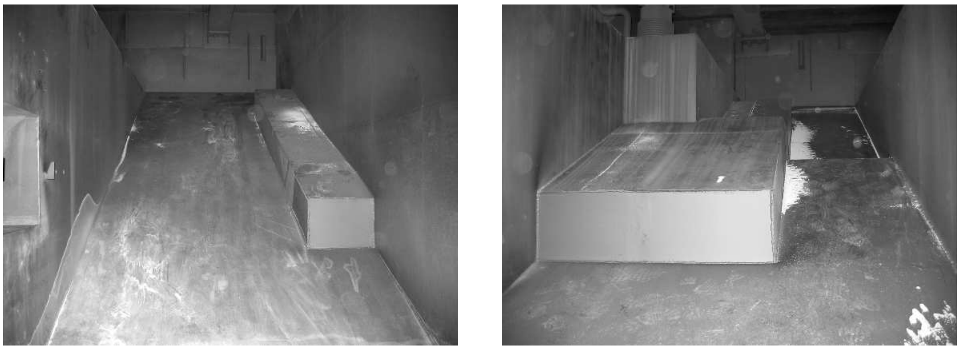

Figure 2. Photographs of the inlet space of (a) the side windbox and (b) the middle windbox with obstacles installed in the way of the air stream

The windbox geometry designed in such a way has constituted a source of major operational problems, the most important of which include:

- the non-uniformity of the velocity field under the air distributor,
- the formation of dead zones within the distributor space, and
- the formation of horizontal pressure gradients that induce the flow of the gas – bed material grain mixture through the air nozzle arms.

These problems made tasks for the numerical analysis, whose outcome was the development of the optimal internal geometry of the windboxes, with their external shape unchanged. Simultaneously with the numerical analysis, a detailed verification of windbox operation was carried out under different conditions of Unit loading. The results of the analysis can be found in references [1, 2, 7].

3. Generating the computation grid and defining the boundary conditions

Figure 3 shows the geometry of the side windbox (Figure 3a) and the middle windbox (Figure 3b), as defined in the GAMBIT pre-processor. On the basis of the geometric shape description entered, a computation grid was generated, whose density was higher in regions with higher velocity gradients, and lower in regions, where the velocity gradients were smaller.

The numerical computations were carried out for the maximum (approx. 235 MW_e, 100% Maximum Continuous Rating) and 65% MCR (approx. 150 MW_e) load of the Unit, for the input parameters, as given in Table 1.

During the computations a 3D segregated solver was used with the semi-empirical model k-ε (Standard and RNG models), which is based on the model of

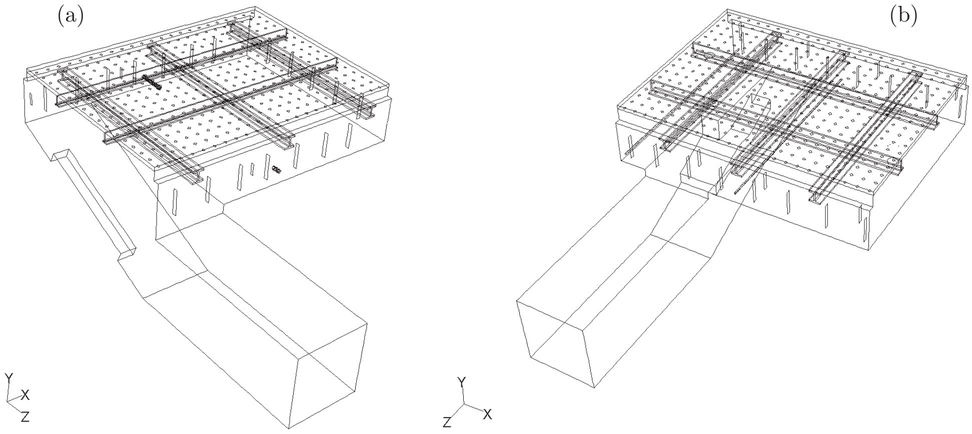

Figure 3. Geometry of (a) the side windbox and (b) the middle windbox, as defined in the GAMBIT program

Table 1. Input parameters for the computation of the windboxes of the 235 MW_e boiler

LEFT-HAND WINDBOX		
unit load	100%	65%
static pressure [Pa]	116 315	116 138
air mass flux [kg/s]	27.89	37.437
air density [kg/m^3]	0.632	0.716
viscosity [kg/(ms)]	$2.73\cdot10^{-5}$	$2.65\cdot10^{-5}$
MIDDLE WINDBOX		
unit load	100%	65%
static pressure [Pa]	117 465	115 265
air mass flux [kg/s]	42.27	28.027
air density [kg/m^3]	0.632	0.716
viscosity [kg/(ms)]	$2.73\cdot10^{-5}$	$2.65\cdot10^{-5}$
RIGHT-HAND WINDBOX		
unit load	100%	65%
static pressure [Pa]	117 595	115 139
air mass flux [kg/s]	41.29	28.023
air density [kg/m^3]	0.632	0.716
viscosity [kg/(ms)]	$2.73\cdot10^{-5}$	$2.65\cdot10^{-5}$

transport equations for the kinetic energy of turbulence and its dissipation rate, as defined by the commonly known relationships.

4. Numerical computation results – the pre-upgrade state

In the presentation of numerical analysis results, the case of 100% Unit load will only be shown. The results for the 65% load are qualitatively similar, with only the range of calculated velocity and pressure values being changed. Figure 4 shows examples of results for the velocity field (Figure 4a) and the static pressure field (Figure 4b) generating just under the grid of the left-hand side windbox.

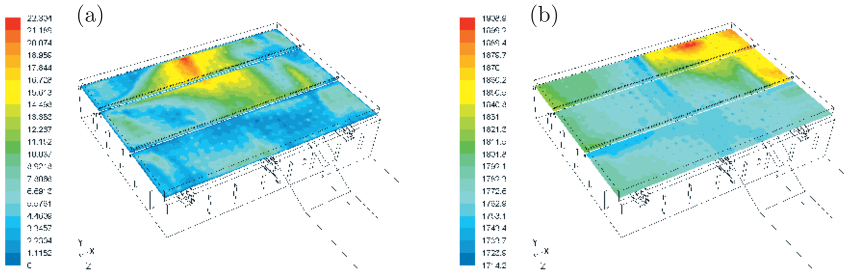

Figure 4. (a) The contour-plot velocity field [m/s] and (b) static pressure field [Pa] in the grid space of the side windbox for 100% MCR

As follows from Figure 4, the asymmetrical air supply system favours the generation of a vortex within the whole internal volume of the windbox, and the formation of dead zones, in which the velocity takes on a zero value. This condition promotes the formation of horizontal static pressure gradients and the pouring over of the bed material into the windbox space.

Figure 5 shows the velocity field (Figure 5a) and the static pressure field (Figure 5b) generating just under the grid of the middle windbox.

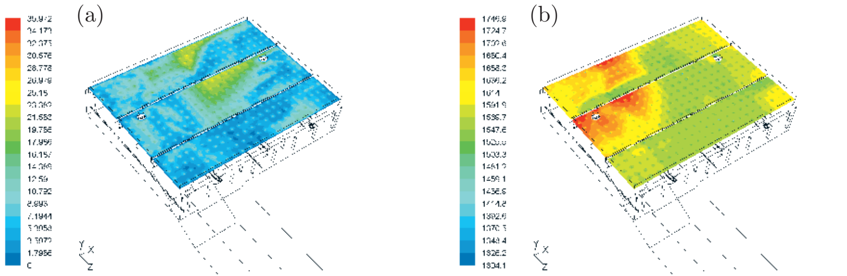

Figure 5. (a) The contour-plot velocity field [m/s] and (b) static pressure field [Pa] in the grid space of the middle windbox for 100% MCR

As indicated by Figure 5, similarly as for the side windbox, the asymmetrical air supply system favours the generation of a vortex within the entire windbox space and the formation of a highly inhomogeneous velocity field in the vicinity of the air distributor. As a result, the adjacent air nozzles are supplied with an air stream of values differing significantly.

5. Upgrading the geometry of the windboxes

Figure 6 shows the modified geometries of the side windbox (Figure 6a) and the middle windbox (Figure 6b) of the 670 MW_{th} CFB boiler. Due to the non-uniformity of static pressure within the windbox inlet space, the asymmetrical construction of the inlet channel favouring the formation of an inner vortex within the entire windbox space, as well as owing to the small windbox depth, the equalization of pressure in the grid space will only be possible after a prior division of the air stream delivered to the windboxes.

This function is to be performed by the baffles marked in Figure 6 with blue colour. The divided air stream should feed, in a similar proportion, three windbox

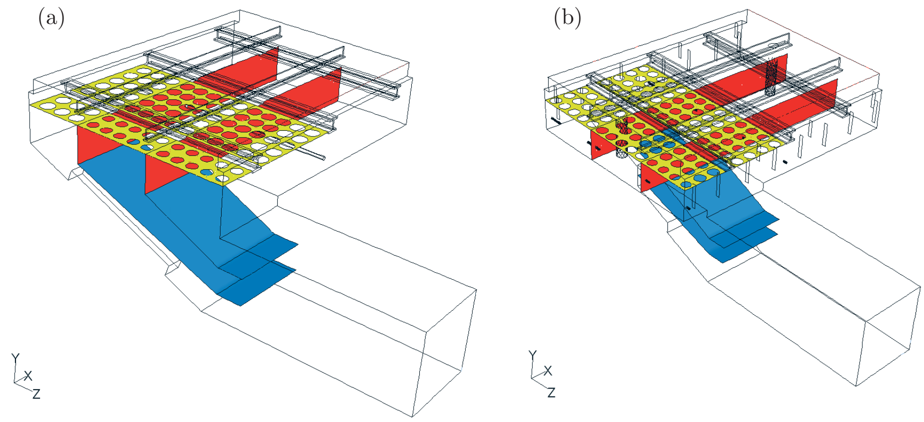

Figure 6. The modified geometry of (a) the side windbox and (b) the middle windbox

zones resulting from the arrangement of the two beams mounted perpendicularly to the air inlet direction. To this end, vertical partitions have been designed, which are marked in Figure 6 with red colour. As the air stream is delivered to the windbox asymmetrically, an additional need arises to reduce the pressure in the zone immediately above the inlet channel, which should result in equalization of static pressure in the whole cross-section under the grid. This function is fulfilled by the partition with variable-diameter holes, which is marked in Figure 6 with yellow colour.

6. Numerical computation results – the post-upgrade state

Figure 7a shows a velocity distribution in the channel supplying air to the boiler's side windbox, while Figure 7b shows a velocity field in the grid zone of the 670 MWth CFB boiler for 100% MCR. It can be seen from Figure 7a that the division of the air stream has an effect of producing a uniform velocity distribution in all windbox zones. As a result, the velocity field under the air distributor (Figure 7b) has a more equalized profile compared to Figure 4a, thanks to which the air nozzles can be fed with an air stream of a similar magnitude, and no horizontal pressure gradients are likely to form.

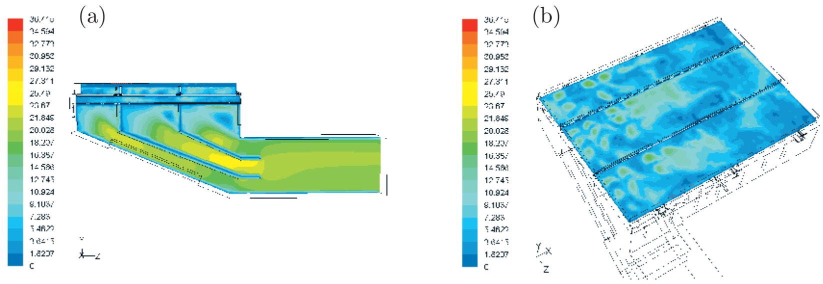

Figure 7. Velocity [m/s] distribution in the (a) inlet channel and in (b) the grid zone of the side windbox after upgrading, for 100% MCR

In the case of the middle windbox, the degree of windbox inlet obstruction is much higher, which is clearly seen in Figure 8a. Nevertheless, the division of the inlet air stream and the application of perforated horizontal partitions have allowed the equalization of the velocity field under the grid. The change of the internal windbox geometry has resulted in the reduction of the velocity magnitude differences from several dozens to several m/s. The velocity vector direction, resulting from the breaking of the vortex forming in the windbox, has also changed. Owing to this, now the air flows to the air distributor normally, and not tangentially, as before.

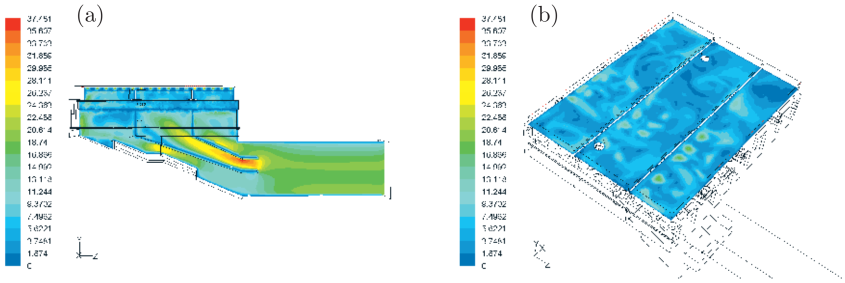

Figure 8. Velocity [m/s] distribution in (a) the inlet channel and in (b) the grid zone of the middle windbox after upgrading, for 100% MCR

Figure 9 shows static pressure distributions in the grid zone of the side windbox (Figure 9a) and the middle windbox (Figure 9b). In comparison with the distribution shown in Figures 4b and 5b, a clear improvement in the uniformity of pressure in this zone can be seen.

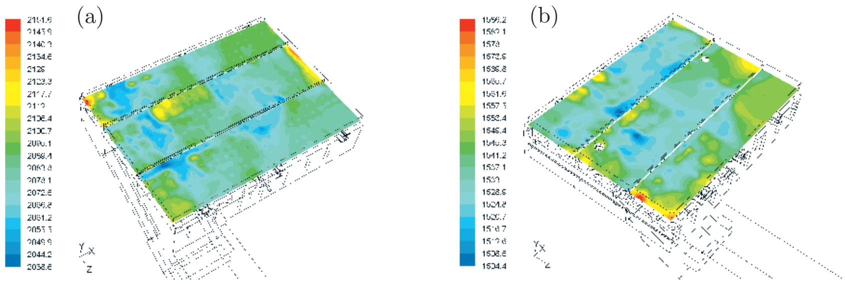

Figure 9. Static pressure [Pa] distribution in the grid zone of (a) the side windbox and (b) the middle windbox after upgrading, for 100% MCR

For the side windbox, the differences between the extreme values do not exceed 30 Pa, while for the unmodified windbox construction this value was around 200 Pa. In the case of the middle windbox, the difference between the extreme values does not exceed 20Pa, while in the unmodified construction these values were larger by the order of magnitudes.

7. Summary

The numerical computations of the windboxes of the 670 $\mathrm{MW_{th}}$ CFB boiler have shown that both the velocity field and the pressure field are characterized by a high inhomogeneity across the windbox height, and particularly in the grid zone. This inhomogeneity results from:

- the asymmetrical system of air delivery to the internal windbox volume, as a result of which a vortex forms in the windbox interiors, which generates dead zones in the air grid space,
- the non-uniform velocity profiles at the windbox inlet, resulting from the incorrect modelling of air distribution in the channels supplying gas to the windboxes.

The elimination of the vortex generated in the windbox volume as a result of the asymmetrical air feed is accomplished by dividing the windbox interior into three separate zones using vertical partitions, to which air is supplied through separate channels. The equalization of the amount of air supplied to the grid is achieved by dividing the air stream at the windbox inlet into two smaller streams. The equalization of static pressure in the grid zone of the windboxes is accomplished based on a system of partitions with variable-diameter holes. By modifying the windbox geometries, both the static pressure field under the grid and the velocity field have been equalized, owing to which all nozzles mounted on the grid will be fed with air with an equal mass output. The implementation of windbox geometry modification has reduced the spread of the extreme velocity and pressure values from several hundred Pa for the existing state to approx. 20 Pa for the modified state.

It should also be noted that the proposed windbox geometry modifications have been implemented on a real facility, and their effect should include:

- the minimization of the phenomenon of bed material pouring over to the windbox interior through the air nozzles,
- the reduction of the erosion of the boiler's rear wall, and
- the reduction of nitrogen oxide emissions.

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