COLD AIR FLOW CHARACTERISTICS OF A LOW NO_X AXIAL SWIRL BURNER

Sławomir J. Golec, PhD. Eng.
General Electric Company Polska

Abstract

Recent technological changes in the Polish power industry have created opportunities for reducing NO_x, CO, SO_2 emissions, but - at the same time - created another operation problem: sulphur corrosion and erosion of boilers' water-walls as well decreasing of the boiler's efficiency. This has been the motivation for performing a detailed study of the air flow in low-NO_x burners. A measuring stand was built inside a real medium power OP-230 boiler equipped with a low-NO_x burner to measure the velocity field at the burner's outlet and to prepare experimental characteristics of the burner. To extend the description, a numerical model of the burner was constructed and numerical calculations were executed by means of the Fluent program. Numerically calculated velocity profiles were compared with the results of measurements. The obtained results have been helpful in formulating recommendations to improve burner geometry.

Keywords: *combustion, pulverised coal burner, NO_x, SO_2, environmental pollution, sulphur corrosion, LNASB*

1. Introduction

There have been many technological changes in the Polish power industry in the recent years, but coal remains a dominating source of energy and its position will certainly not be shaken in the next several years. It results both from economic reasons and from the imperative of energetic security of the country. The cost of electricity obtained from coal is half that of electricity produced from natural gas. According to a DOE report [1], natural gas fuel costs are expected to rise whereas those of coal will decline. Moreover, the question of permanent and undisturbed access to energy sources is becoming more and more important nowadays. The persistent instability in the former Soviet Union countries and in the Middle East shows that excessive reliance on foreign oil is a costly proposition - in political, military and economic terms. Fortunately, Poland has plentiful domestic resources of coal to generate electricity - and new technologies allow to meet the growing demand for electricity more efficiently. However, coal combustion is inseparably associated with environmental pollution. The major pollutants produced in the combustion process are unburned and partially burned hydrocarbons, carbon monoxide, sulphur oxides, nitrogen oxides, and particulate matter in various forms. All these compounds affect the environment and human health in many ways, the most important of which are:

- potential increase of sickness and mortality of the population,
- altered properties of the atmosphere and precipitation,
- worsened conditions of vegetation,
- soiling and deterioration of materials.

Because of the large number of uncontrolled variables, it is not easy to explicitly measure the effect of pollution on human health. However it is well known that carbon-based particles may contain adsorbed carcinogens. It is also observed that pollutants can aggravate pre-existing respiratory ailments. The occurrence of acute and chronic bronchitis can be correlated with SO2 and particulate matter. Altered properties of the atmosphere affecting local areas include: reducing visibility, increasing fog formation and precipitation, altering temperature and wind distributions, reducing solar radiation. On a larger scale, greenhouse gases may alter global climates.

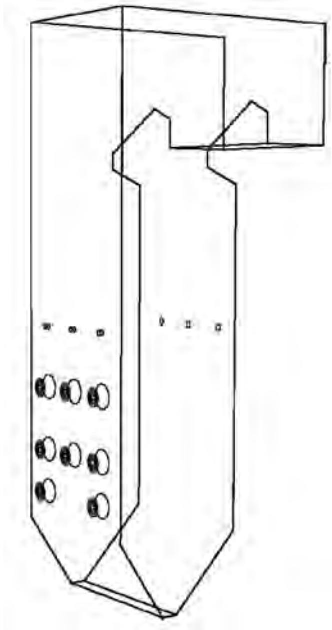

Figure 1. Burners and OFA nozzles' configuration in the OP-230 boiler

Lakes and susceptible soils are affected by acid rain produced from SO_x and NO_x emissions. Vegetation is harmed by the action of phytotoxicants SO_2, peroxyacetyl nitrate (PAN), C_2H_2 and others. Particulate matter, especially that containing sulphur, corrodes paint, masonry and electrical contacts, while ozone severely deteriorates rubber. The huge volume of combusted coal and environmental pollution caused by flue gases have resulted in a growing interest in the improvement of the coal combustion technology. In order to reduce the pollution, Poland, like other industrialized countries, has adopted stringent emission standards and implemented emission control. In the early nineties the power industry made a great organizational and financial effort to reduce the emission of nitric oxides and carbon monoxide. It was achieved in various forms, depending on the individual energy producer. Air gradation has been applied in certain installations, whereas others employed low-emission burners with air redistribution. These two types of rebuilding required only a slight modernization of air ducts and met the environmental standards close enough. Moreover, these solutions are relatively cheap.

Like many other power plants, the Heat and Power Plant „Wybrzeże" in Gdańsk took it upon themselves to modernize most of their boilers. A general overhaul of the boilers was performed in 1994.

In the case of the OP-230 boiler, with tight screening of the burning chamber with natural circulation (boiler No. 10), the modernization mainly consisted in replacing swirl-type burners with low-emission units manufactured by Babcock Energy Ltd. and in admitting additional volume of air to the combustion chamber via OFA nozzles located in front of and behind the water wall. A sketch of the side view of the boiler with eight burners and six small OFA nozzles is shown in Fig. 1. The boiler is equipped with a three-stage steam superheater, a water heater, and two rotating air heaters. It is supplied by four mills, three of them in continuous operation and the fourth kept in reserve. Each mill feeds two burners, so the fuel is injected by six burners. The burners are located on the boiler's front wall at a distance of 2.5 m from each other.

After the modernization, the boiler was in operation for 27 thousand hours, when its rear water wall was damaged in the spring of 1998 [4]. A tube was torn apart at the level of 14 m - the top row of burners. Thickness measurements of the tube walls in the vicinity of the damaged part made after the failure, revealed a reduction in thickness from 5 mm, which was the nominal value, down to a minimum thickness of 1.4 mm. The thickness defect was recorded along half-perimeter from the furnace side, 'from fin to fin', the minimum thickness being located at the top of the tube.

Chemical analyses confirmed unmistakably the correct ferrite-and-bainite structure of the tube's steel, and its low degradation level, recorded both from the side of the furnace gas and that of the furnace lining. An increased concentration of sulphur was observed in the deposits taken from tubes along with increased contents of oxygen, potassium, magnesium and calcium, which testified to a high concentration of sulphides. High contents of sulphur in the layer and uniform material decrement in the tubes testified to sulphide corrosion of the boiler's rear water wall.

Measurements of the pipe's thickness have shown that the rate of corrosion in this boiler was equal to 0.7 mm ÷ 1 mm per year, while it had been 10 times lower before the modernization.

It thus came out that the new installation significantly reduced NO_x emission, but at the same time caused serious damage to the boiler, and remained a threat to its faultless exploitation. A detailed study of combustion process in the new low-emission burner became necessary also for technological reasons.

2. Burner characteristics

The geometry of the low-NO_x emission swirl burner manufactured by Babcock Energy (Fig. 2) is more complex than that of a standard swirl burner. The air flowing into the combustion chamber is divided into core, primary, secondary and tertiary. The secondary air of the standard low-NOx burners is divided into secondary and tertiary air. In this way an additional possibility of combustion process control is achieved, through diversification of the air fluxes at the outlet. The angles of vanes mounted in the second and third air channels are different and adjustable, providing opportunities for changing the length of the swirl jet. Series of measurements were carried out to prepare the experimental characteristics of the burner and determine the velocity field at the outlet [5].

Figure 2. A Babcock Energy burner during measurements of the velocity components

in the OP-230 boiler No. 10, Heat and Power Plant in Gdańsk

Table 1. Measurement conditions for the Babcock Energy burner [4]

	Volume flow m^3/hr	Temperature °C
Core air	2800	22
Primary air	7500	45
Secondary air	17000	22

During the experiment the coal mill was merely ventilated and no coal was flowing through the burner, while in the normal operation of the boiler pulverized coal is mixed with primary air. The measuring probe was mounted on a system of movable guiding rails located co-axially with the burner (Figs 2 and 3). Because of a high level of dust in the chamber, a strengthened Dantec fibre-split thermo-anemometer probe was used. The probe made it possible to measure the axial and the tangential velocity components, as well as their fluctuations. The measurements were realized in cross-sections 0, I, II, III (Fig. 3). Cross-section 0 was situated at a distance of l cm from the burner's outlet, cross-section I -20 cm, cross-section II - 66 cm, and cross-section III - 91 cm from the outlet of the burner. The output of primary and secondary air was measured independently and recorded in the control room of the power unit. Moreover, it was possible to control the swirl of secondary air using a special swirler situated in the secondary air space inside the burner. Approximate conditions of burner work are given in Tab. 1. Properties of the swirl flow can be correctly described by the swirl number, according to the following formula:

$$S = \frac{2}{d} \cdot \frac{G_\theta}{G_x} \tag{1}$$

where d is the stream diameter, G_θ is the tangential momentum component and G_x is the axial momentum component, both given by the following formulas:

$$G_\theta = \int_0^\infty \left(\rho U W + \rho u' w'\right) r^2 dr \tag{2}$$

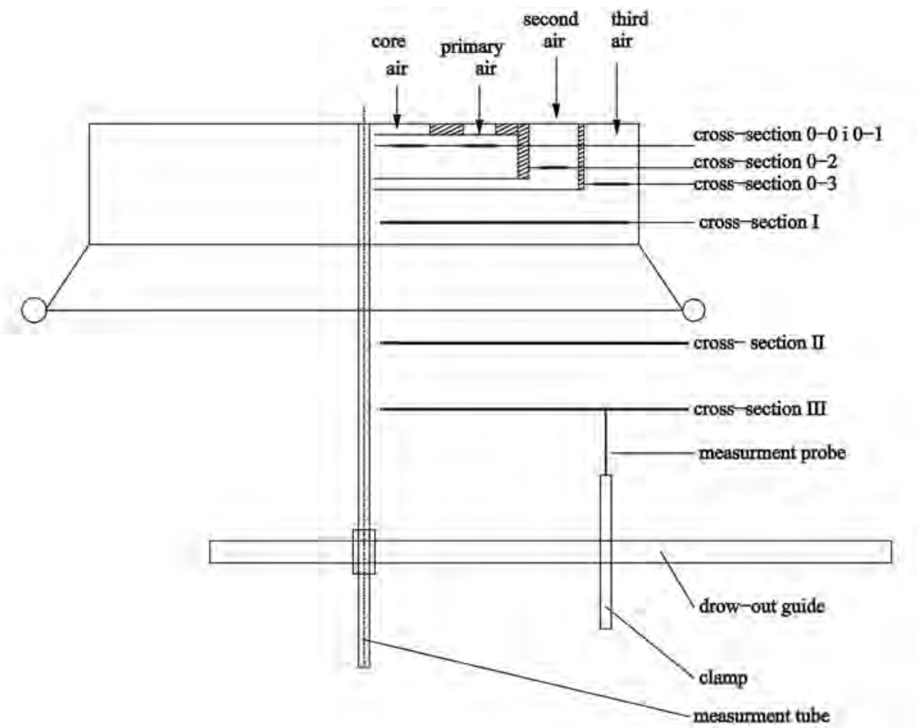

Figure 3. Measurement cross-sections at the outlet of the Babcock Energy burner

$$G_x = G_\theta = \int_0^\infty \left(\rho U^2 + \rho u'^2 + \left(p - p_\infty\right)\right) r\, dr \tag{3}$$

where U and W are the axial and circumferential components of the air stream, while u' and w' are fluctuations of axial and circumferential components of velocity, respectively, ρ is density, p and p_∞ stand for the actual value of pressure and the value of pressure at infinity.

In the case of incompressible flow, disregarding the influence of fluctuations of velocities u' and w' simplifies the formula considerably:

$$S = \frac{2}{d} \cdot \frac{\int_0^\infty UWr^2 dr}{\int_0^\infty U^2 r dr} \tag{4}$$

On the basis of the measurements, a square-mean approximation of the swirl number was computed in relation to the swirl vane used and diaphragm settings. Their influence on the averaged S is relatively low, and the swirl number curve as a function of diaphragm setting and the swirl vane varies within the range of 0.47÷0.69.

Figure 4. Geometry of the numerical model of the burner and the profile of velocity magnitude [m/s] at a distance of 20 cm from the outlet

Table 2. Air boundary conditions for the numerical calculations of the Babcock Energy burner

	Mass flow [kg/s]	Temperature K
Core air	0.75	293
Primary air	1.7	318
Secondary air	1.2	293
Tertiary air	3.45	293

3. Measurements versus numeric

As mentioned above, the experimental characteristics of the burner were developed in several cross-sections only. To extend the description of the burner to the whole of the combustion chamber, a numerical model of the burner was constructed (Fig. 4, 5 and 8) with a part of the combustion chamber of the size 4m × 4m × 6m. The geometry of the burner was simplified. It was assumed that some of the blades were plane, while in practice they were half-rounded, and the thickness of most of the burner walls and blades was assumed to equal zero. However, the inner walls and blades were included, as shown in Fig. 9. Because of the complicated geometry, different types of cells were used. A majority of the burner cells was of the tetrahedral type whereas the combustion chamber consisted of hexahedral cells. For most of the numerical tests the number of cells did not exceed 1000 000. All computations concerning the flow of air through the burner were carried out by means of Fluent [6]. The numerical air boundary conditions were based on the measurements and are presented in the Tab. 2. The numerical calculations were executed using a k-ε turbulence model of very good convergence, and the RNG k-ε model, which yielded a solution with the residuum exceeding 10^{-3}. Selected results of these calculations are shown in Figs 4-9. Fig. 4 shows a view of the burner in the horizontal plane, along with the velocity profile at a distance of 20 cm from the burner outlet. Looking from the left, the inlets of core and primary air are visible. One can also see covered inlets of secondary and tertiary air. The velocity profile in the plane marked in the picture is not symmetric with respect to the burner axis. This asymmetry is insignificant and results from the burner's construction.

Fig. 5 shows, in an axonometric projection, velocity magnitude contours in the vertical plane along the burner's axis. The edges of the inner walls and burner blades are also marked, along with a fragment of the modelled combustion chamber. The tangential velocity component, in the intersection along the burner axis in the vertical plane and the completely modelled combustion chamber, are presented in Fig. 6.

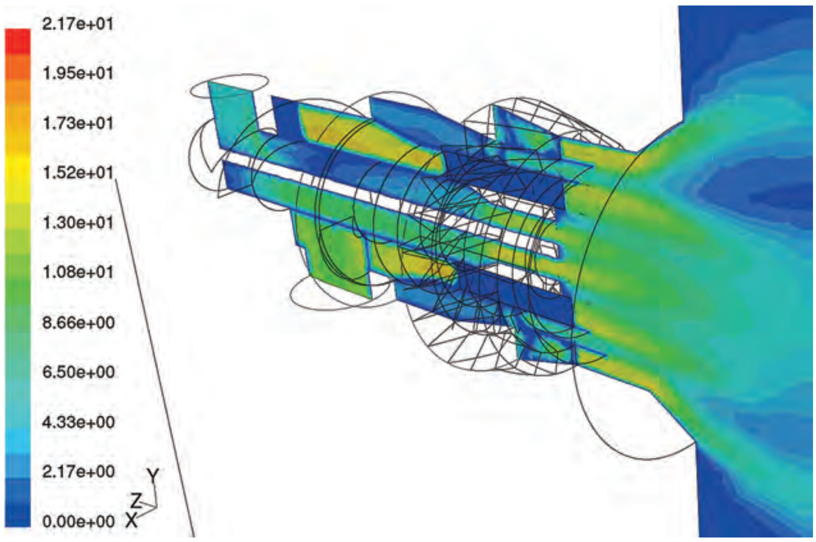

Figure 5. The velocity magnitude [m/s] in the cross-section along the burner axis

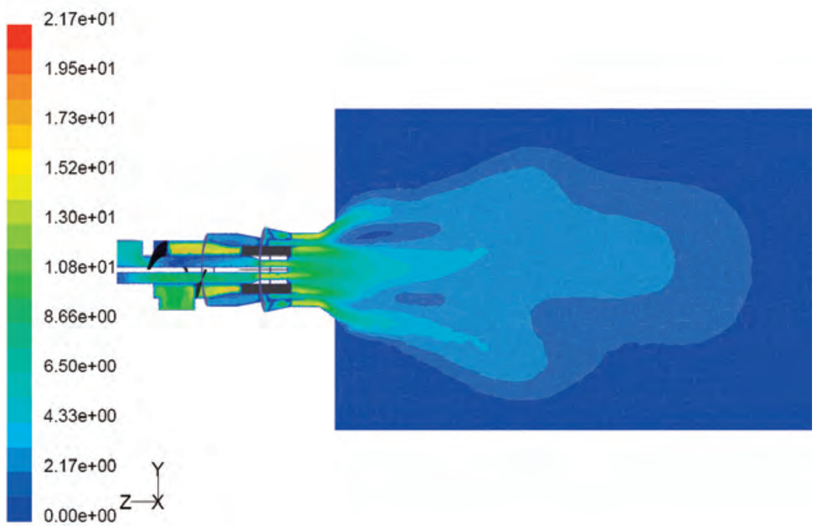

Figure 6. The velocity magnitude [m/s] in the cross-section along the burner axis - - chamber view

Velocity modulus contours at the outlet of the burner are shown in Fig. 7. One can see the influence of four separating blades and tertiary air blades on velocity. An asymmetry of the burner's work can be observed as well.

Fig. 8 shows the streamlines. Inner blades of the burner and selected fragments of walls separating particular streams of air are also shown in the figure. One can easily observe the configuration of streamlines inside the burner and inside the combustion chamber. It is noteworthy that the air blown into the numerically modelled chamber has the form of a slightly expanding stream. Velocity profiles, calculated numerically, are compared with the results of measurements in Fig. 9. The figure consists of eight plots, arranged in two columns and four rows. The first and second columns show the axial and circumferential components of the velocity vector, respectively. The rows correspond to cross-sections 0, I, II and III. In each plot, the „X" axis represents radius r [m] (measured from the axis of the burner), while the „Y" axis represents a component of the velocity vector [m/s]. The solid line corresponds to numerically computed values, while the dots mark the measurements data.

The least compatibility between the measurements and the calculations is observed for core air, particularly in cross-section I, for the axial component (see Fig. 9).

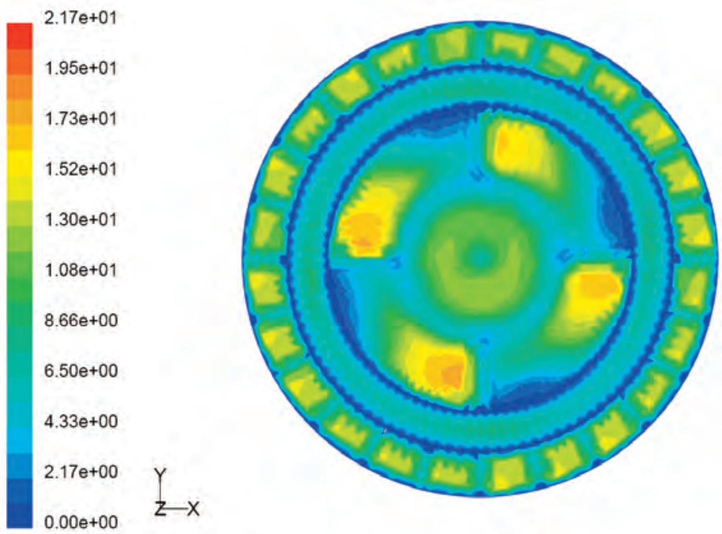

Figure 7. Velocity modulus in the crosswise direction (with respect to the axis of the burner) at the burner outlet

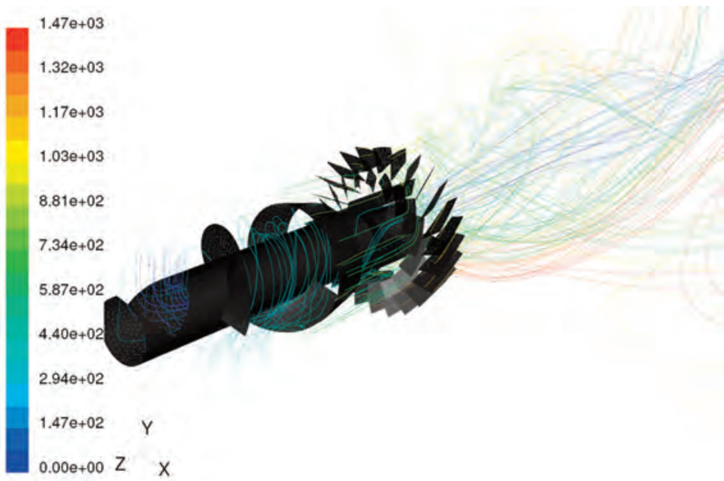

Figure 8. Streamlines with marked internal blades and the wall separating primary and secondary air; the beginning fragment of the wall separating the second from the third air flow is marked

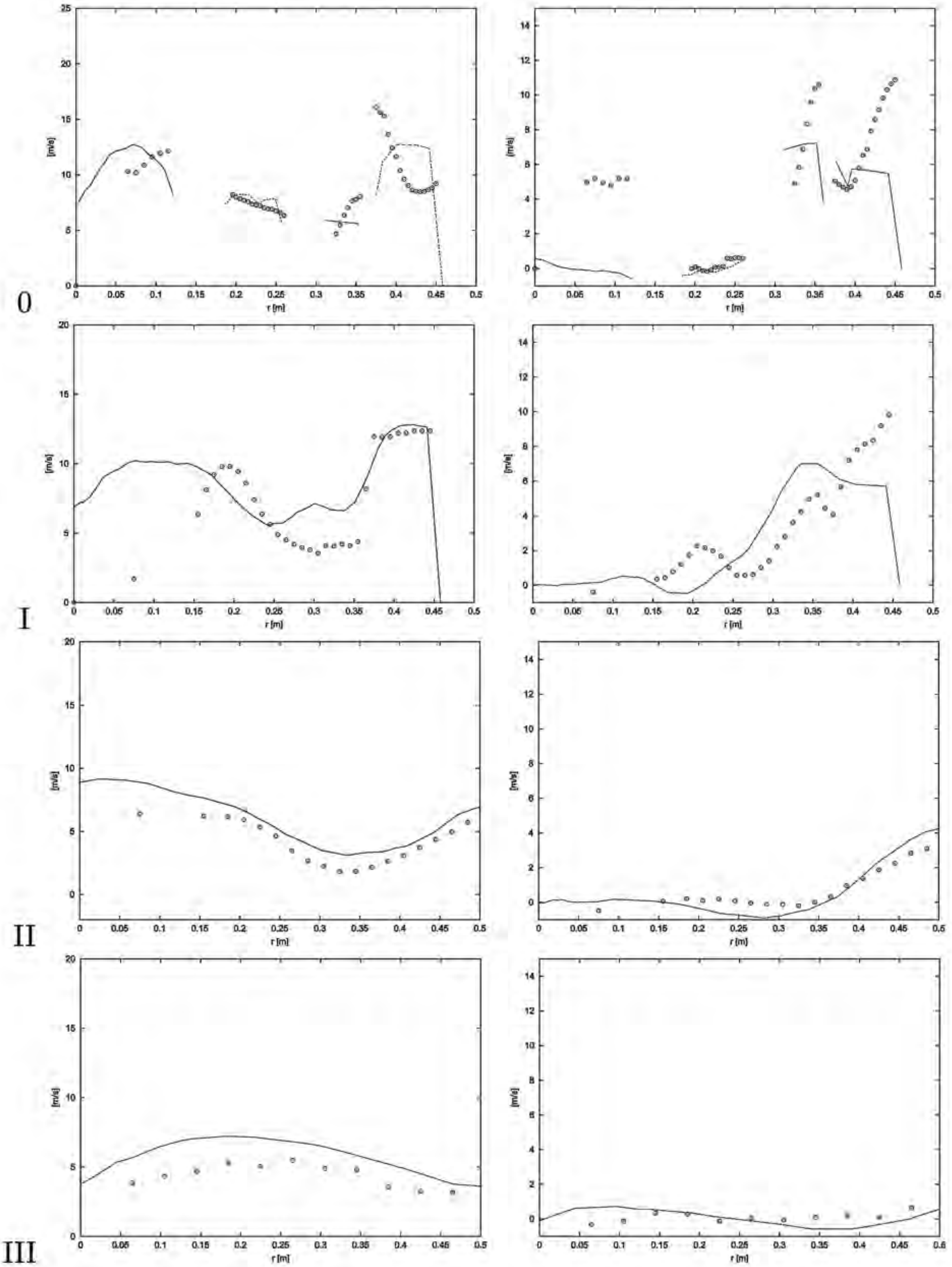

Figure 9. Velocity component cross-sections 0, I, II, III. The first and second columns present the axial and radial components, respectively. Measurement data are marked with dots, numerical results - with lines

This discrepancy may be due to the presence of the leading pipe along the burner axis. The pipe was neglected in the numerical model used for the calculations.

Further from the burner outlet (cross-sections II and III) the consistency between the calculated and measured profiles of the axial and circumferential components is better.

There is qualitatively good consistency of calculations and measurements for primary air, particularly in cross-section 0. In other cross-sections, the numerical solution is similar to most of the measurements of velocity vector components. The least consistency is observed in cross-section I. It may result from the different shapes of primary air blades (separators).

There is qualitatively good agreement for secondary air in cross-section 0, while further from the burner outlet, i.e. in cross-section I, one can observe excessive values of the axial component of the velocity vector (Fig. 9). However, the difference is insignificant.

In cross-section II, there is good consistency of the axial and tangential components of the velocity vector. These discrepancies were undoubtedly caused by the simplification of the burner geometry.

Other inconsistencies could have resulted from inaccuracies of measurement. While the real flow was three-dimensional, the probes used in the measurements were appropriate for 2D flows, which increased the measurement error. One should also bear in mind the differences in the temperature of core and primary air, and between primary (45°C) and secondary air (22°C), which were assumed equal.

4. Conclusions

Measurements and numerical calculations presented above allow the basic characteristics of the low-NO_x burner to be defined. First of them is a relatively low swirl number. The swirl is very weak at the core and primary air areas and increases in secondary and tertiary air areas. Thus, it can be concluded that primary air transports coal powder deep into the combustion chamber. This type of combustion may lead to corrosion and erosion of a boiler's rear water wail, which took place at the Wybrzeże Heat and Power Plant. This non-uniformity can be reduced by means of an additional screw blade.

Acknowledgements and additional Information

The majority of calculations were made at the Academic Computer Center TASK Gdańsk during creating of author's PhD thesis [2].

This paper is a part of paper [3] which is based on the author's PhD thesis.

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S. Golec

CHARAKTERYSTYKI PRZEPŁYWU ZIMNEGO POWIETRZA DLA NISKOEMISYJNEGO OSIOWEGO PALNIKA WIROWEGO (LNASB)

Streszczenie

Obecne zmiany technologiczne w polskich elektrowniach i electrociepłowniach stworzyły szanse do redukcji emisji NO_x*, CO oraz* SO_2 *ale jednocześnie przyczyniły sie do powstania nowych problemów eksploatacyjnych takich jak np.: korozji siarkowej i erozji płaszczy kotłów jak i również obniżenia sprawności pracy kotłów. Powyższe problemy były motywacją do dogłębnej analizy przepływu powietrza w niskoemisyjnych palnikach wirowych. Stanowisko pomiarowe przeznaczone do wyznaczania pola prędkości u wylotu z palnika oraz charakterystyk pomiarowych palnika było stworzone w rzeczywistym kotle OP-230 wyposażonym w niskoemisyjny palnik. Do poszerzenia opisu zbudowano numeryczny model palnika, a obliczenia numeryczne były wykonane za pomocą pakietu oprogramowania o nazwie Fluent. Rezultaty tych obliczeń numerycznych były porównane z pomiarami. Otrzymanane wyniki były pomocne w tworzeniu wytycznych modernizacji palnika.*