ZESZYTY NAUKOWE POLITECHNIKI ŚLĄSKIEJ 1988

Seria: ENERGETYKA z. 104 Nr kol. 973

Vladimir LAPČÍK

Department of Energetics

Technical University of Ostrava

HEAT AND MASS TRANSFER AT FLUIDIZED-BED BOILERS AND REDUCTION OF HARMFUL EMISSIONS

Summary. An attention is paid in the article to the purposefulness of using the fluid-bed furnaces on account of reduced emission of toxical components of the combustion gases. The results of experimental tests carried out on the fluid - bed furnace mounted on the Galloway boiler have been given in the form of the dependence Sh = f(Re). The test results of the NO_x and SO_2 emission measured also in the other object have been discussed with full particulars. They have been compared with the ones obtained in other furnaces. The influence of the quantity of nitrogen, oxygen, volatile matters and furnace aerodynamics index and additives on quantity of nitric oxides being formed has been presented.

1. INTRODUCTION

In our country as well as in other highly industrialized countries the air pollution is one of the most burning ecological problems.

The most significant source of the air pollution is combustion of fossil fuels having the high sulphur content and that of incombustible substances. Almost three quarters of sulphur dioxide produced in our country come from combustion processes, i.e. from the heat and electric energy generating. It is chemistry and metallurgy that produces the remaining part. Energetic industry and industrial energetics cause approximately 80% of production of nitrogen oxides and 65% of emissions of fly ash.

In July 1985 the environmental ministers of twenty-one countries signed a so-called Protocol on sulphur emissions at Helsinki's sessions. This is a document obliging all these countries (Czechoslovakia is one of them) to reduce their emissions or transboundary fluxes of sulphur dioxide by at least 30 per cent as soon as possible, or by 1993 at the latest. A similar agreement is expected for the emissions of nitrogen oxides.

While regarding to this fact and to an incessant effort of our socialist society to improve its environment a new conception of structure of energetic sources is introduced to life in Czechoslovakia. It concentrates on central supply of heat, nuclear power stations and on new ways of combustion of coal and industrial wastes with flue gas desulphurization and with the reduction of harmful emissions.

One of these progressive methods is the application of fluidization engineering in combustion process. Unlike of the present technology of combustion, the fluidized-bed combustion solves also important question of reduction of the sulphur dioxide, nitrogen oxides and toxic metals content in flue gas. Up to that, the combustion in fluidized bed is characterized by very intensive heat and mass transfer so that the high efficiency of combustion process is reached, which creates the chance for the application of low-value brown coal with high ash content.

The course of turbulent transfer magnitudes has the deciding influence on the quality of the combustion process and - as it appears - on formation of harmful emissions. The series of measurements were carried out in the pilot plant of fluidized-bed combustors (reaching the out-put 3 MW_{th}) situated in SONP Kladno Steel Works. The measurements were to determine the values of the turbulent transfer magnituedes.

It must be pointed up that the literature cites relatively few values of the transfer magnitudes that might be useful in solving the problems of the fluidized bed combustions when the relatively large particles of the bed (up to 10 mm) have to be taken into the consideration. Most of the results, which were published up to now, treat the beds consisting of the small particles (up to 1 mm), which, however, don't suit to our purpose. That is why the results referring to this area had to be reached as soon as possible.

Simultaneously, the experimental verification and the particularization of the research and construction data of the combustor with a fluidized furnace were carried out. This combustor - having the output 19 MW_{th} and being constructed for the Heating Plant of Trmice by then - uses the same construction features as the combustor with fluidized furnace (3 MW_{th}) measured in the SONP Kladno Steel Works.

2. THE CHARACTERISTICS OF THE FLUIDIZED-BED FURNACE (3 MW_{th}) IN THE SONP KLADNO STEEL WORKS

The one-stage atmospheric combustor with a bubble fluidized bed (3 MW_{th}) of the SONP Kladno Steel Works was made up by the reconstruction of one of the 8 flue-tube boilers of the boiler-plant in the Koněv Iron Works. The conception of the reconstruction was designed by the Department of Energetics at the Technical University of Ostrava.

The reconstruction itself consists in situating the fluidized-bed furnace in front of the flue-tube boiler (see Fig. 1).

After the reconstruction the facility achieved the output 3 MW_{th} and delivered 4,170 kg/hr of vapour under the pressure 0.9 MPa and temperature 230 °C (these values have been preserved by now as the depicted facility was put in pieces during the renewal of the Koněv Plants and waits for the future utilization).

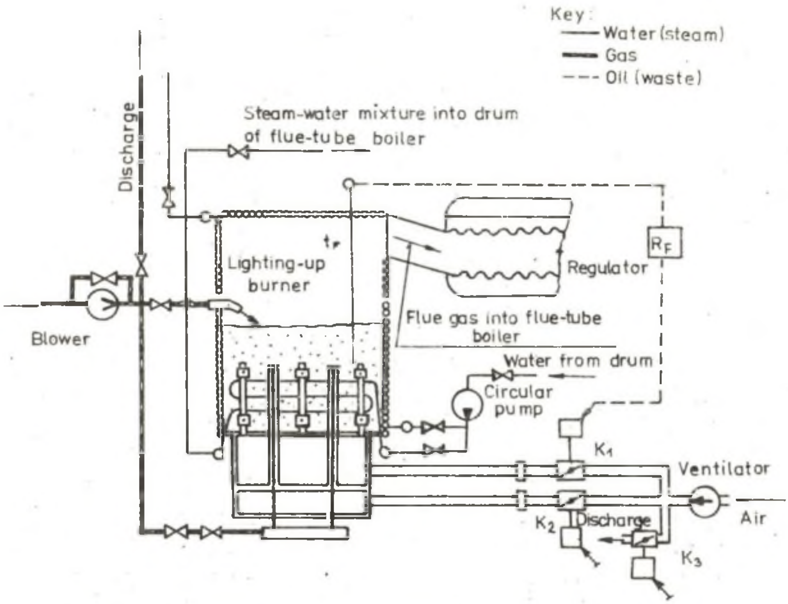

Fig. 1. Lay-out of the fluidized-bed boiler in the SONP Kladno ($3\ MW_{th}$) Steel Works

Rys. 1. Układ kotła fluidyzacyjnego w stalowni SONP Kladno (3 MW)

The fluidized-bed furnace is gasproof, fabricated of welded-up tube walls and ceiling. The axis-distance of the walls is 2,400 x 1,200 mm, while the height of the furnace reaches 3,080 mm. It is positioned in the axis of the combustor, has a self-carrying construction and it is situated on the supporting construction of the combustor.

The flue gas of the furnace leaves out through its back wall and enters into the combustor itself in the place of the former grate forefurnace front wall. The temperature of the outgoing flue gas reaches approximately 800--900°C.

The fluidized-bed furnace has its own circulation system with a circular pump. The circulation system is divided into two parallel branches. The first branch forms tube walls of the furnace, the second one makes up convection heating surfaces immersed in the fluidized bed. The tube walls are manufactured of horizontal tubes ϕ 38 x 3 mm, pitch 56 mm. Water flows through seven parallel tubes. The vertical walls of the furnace consist of 8 tube bundles and the ceiling of the three ones. The convection heating surfaces are manufactured of 12 parallel tubes ϕ 38 x 4 mm. Two tubes are always wound in one block the width of which is 240 mm. Altogether there are six blocks along the length of the furnace (2,400 mm).

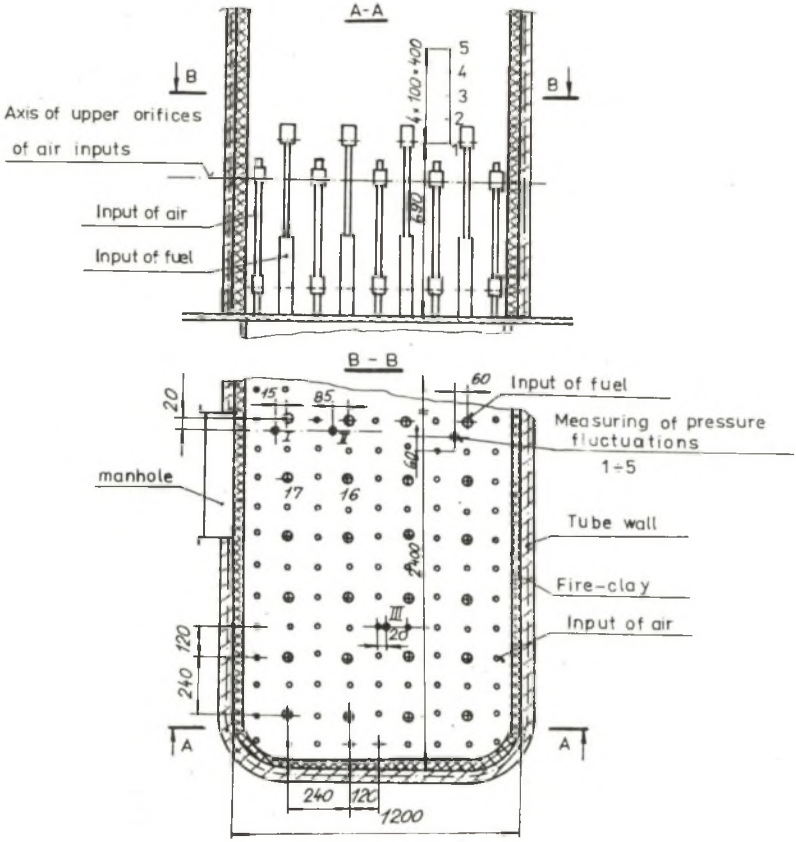

Fig. 2. Scheme of measuring places of pressure fluctuations and of static pressure (places I, II, III) in the fluidized bed of the SONP Kladno boiler (evaporator coils are not drawn)

Rys. 2. Rozmieszczenie punktów pomiarowych zmian ciśnienia oraz ciśnienia statycznego (punkty I, II, III) w złożu fluidalnym kotła stalowni SONP Kladno (cewki parowników nie zostały naniesione)

The distributor (as illustrated in Fig. 2) consists of 135 air and 33 fuel inputs. The air inputs have orifices in two levels (lower orifices are in the distance of 90 mm and the upper ones in the distance of 530 mm over the bottom) and are attached to cone sockets by a lock. The sockets lead into the upper chamber of the distributor. The sockets of fuel feeds lead into the same chamber supplying air into the lower level of the fluidized bed. The air is supplied into the boiler by one ventilator fan, on whose discharge it is divided into two branches.

The fundamental aim of this fluidized-bed furnace project was to solve the temperature control in the fluidized bed so that the temperature of the fluidized bed may be held at the optimum temperature of desulphurization process (750-900°C) independently of heat quantity led away from the fluidized bed. The regulating circuit is used to hold the fluidized bed temperature at the pre-set value.

The fluidized bed described here consisted of keramzit gravel (a special kaolin sinter) and it combusted coke-oven gas.

3. MEASURED QUANTITIES AND MEASURING DEVICES

Following measuring devices were used:

The temperature profiles were measured both with a fixed thermocouple in the lower part of the fluidized bed and with a sliding thermocouple in the range of the whole height profile of the fluidized bed. The measurements of the temperature field across the fluidized bed section were taken as well as the measurements of the temperatures above one fuel input into fluidized bed. The Ni-Cr, Ni thermocouples were used for measurements.

The value of the heat passage coefficient in the fluidized bed was determined in various vertical heights by the heat loops of various tube diameters (ϕ 38 x 4 mm steel tube and ϕ 14 x 2 mm and ϕ 10 x 1 mm copper tubes) in dependence on the superficial fluid velocity, on the temperature and on the size of the particles of the fluidized bed.

The quantity of the air entering the upper and the lower chambers of the distributor and the quantity of coke-oven gas were measured by means of diagrams. The static pressure in fluidized bed was measured by the probe consisting of six ϕ 8 mm tubes of different length, the material being AKX steel. The places of measurement are shown in Fig. 2.

The pressure fluctuations were measured using a non-cooled probe consisting of two ϕ 8 mm tubes made from the steel AKX, the length of which was 2,800 mm. The jacketed Ni-Cr, Ni thermocouples for temperature measurements in the given places presented in Fig. 2 were installed on the non-coold probe. The values of pressure fluctuations were taken off by a piezoelectric sensor made by the firm Kistler, with the range $\pm 10^5$ Pa and with its own frequency 1,000 s^{-1}. The sensor had a through thermal insulation. The signal from the piezoelectric sensor was registered after amplifying by the moving-coil oscillograph Lumiscript 300 which recorded deviation of the moving-coil on the sensitive paper by means of UV-ray.

The evaluation of the records was carried out every 0,02 s, the length of records being 200 mm (2 seconds). Judging from the course of the measured values we can determine turbulent transfer quantities, as stated below.

Gas sampling for CO_2 and O_2 analyses by means of Orsat's chemical absorption analyzer was carried out to enable combustion process evaluation and the determination of laminar quantities courses needed for the analysis of the fluidized-bed furnace aerodynamics. The cooled probe used for sampling was applied in the fluidized bed and in the space over it. The points of measurements were indentical with those of pressure fluctuations (Fig. 2).

The granulometric composition of the fluidized bed was determined on the basis of solid samples from the fluidized bed.

4. AERODYNAMIC ANALYSIS OF THE 3 MW_{th} FLUIDIZED-BED BOILER IN THE SONP KLADNO STEEL WORKS

The aerodynamic analysis of the 3 MW_{th} fluidized-bed boiler in the SONP Kladno Steel Works was based on the values obtained during measurements. The courses of laminar quantities were calculated, mass-transfer coefficient, diffusivity, turbulent kinematic viscosity and other turbulent transfer quantities were determined. The courses of turbulent quantities, as well as those of the mass-transfer coefficient and of turbulent kinematic viscosity for various outputs are shown in Fig. 3, 4 and 5.

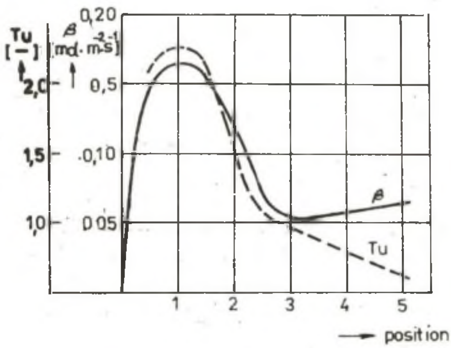

Fig. 3. Course of turbulent magnitude

Rys. 3. Przebieg wielkości turbulentnych

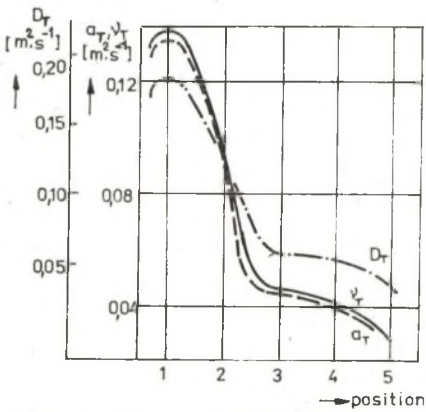

Fig. 4. Course of turbulent magnitude

Rys. 4. Przebieg wielkości turbulentnych

Similarity criteria using various characteristic dimensions were calculated, the characteristic dimensions being the fluidized bed particle diameter (d_s), the fluidized bed bubble diameter (d_b) and tube outside diameter of boiler convection heating surfaces immersed in the fluidized bed (d_{ti}). The courses of similarity numbers are depicted in Fig. 6, 7, 8, 9.

Regression dependences $Sh = f(Re_T)$ as well as correlation dependences for mass transfer were determined for characteristic dimensions d_s, d_b, d_{ti}:

$$Sh_1 = 2{,}992 \times 10^{-4} \; Re_{T_1}^{0{,}1887} \quad \text{(the characteristic dimension - } d_s\text{)}$$

$$Sh_2 = 6.565 \times 10^{-3} \; Re_{T_2}^{0{,}558} \quad \text{(the characteristic dimension - } d_b\text{)}$$

$$Sh_3 = 4,126 \times 10^{-3}\ Re_{T_3}^{0,191}$$ (the characteristic dimension - d_{ti})

The courses of turbulent quantities, turbulent kinematic viscosity and the mass-transfer coefficient β (Fig. 3, 4, 5) show that the maximum is near fuel inputs (position 1 - Fig. 2). The farther from fuel inputs, the smaller value of turbulent quantities, the value of the mass-transfer coef-

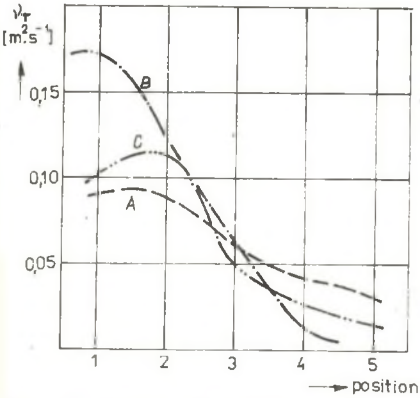

Fig. 5. Course of turbulent kinematic viscosity (output A, B, C)

Rys. 5. Przebieg lepkości kinematycznej turbulentnej (wyjście A, B, C)

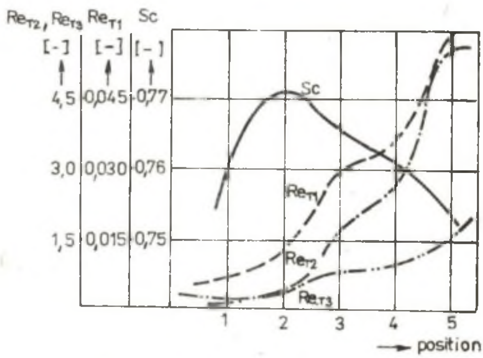

Fig. 6. Course of similarity numbers the characteristic dimension being d_s - 1, d_b - 2 and d_{ti} - 3

Rys. 6. Przebieg liczb podobieństwa dla d_s - 1, d_b - 2 oraz d_{ti} - 3 będących wymiarami charakterystycznymi

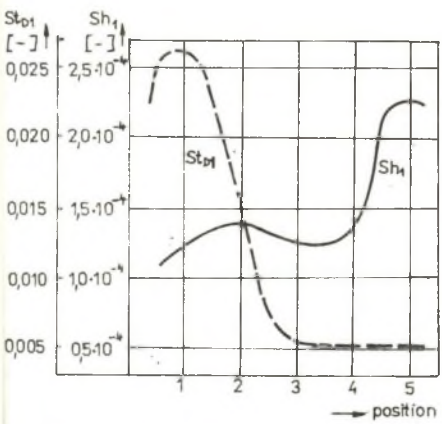

Fig. 7. Course of similarity numbers, the characteristic dimension being particle diameter - d_s

Rys. 7. Przebieg liczb podobieństwa dla średnicy pęcherzyka d_s będącej wymiarem charakterystycznym

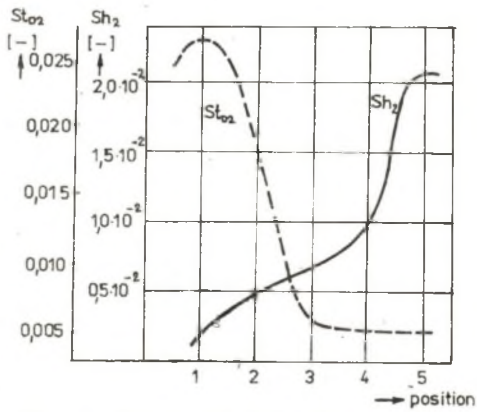

Fig. 8. Course of similarity numbers, the characteristic dimension being bubble diameter - d_b

Rys. 8. Przebieg liczb podobieństwa dla średnicy pęcherzyka d_b - bedącej wymiarem charakterystycznym ficient remaining near the constant. In the whole field the explosive combustion in the fluidized bed was going on, which is manifested by increased microturbulence which causes turbulent quantities growth as well as that of the mass-transfer coefficient. Stability of combustion in the fluidized bed including optimum momentum, energy and mass transfer is regression dependent on Sherwood number. Regression relations $Sh = f(Re_T)$ were established for the three above mentioned characteristic dimensions. After the comparison of these regression dependences using correlation coefficients r (following correlation coefficients were determined for the above characteristic dimensions: r = 0.666 for d_s, r = 0,979 for d_b and r = 0,674 for d_{ti}) has been carried out, the highest interdependence is apparent in case of the characteristic dimension being bubble diameter in the fluidized bed.

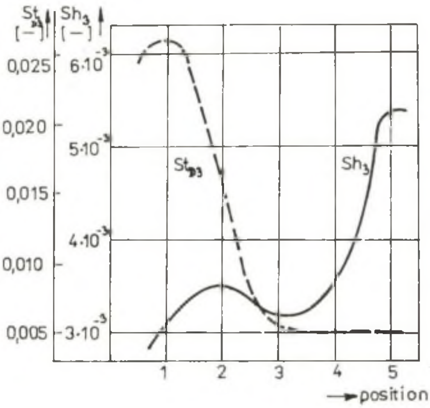

Fig. 9. Course of similarity numbers, the characteristic dimension being tube outside diameter of the convection heating surfaces - d_{ti}

Rys. 9. Przebieg liczb podobieństwa dla zewnętrznej średnicy rury powierzchni ogrzewania konwekcyjnego d_{ti} będącej wymiarem charakterystycznym

The character of Sherwood number regression dependence Sh should be as flat as possible, which is important for the fluidized-bed furnace construction, because in such a situation a vaster dissipation of mass transfer does not take place and the mass transfer is therefore stable. Stable combustion supports high transfer rates, high service life, fluidized bed stability and thus the required fluidized-bed boiler dynamics. If the course of the curve is flat the regime is less sensitive to the changes in the fuel granularity, to the excess of air and other changes in operation.

5. REDUCTION OF HARMFUL EMISSIONS

Successive measurements of fluidized-bed boiler in the Heating Plant of Trmice (using the same construction elements as the fluidized-bed boiler in the SONP Kladno Steel Works) have proved the influence of combustion regime, which depends on the courses of turbulent transfer quantities, on the formation and on the binding the toxic emissions (SO_2, NO_x and heavy metals).

One-stage fluidized-bed boiler are known to be suitable, owing to oxidation atmosphere inside the furnace, for flue gas desulphurization by means of additives (limestone or dolomite are most common). Fluidized-bed combustion technology makes holding the optimum desulphurization temperature possible (which ranges between 750 and 880°C if limestone or dolomite is used).

Fig. 10 shows the course of the achievable desulphurization efficiency in dependence on the fluidized bed temperature during brown coal combustion in the Heating Plant of Trmice using limestone from the quarries Štramberk and Jeseník and dolomite from the quarry Krty. We may compare the curves with the DBW curve (from the F.R.G.) showing the dependence of desulphurization efficiency on fluidized bed temperature as obtained during bituminous (hard) coal combustion.

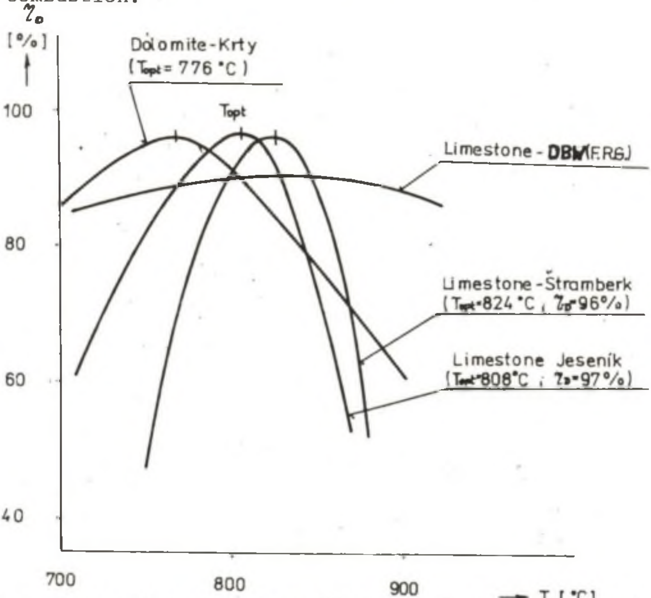

Fig. 10. Dependence of de-sulphurization efficiency on temperature of combustion

Rys. 10. Zależność wydajności odsiarczania od temperatury spalania

From the courses of curves Štramberk, Jesenik a Krty the optimum temperature of the fluidized bed is evident 824°C, 808°C and 776°C respectively. The optimum temperature must be regulated according to the limestone or dolomite types, which must be provided by the tiven system of the fluidized-bed furnace.

Fluidized-bed boilers emit considerably less NO_x than traditional pulverized coal-fired boilers. This fact is due first of all to combustion temperatures, which are much lower than with pulverized coal-fired boilers. Even here it is proved that the amount of NO_x emissions depends on aerodynamics of combustion, i.e. on the course of turbulent transfer quantities. Fig. 11 shows the dependence of Sherwood number on the product $Ar_T \cdot Sc$ (for FBC)

$Sh_{FBC} = 1,19\, Ar_T^{0,67} \cdot Sc^{0,33}$ CHAB 84

$Sh_{FBC} = 1,28\, Ar_T^{0,6} \cdot Sc^{0,33}$ CHAB.85

$Sh_{FBC} = 1,04\, Ar_T^{0,51} \cdot Sc^{0,33}$ KOM 85

$Sh_{PCF} = 0,391\, Re_T^{1,4} \cdot Sc^{0,33}$ ELE

$Sh_{PCF} = 0,0185\, Re_T^{1,7} \cdot Sc^{0,33}$ ELE R

$Sh_{PCF} = 0,0072\, Re_T^{2,1} \cdot Sc^{0,33}$ EDĚ

$Sh_{PCF} = 0,0029\, Re_T^{2,3} \cdot Sc^{0,33}$ EDĚ R

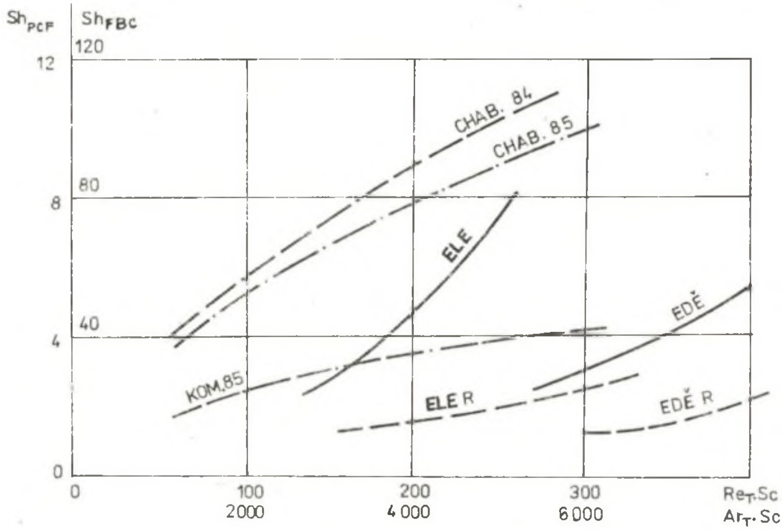

Fig. 11. Dependence of Sherwood number on the product $Ar_T \cdot Sc$ (for FBC) and on $Re_T \cdot Sc$ (for PCF). "R" indicates the boilers which have been reconstructed

Rys. 11. Zależność liczby Sherwooda od produktu $A_{rT} \cdot Sc$ (dla FBC) oraz od $Re_T \cdot Sc$ (dla PCF); "R" wskazuje kotły, które zostały przebudowane

and on $Re_T \cdot Sc$ (for PCF). Correlation relations for mass transfer for fluidized-bed furnaces as well as for pulverized coal-fired furnaces are presented above the Fig. 11. These results are based on the values obtained during the measurements of the fluidized-bed boiler in the Heating Plant of Trmice (using various kinds of coal - CHAB. 84, CHAB. 85, KOMOŘANY 85) and of the pulverized coal-fired boilers in the power plants in Ledvice and in Detmarovice.

Fig. 12 shows the dependence of NO_x amount in flue gas on nitrogen content (N^{daf}) and on oxygen content (O^{daf}) or on $(N^{daf} + \psi \cdot O^{daf})$ in volatile matter. The coefficient ψ 0,1-0,12 is dependent on fuel and its structure.

Curve 3 relates to fluidized-bed furnaces if criterion of aerodynamics defined in the case of fluidized-bed furnaces by the relation

$$Ka = \frac{1}{n} \sum_{0}^{n} \frac{d(Sh)_i}{d(Ar_T \cdot Sc)_i}$$

equals 0,005-0,016. The NO_x emissions of fluidized-bed boiler in the Heating Plant of Trmice are minimum (0,01-0,06 vol.%).

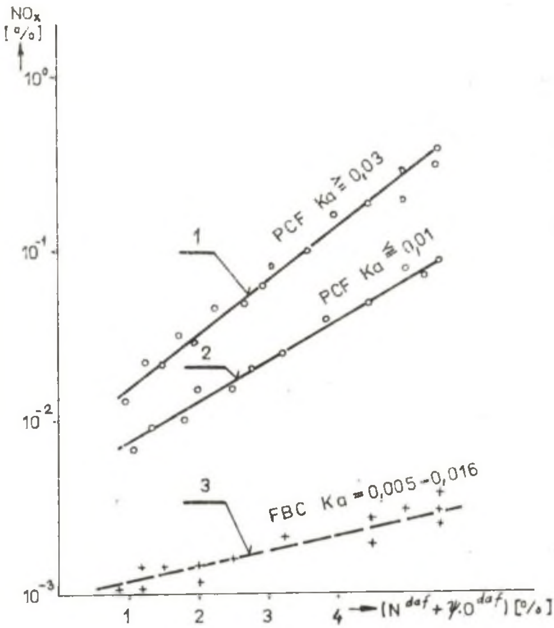

Fig. 12. Dependence of NO_x quantity in flue gas on nitrogen content and oxygen one in volatile matter

Rys. 12. Zależność ilości NO_x w gazie kominowym od zawartości azotu i tlenu w częściach lotnych

Curves 1 and 2 refers to pulverized coal-fired boilers, curve 1 relating to pulverized coal-fired furnaces of 100-500 MW_e blocks with original aerodynamics of combustion. In this case the criterion of aerodynamics expressed for pulverized coal-fired furnaces by the following relation

$$Ka = \frac{1}{n} \sum_{0}^{n} \frac{d(Sh)_i}{d(Re_T \cdot Sc)_i}$$

equals 0,03. Curve 2 refers to same furnaces which have been reconstructed and therefore their aerodynamics has been improved and Ka = 0,01. Emissions of nitrogen oxides have been reduced in this case to 1/3 - 1/5.

Fig. 13 shows dependence of NO_x quantity in flue gas on nitrogen content (N^{daf}) and oxygen content (O^{daf}) in volatile matter for fluidized-bed furnaces and for pulverized coal-fired furnaces with additive dosing (limestone stoichiometry Ca/S = 1,3). If we compare these curves to those in Fig. 12, it becomes evident that NO_x emissions are twice or three times lower if additive dosing is applied. We can say that even the quantity of NO_x emissions from pulverized coal-fired furnaces correspond with required international standards (curve 2: furnace with the improved aerodynamics Ka = 0,01).

The diagram in Fig. 14 depicts dependence of NO_x quantity in flue gas (vol. %) on the criterion of combustion aerodynamics Ka. Area 1 refers to the pulverized coal-fired furnaces of asymmetric shape, with stream burners, area 2 for pulverized swirl burners and area 3 for fluidized-bed furnaces.

The course proves that by diminishing the value of the cirterion Ka and therefore by improving aerodynamics of combustion NO_x emissions are reduced to 1/2 - 1/7.

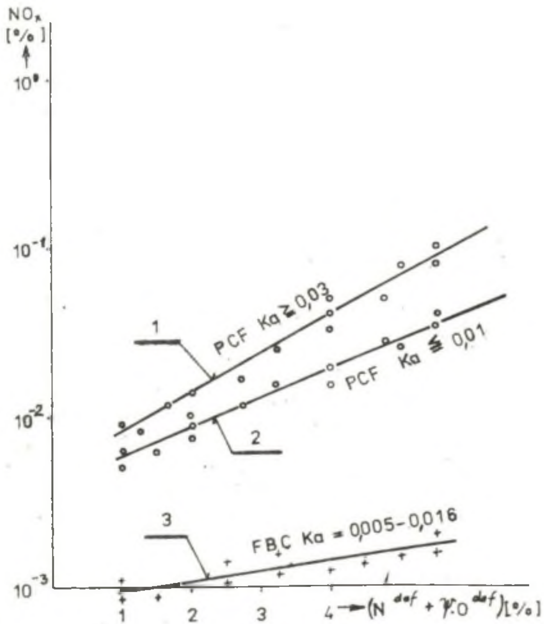

Fig. 13. Dependence of NO_x quantity in flue gas on nitrogen content and oxygen one in volatile matter-operation with dosing of an additive

Rys. 13. Zależności ilości NO_x w gazie kominowym od zawartości azotu i tlenu w częściach lotnych - obsługa z dozowaniem dodatku

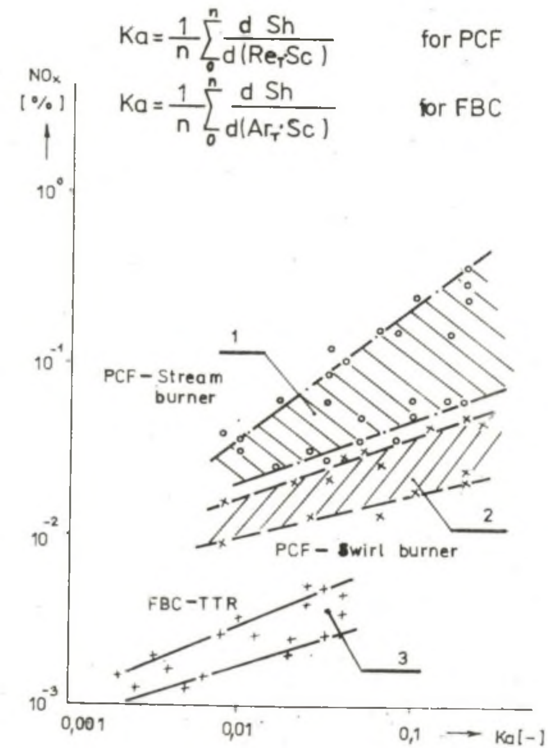

Fig. 14. Dependence of NO_x quantity in flue gas on the criterion of aerodynamics of combustion (Ka)

Rys. 14. Zależność ilości NO_x w gazie kominowym od wskaźnika aerodynamiki spalania (ka)

6. CONCLUSIONS

The fluidized-bed boiler of 19 MW_{th} output installed in the Heating Plant of Trmice designed by the Department of Energetics is a typical kind of one-stage atmospheric boilers with bubble fluidized bed.

During the testing of this boiler brown coal with heating value 5,25-18,8 $MJ.kg^{-1}$ having ash content 22-56%, sulphur content 1,2-6,2% was burnt. The output changed in range from 22 to 100%. The combustion efficiency increased to the value higher than 96% while SO_2 removal efficiency without additive was kept at 40% and with additive (molar ratio Ca/S of 1,2-1,8) was maintained at the value exceeding 80%. The separation efficiency of fly ash in both cases was 99,8%. The reduction of NO_x emissions was significant as well and it achieved the values 30-34 ppm.

The NO_x values obtained during the measuring are much lower than those offerred oby foregin manufacturers of fluidized-bec boilers, e.g., circulating fluidized-bed boiler produced by the Swedish firm Gotaverken Energy Systems AB in cooperation with the West German firm Thyssen has the NO_x concentration in flue gas from 84-105 ppm. A similar boiler manufactured by the French firm Stein (system Lurgi) emits in the air from 100-300 ppm of NO_x. The NO_x emissions of the pressurized fluidized-bed boiler produced by the Swedish firm ASEA are below 400 ppm.

The obtained values of harmful emissions testify the influence of thermokinetics of combustion on the toxic matter formation and binding (first of all SO_2, NO_x and toxic metals), which should be the subject of further research in the field of transfer phenomena in the fluidized beds of boilers using inferior low value solid fuels with high sulphur and ash content.

This is one of the ways leading to the diminishing of the negative influence exerted by energetics on the environment and therefore one of the ways of preserving favourable natural environment.

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Recenzent: Prof. dr hab. inż. Ludwik Cwynar

Wpłynęło do redakcji w marcu 1988 r.

PRZEPŁYW CIEPŁA I MASY W PALENISKACH FLUIDALNYCH
I ZMNIEJSZENIE EMISJI SZKODLIWYCH CZYNNIKÓW

S t r e s z c z e n i e

W artykule zwrócono uwagę na celowość stosowania palenisk fluidalnych z uwagi na obniżoną emisję toksycznych składników spalin.

Podano wyniki badań eksperymentalnych w formie zależności Sh = f(Re) przeprowadzonych na palenisku fluidalnym zabudowanym w kotle płomieniowym.

Szczegółowo przedyskutowano wyniki badań emisji NO_x, SO_x zmierzonych także na drugim obiekcie. Porównano je z uzyskanymi w innych paleniskach. Przedstawiono wpływ ilości azotu, tlenu, części lotnych i wskaźnika aerodynamiki paleniska oraz addytywów na ilość wytwarzanych tlenków azotu.

ПРОХОД ТЕПЛА И МАССЫ ВО ФЛЮИДНЫХ ТОПКАХ
И УМЕНЬШЕНИЕ РАДИАЦИИ ВРЕДНЫХ ВЕЩЕСТВ

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В статье обращено внимание на целесообразность применения флюидных топок в виду на пониженную радиацию токсических элементов сгорания. Даны результаты экспериментальных исследований в форме зависимости Sh = f(Re) проведенных во флюидной топке жарового котла. Детально оговорены результаты исследований радиации NO_x, SO_2 измеренных также на другом объекте и сравнены с результатами полученными в других топках. Представлено влияние количества азота, кислорода, летучих частей а также аэродинамического показателя топки и аддитивов на количество полученных окисей азота.