

DIAGNOSTIC METHODS OF COMBUSTION IN THE FLUID BED BOILERS

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(Received October 2005, accepted January 2006)

ABSTRACT

The articles gives a summary of measurement units that are used for diagnostic measurements of fluid boilers combustion channels. During the verification process VŠB-TU Ostrava designed and tested various types of probes for temperature and velocity measurements, off-take of both gaseous samples of waste gases and solid particles samples. Taken results gives more detailed information about fluid layer behaviour for various fluid bed boiler types. Moreover they can be of use in case of boiler modifications or boiler operation improvements.

This article is based on the project GA 617 50 11 solving – „Combine combustion of coal and biomass in fluid bed boilers“.

KEYWORDS: coal, fluid bed boiler diagnostics, temperature measurement, pressure measurement, flow measurement, solid particles concentration, gas concentration, probes for measuring

1. INTRODUCTION

Since 1995 28 big fluid chambers of different conception and power output have been put into operation in the Czech Republic. All fluid chambers were constructed based on foreign experience, foundation, licence and engineering, if need be the chambers were builder up by foreign authorities. There was almost no experience with these types of chambers in the Czech Republic. During building up and trial process both operator and commonly designer and constructor of entire operation unit were gaining valued experience.

Every big project of energetical equipment is always preceded by trial measurements and measurements on smaller, pilot, trial or if need be model equipments. Due to expressive enlarging of scale some unexpected measuring equipment behaviour or problems must be taken into consideration.

Once big units are put into operation guarantee test must be done. The aim of the guarantee tests is to verify designed parameters. Physically expressed units are compared with reality. Apart from basic measurements there is number of other similar measurements of specific parts of equipment that might be initiated because of: manufacturer interest is to use the experience to improve or design new energetical measurement units operator interest is to both eliminate problems and improve economic figures of operation process

Many parameters of fluid chambers can be got from operating units by condition and surface monitoring, sampling and long-term statistic data evaluation. Computer simulation of operation process and using various simulation software might be another possibility how to get data. Operation combustion process simulation is very useful and valuable but has one big disadvantage. If marginal conditions are unknown or results are not verified by measurement of real operation data simulated results might be far away from reality.

The only fast method (not only the cheapest one) is to work with real data. That means to make measurements right in operation process. Physically expressed units thus can be supported by real measurement equipment behaviour.

The article indicates development and verification methods and mentions some apparatus equipment for determination of all-important and interesting measuring data mostly concerning boiler waste gases channels.

To make the measurements happen it had been necessary to design special measurement unit just for this single purpose. It means such a unit that manages measurements of various peculiarities of fluid boiler from the point of temperatures, flow velocity, solid waste concentrations, pressures etc. Described units and methods were tested in practise operation or were developed and modified based on former failures.

Table 1 Newly built up fluid boilers with circulating fluid layer in the Czech Republic

Place	Year	Type	Number	Output Tph	Producer	Fuel	Operating system
Třinec	1995	CFB	1	160	Lurgi	HC	ABB
	1997	CFB	1	160	(SES Tlmače)		Siemens
Poříčí	1996	CFB	1	250	Foster Wheeler	HC/BC	Siemens
	1998	CFB	1	250	(CNIM)	BC	
Tisová	1996	CFB	1	350	EVT (Vítkovice)	BC	Valmet
	1998	CFB	1	350	LURGI (SES Tlmače)	BC	Valmet
Zlín	1996	CFB	1	160	Babcock Wilcox ABB Alstom	HC	Honeywell
	2000	CFB	1	125	Lurgi (SES Tlmače)	HC	Honeywell
Komořany	1995 to 1999	BB Retrofil	10	125	Power Internat	HC	ABB-1x, Honeywell Foxboro-5x
Hodonín	1996	CFB	2	170	AEE Austria	Lignit, HC	Valmet
Ledvice	1998	CFB	1	350	ABB Alstom	BC	ABB
Olomouc	1998	Compact	1	190	Foster Wheeler (FORTUM)	HC, BC	Valmet
Štětí	1998	CFB Retrofil	1	220	Foster Wheeler	BC, BIO	Valmet
Ml.Boleslav	1998	CFB	2	140	EVT (Vítkovice)	HC	ABB
Kladno	1999	CFB	2	375	ABB Alstom	HC	ABB
Plzeň	1999	CFB	1	180	ABB Alstom	BC	

HC – hard coal, BC – brown coal, BIO – biomass, tph – tons steam per hour (tph)

Conclusions of this project might be useful to all energetics centers or producers and operators that want to verify operation data of fluid boiler waste gases and air channels.

Concerning diagnostical measurements from the point of single physical units it basically covers measuring of:

- fluid layer temperatures, furnace chamber temperatures, waste gases temperatures in additional surfaces up to waste gases boiler exit,
- waste gases velocity in furnace chamber and at furnace chamber exit to cyclones, in cyclones, at cyclone exit to II.duct and area of additional boiler surfaces,
- off-take of gaseous waste gases samples in all burning channels of boiler,
- off-take of characteristic samples of solid ash particles included isokinetic off-take to determine solid particles concentrations,
- approximate determination of heat transfers.

Choice of measuring points depends on producer demands or willingness of operator to prepare sufficient number of holes in suitable parts of boiler. If producer is interested in testing special

characteristics of operating equipment-measuring points are designed and prepared right way during construction process. If measuring holes are prepared additionally many problems and complications might pop up. Refractory drilling out is quite demanding job. On the other hand measuring holes removal and bringing lining to its former state condition is operator interest. Anyway both producer and operator is interested in gaining as much information as possible and they want measuring through sections to be as small as possible at the same time. Another limitation is fan width of membrane wall because tube bending for single application is extremely expensive. Measuring equipment must be adapted to all these circumstances so as taken data can be fully credible.

If all chosen and accesible characteristics are measured in details we can get enough information about fluid boiler operation qualities. Comparing measurable physical characteristics we can get real picture of functioning of each single technological part of fluid boiler and to make necessary modifications in construction design and technology of fluid boiler main parts.

2. TEMPERATURE MEASUREMENTS

From the point of absolute value temperature measurements in furnace chambers of fluid boilers can

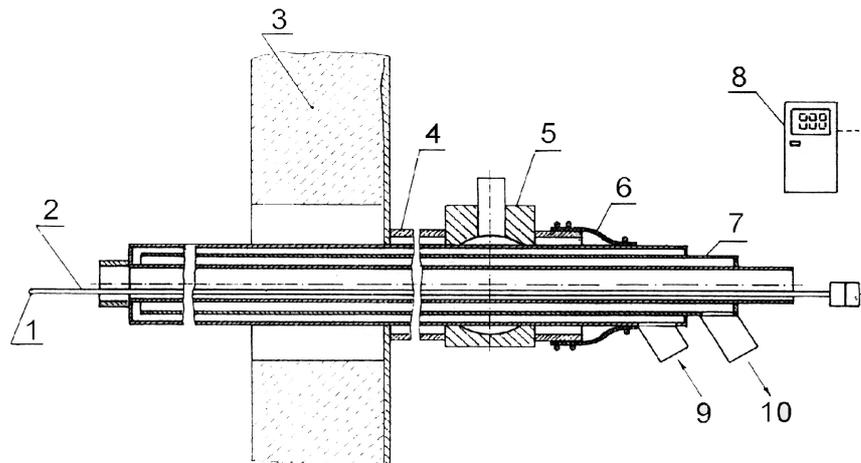


Fig. 1 Diagram of probe for temperature measurements in lower part of fluid layer
 1 – approx. 200 mm sticking out, 2 – thermocouple, 3 – boiler wall, 4 – input pipe, 5 – spheric valve DN 80, 6 – protective collar, 7 – cooled probe (for example $\phi 50 \times 5000$ mm), 8 – temperature indicator, 9 – water supply, 10 – water outlet

be divided into two basic groups. Concerning basic fluid layer formed mostly by ash particles or boilers with circulating fluid layer measured burning temperature might reach $800 \div 900$ °C and common thermocouple (for example type „K“) might be used for temperature taking.

On the other hand temperature of fluid layer of Ignifluid type boiler might reach $1200 \div 1250$ °C that might be for common thermocouple type their material possibility limit. Temperature taking is not only focused on fluid layer temperature but it also influences waste gases temperature taking in all parts of waste gases channels of boiler as well.

2.1. TEMPERATURE TAKING IN STATIONARY OR CIRCULATING FLUID LAYER

Mostly it covers measurements up to temperature limit 900 °C so as common jacketed „K“ (Ni-NiCr) type thermocouple might be used. Due to fact that thermocouple temperature during operation process reaches temperature of average fluid layer temperature. Therefore thermocouple must be placed in solid heat-proof pipe or cooled probe. During verification measurements jacketed thermocouple of outside diameter 6mm was tested. The thermocouple was placed in cooled probe of operation length 4m, inside diameter 20mm and outside diameter of cooled jacket 50mm. During these measurements thermocouple sticks out of probe approximately 20mm. For intensive heat transfer the length of sticking out is sufficient. Temperature drop due to heat conduction through thermocouple jacket to cooled probe is irrelevant. Diagram of probe for temperature measurements in lower part of fluid layer is illustrated in Fig. 1.

Some obstacles might be with inserting probe to lower layer of boiler. If there is excess pressure in lower part of fluid layer there is a danger of fluid layer outflow when handling with probe and valve. Method of inserting probe to boiler through spheric valve DN 80 was tested during measurements. Spheric valve is mobile even if it is clogged and choked with inert material. Hot thermocouple end of diameter 6mm was stucked out of probe 200mm after inserting of cooled probe to fluid layer. Probe in boiler was sufficiently sealed with inert material, fluidised air (waste gases) escape out of boiler was not apparent during measurements. Anyway using protective collar is highly recommended.

2.2. TEMPERATURE TAKING IN FURNACE CHAMBER PARTS WITH CIRCULATING FLUID LAYER APPROX. 2M ABOVE FURNACE GRATE AND HIGHER ON

Fluid layer at cyclone input and output is considerably thin in upper parts above furnace chamber grate. Dynamic effects of waste gases and solid particles are so small that enables thermocouple to be hold in heatproof probe or cooled probe for short time. Jacketed „K“ type thermocouple of outside diameter 3mm was used for this measurement. The thermocouple was inserted to water-cooled cylindrical probe of operation length approx. 5m. Internal excess pressure in upper part of furnace chamber with circulating fluid layer is approx. $50 \div 500$ Pa. It depends on boiler power output. If measuring hole to boiler is small enough mineral felt might be used to seal the tube in measuring hole. It is necessary to use gloves and face shield to manage this operation safely. Diagram of probe is illustrated in Fig. 2.

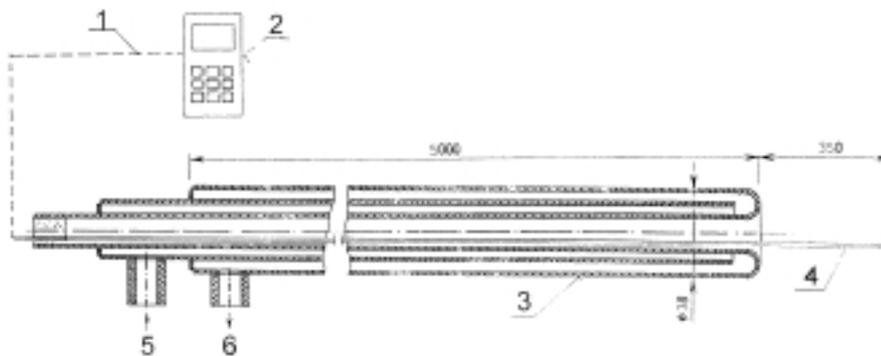


Fig. 2 Diagram of temperature taking using cooled probe – not-shielded thermocouple connexion (approx. 2m in furnace above grate bottom) inclusive
 1 – compensation line, 2 – digital temperature indicator, 3 – cooled cylindrical probe, 4 – jacketed thermocouple of ϕ 3 mm, 5 – water supply, 6 – water outlet

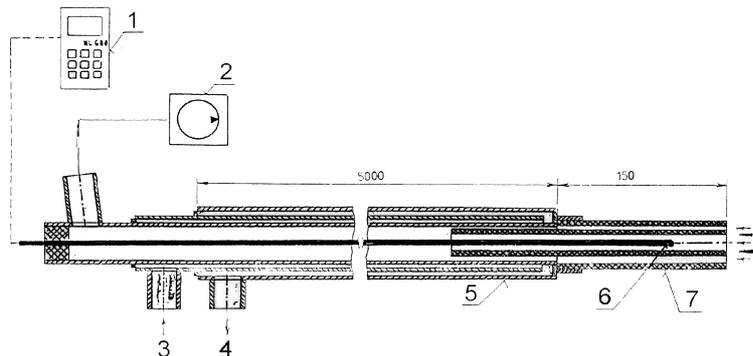


Fig. 3 Diagram of exhaustion pyrometer for temperature taking in II. boiler duct
 1 – digital temperature indicator, 2 – exhauster fan, 3 – water supply, 4 – water outlet, 5 – cooled cylindrical probe, 6 – thermocouple, 7 – double-jacket ceramic head

2.3. TEMPERATURE TAKING IN II. BOILER DUCT – EXHAUSTION PYROMETER

Temperature taking in II. boiler duct happens in area of water and air superheaters, reheaters and heaters. It covers areas where heat-exchange areas of surface temperature $100 \div 500$ °C lower than waste gases temperatures in entire point are very close to waste gases measured by thermocouple. If common thermocouple placed in waste gases is used we get error data about temperature because due to heat radiation exchange between hot thermocouple end and quite cold surface temperature of heat-exchange areas taken temperature is lower than the real one.

Interval for taken error temperatures is $30 \div 80$ °C. It depends on waste gases temperature, waste

gases velocity and distance between thermocouple hot end and cold areas. Measuring error can be eliminated by using exhaustion pyrometer. Diagram of exhaustion pyrometer used for temperature measurements in entire areas is illustrated in Fig. 3.

Thermocouple hot end is placed in internal tube of shielding head. Head might be double-jacket ceramic (made of Al_2O_3) one managing high temperature taking. Thermocouple is fixed in front part of head so as not to be touching inside walls of head. Waste gases are exhausted by internal probe tube with such intensity that waste gases velocity in internal tube around thermocouple hot end reaches values approx. $30 \div 50$ m.s⁻¹. Taking into consideration such flow intensity almost all heat is

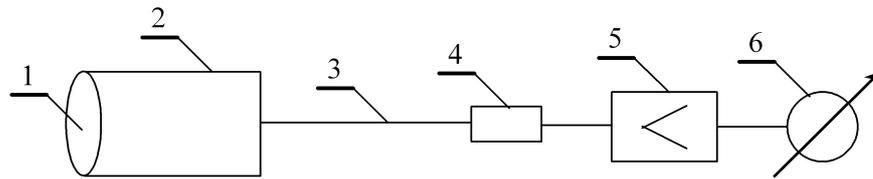


Fig. 4 Diagram of optical pyrometer
 1 – input lens, 2 – optical connector, 3 – light-conductive fibre,
 4 – photodiode, 5 – preamplifier, 6 – measuring instrument

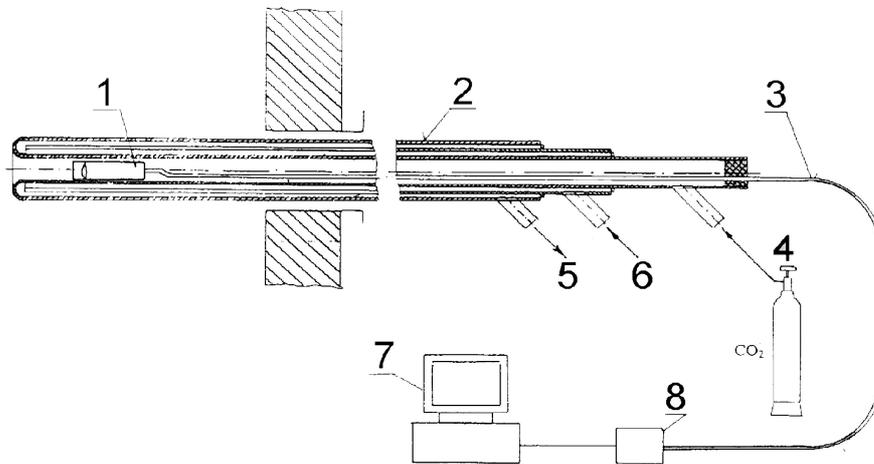


Fig. 5 Diagram of placing optical pyrometer in cooled probe
 1 – optical scanner, 2 – cooled probe, 3 – light-conductive cable, 4 – inert gas, 5 – water outlet, 6 – water supply, 7 – computer, 8 – photodiode

transferred to thermocouple thanks to convection. Radiation component is totally suppressed. Taken temperature corresponds with reality.

2.4. TEMPERATURE TAKING OF 1000 ÷ 1250 °C HOT SLAGGING FLUID LAYER

Compare to stationary or circulating fluid layers slagging fluid layer has these different characteristics:

- significantly higher waste gases and solid particles temperature,
- significantly bigger dynamic effects of fluidized fuel and ash particles,
- fluidization medium contains bigger volume of CO concentration (ordinally per cents).

For this purpose jacketed „K“ type thermocouple of outside diameter 6mm is satisfactory. We must be aware of fact that material limit of usage of this thermocouple is up maximum temperature 1200 °C.

Higher the temperature is more likely the thermocouple is to be damaged.

Using „S“ PtRh10-Pt and „R“ PtRh30-PtRh6 type thermocouple is not recommended. Despite the fact that these thermocouples manage temperatures up to 1800 °C platinum carburization happens due to reducing atmosphere and platinum sponge results up from. Thermocouple becomes brittle and breaks down to pieces.

2.5. TEMPERATURE TAKING USING OPTICAL PYROMETER PLACED IN COOLED PROBE

To measure flame temperature pulsation in boiler optical pyrometer was developed at the Faculty of energetics. This equipment is able to take temperature and temperature changes with quite high sampling frequency (ordinally up to numbers of kHz). Non-contact temperature taking is based on radiation of hot bodies. Diagram of pyrometer is illustrated in Fig. 4.

Table 2 Average temperatures in single measuring points in cyclone

Measuring areas	Measuring line	Measuring points	Temperatures (°C)		
			Boiler output 350tph	Boiler output 280tph	Boiler output 140tph
Cyclone waste gases input + 32000 m	A	1	859	852	-
		2	-	-	865
		3	893	884	888
	A - middle		876	868	876
Cyclone waste gases output + 43200 m	B	1	-	830	831
		2	861	865	871
		3	863	847	852
		4	863	856	864
		5	878	870	875
B - middle		866	854	859	
Boiler II duct beginning at level 41500 m	C	1	795	782	783
		2	796	786	789
	C - middle		795.5	784	786
Cyclone cylindrical part + 28000 m	D	1	888	856	851
		2	871	844	860
		3	876	865	867
		4	884	874	878
		D - middle		879.8	859.8
Cyclone cylindrical part + 23500 m	E	1	873	844	865
		2	860	811	864
		3	852	861	868
		4	834	824	845
		5	886	875	883
E - middle		861	843	865	
Cyclone cylindrical part + 22200 m	F	1	880	870	850
		2	882	876	860
		3	841	872	869
		4	857	814	835
		5	885	876	859
		F - middle		869	861.6
Cyclone bottom cylindrical part + 21200 m	G	1	860	860	860
		2	860	860	870
		3	864	873	880
		4	834	851	878
		5	830	877	878
		G - middle		849.6	864.2
Cyclone chute beginning + 19200 m	H	1	884	869	885
		2	887	846	886
		3	883	871	875
	H - middle		884.7	862.0	882.0

Pyrometer construction enables total radiation measuring the way that single optical parts or electronic optics behave as elements with limited spectral transmittance. Thus simple pyrometer construction of sufficient accuracy can be got. Measured radiation impinges on input lens 1 that focuses radiation to optical connector face 2. Connector is settled on PCS fibre 3 250/380. Thus it is possible to transfer radiation from the point of scanning to the point of data processing where

photodiode PIN 4 with linear characteristic is attached to. Photodiode is further linked to preamplifier 5 and measuring instrument 6.

Length of used cable might be up to hundreds meters. Every measurement requires calibration to known heat supply because volume of measured energy depends both on gap between lens and measured supply and preamplifier sensitivity setting and optical cable length. Greyness rate approach to one for most of gaseous environments. Therewise

output signal changes gives evidence of processes happening in measured radiator.

Diagram of placing optical pyrometer in cooled probe is illustrated in Fig. 5. It is the way that it is possible to measure both absolute temperature rate and very fast fluid layer temperature changes (temperature pulsation).

Probe mouth and lens at optic cable input must be protected against solid particles and hot gas penetration. It might be managed by probe air or inert gas blow-through. Air can be used during measurement process in oxidizing or slightly reducing atmosphere. At areas of highly reducing atmosphere inert gas must be used so as temperature field in probe mouth surroundings was not affected by oxidation.

- Figs. 6a-6c illustrate example of temperature field measured in fluid boiler furnace chamber of output 160 tph. It is obvious that temperature field is not completely homogeneous and changes in accordance with conception and shape of boiler combustion chamber, fuel supply, air ratio setting and fuel type. Picture shows horizontal through sections of combustion chamber at height.
- Fig. 7 shows results of temperature taking in waste gases input channels to boiler cyclone 350 t/h steam. There are two not cooled waste gases channels with ceramic lining. Measurements were done for boiler output 350, 280 and 140 tph.
- Fig. 8 illustrates temperature field in bottom part of boiler cyclone 350t/h. Measurement followed unpleasant boiler failure. Cyclone was choked with inert material from fluid layer. Measurements were done for boiler output 350, 280 and 140 tph. To maintain cyclone failure there were drilled out releasing holes to steel jacket and ceramic lining. These holes were later on used for diagnostical measurements. Measurements were continuous with thermocouple data recording. Average measured temperature data are shown in Table 2.
- Fig. 9 illustrates comparison of average temperatures taken at input using net measurement method and temperatures taken with operation thermometer with abrasion protection.

Based on data taken during temperature measurement process some conclusions might be derived from.

Temperature distribution at height of fluid layer is affected by followed characteristics:

- fuel type according volatile matter content - More reactive fuel is shorter is combustion time,
- fuel granulometrics - Finer particles has got bigger reactive surface but fine particles are more quickly blown out as well. With Upward direction temperature rises. On the contrary when there is small ratio of fine particles temperature drops down,

- control of ratio of primary and secondary air (after-combustion air) or waste gases control,
- waste gases temperature at furnace chamber output is not stable. It varies in accordance with time and fluid chamber output. It is highly probable that there are unevennesses due to flow of solid particles downcurrents and upcurrents in furnace chamber. This process has no acceptance. It is distinctive for specific combustion chamber size, configuration and boiler output. Temperature changes are proportionally direct and correspond with pressure pulsations in upper part of combustion chamber and cyclone,
- temperature field in not cooled cyclone is not homogeneous. For majority outputs highest temperatures are usually by cyclone walls. On the contrary temperatures at cyclone axe are $10 \div 30$ °C lower. These differences happen more likely due to intensive off-combustion of combustible element residues in circulating solid phase. Difference between velocity of solid and gaseous phase causes faster off-combustion. Important area of off-combustion is chute under cyclone. There is high density of solid phase there and thus fluidization air under cyclones causes faster off-combustion of combustible particles in circulating mass,
- process of putting boiler 350 tph into operation from cold state was monitored from hot start. Fig. 9 illustrates both course of the putting into operation when thermocouple of ϕ 3 mm was used at the end of combustion chamber (data taken by VŠB- TU Ostrava) and temperature taking in combustion chamber using common operation thermometers. Measurement proved the fact that operation thermometer protection against abrasion is sufficient. Consequently there is high heat inertia and operation thermometers are not able to illustrate credibly real temperatures during course of putting boiler in operation. Differences between operation measurements and real temperature were up to 150 °C in some moments. Concerning boiler 350 tph modification of thermocouple with effective abrasion protection but with low heat inertia constant was suggested. Suggested modification is illustrated in Fig. 10.

3. THROUGH FLOW MEASUREMENTS

3.1. MEASUREMENT METHODS

Waste gases amount flowing through boiler might be calculated with high accuracy based on taken amount of air supply, element composition of fuel, boiler output, waste gases temperature and analysis of waste gases gaseous components of CO and O₂. Average calculated velocities in single boiler through sections can be got easily. From this point measurements are not necessary. Different is the

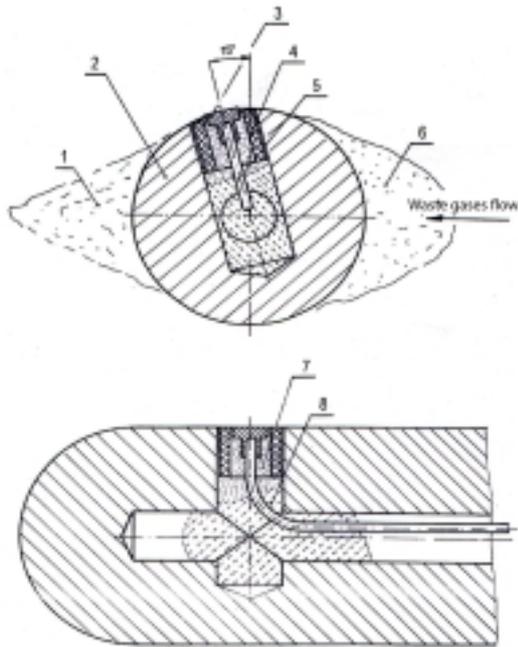


Fig. 10 Suggested modification of thermocouple with low heat constant for temperature measurements at cyclone input
1 –deposit on wake side of protection, **2** – thick-wall protection, **3** – protection of thermocouple hot end, **4** – ceramic tubule, **5** - thermocouple ϕ 3 mm, **6** – deposit on approach side of protection, **7** – ceramic cotton, **8** – refractory concrete

situation in velocity distribution in single parts of fluid chamber where significant unevennesses can be expected. Several measurements proved this effect. It must be mentioned that concerning velocity measurements it means always air flow measurements as well.

From the point of fluid boiler characteristic parts and fluid layer characteristics measurements can be divided into following groups:

- velocity measurements in area of stationary fluid layer,
- velocity measurements in fluid boiler furnace,
- velocity measurements at cyclone output and inside of cyclone,
- velocity measurements in additional boiler ducts.

3.1.1. VELOCITY MEASUREMENTS IN AREA OF STATIONARY FLUID LAYER

Fluidization medium flow velocity through steady fluid layer depends on volume of medium supply, waste gases volume, layer temperature, fluid layer granulometrics and fluid layer expansion that determines fluidization intensity rate. Talking about fluidization velocity professional literature means so called off-layer velocity. It means that flow velocity above fluid layer or velocity that might be in entire point if fluid layer particles were excluded is taken into consideration. Real velocity that flows alongside of each single particle is always higher than off-layer velocity. If any measuring instrument is inserted in fluid layer final results would be always affected and distorted.

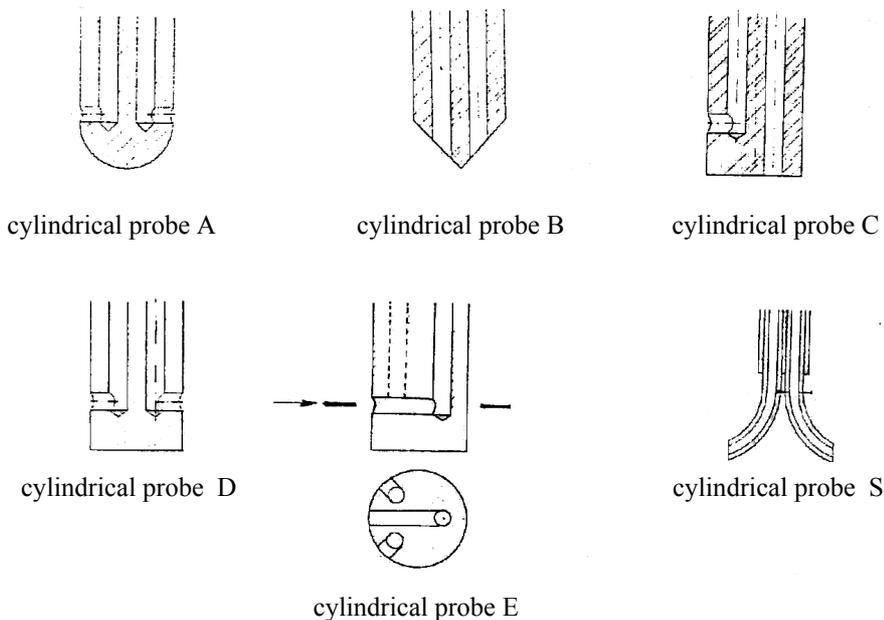


Fig. 11 Cylindrical probes of various types and „S“ probe

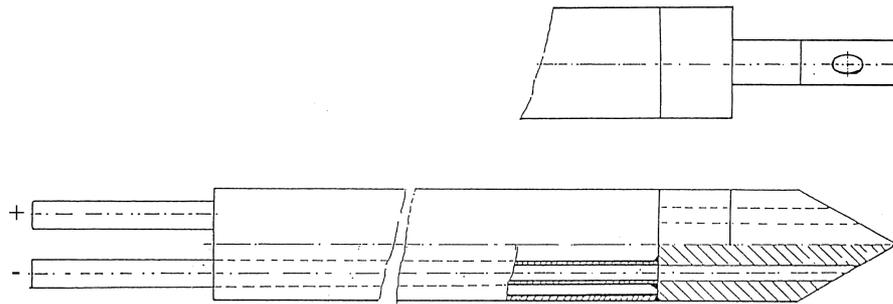


Fig. 12 Diagram of wedge probe

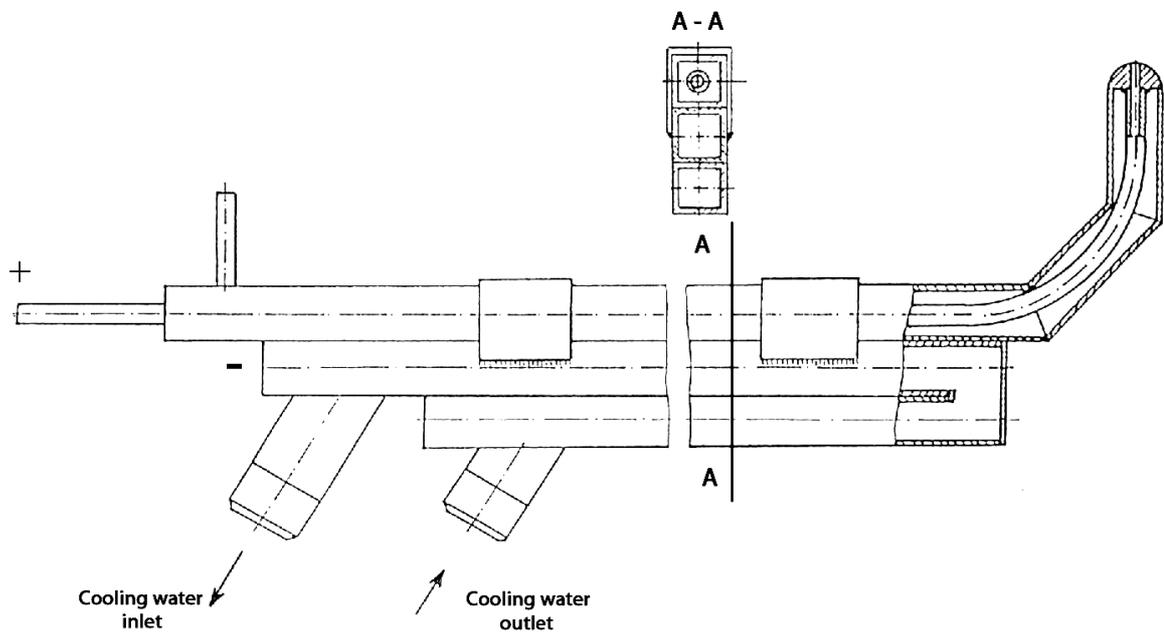


Fig. 13 Diagram of probe for velocity measurements in II. duct and additional surfaces of boiler

3.1.2. VELOCITY MEASUREMENTS IN FURNACE OF FLUID BOILER WITH CIRCULATING LAYER OR ABOVE STATIONARY FLUID LAYER.

There is gradual fluid layer particles blow-off above stationary fluid layer. Especially concerning boilers with circulating fluid layer. Fluid layer density varies at height. Values are in interval from tens kg.m^{-3} up to $0.1 \div 0.3 \text{ kg.m}^{-3}$ at fluid furnace output. Choice of suitable measurement equipment depends on solid particles density and size. If probes of Prandtl tube or Pitot tube types are used off-takes are quickly choked with solid phase and measuring process must be interrupted. Possibility is to use these velocity probes with bigger holes where self-cleaning effect would be initiated due to solid phase flow velocity drop and gravitation.

3.1.3. VELOCITY MEASUREMENTS AT CYCLONE INPUT, INSIDE OF CYCLONE AND CYCLONE CHUTE

Taking into consideration relatively lower concentration level of solid particles it is possible to use common measuring instruments of Prandtl or Pitot tube types. However these measuring instruments have a disadvantage of necessity of drilling big holes to insert a probe in boiler. Required size of hole is usually $150 \div 200 \text{ mm}$. As for net measuring sufficient number of holes of such size highly affects boiler ceramic lining. Client wants the hole to be as small as possible. Usually measuring holes can be of diameter $40 \div 60 \text{ mm}$. Therefore only cylindrical probes, „S“ probes and wedge probes out of all types of velocity probes might be used in this case.

However presence of solid phase of high concentration exclude using cylindrical and „S“ probes because they are to be very quickly choked.

Diagram of velocity probes of various types is illustrated in Fig. 11. Design of these probes differs in placing the holes for static or differential pressure off-take. If cylindrical probe coefficient is to be equal to 1 it is necessary to drill off static pressure off-takes at angle 43° to total pressure off-take. These probes are used by VŠB - TU Ostrava. Due to rapid choking of cylindrical probe off-take holes not-ooled wedge probe was used for this measurement. Diagram of wedge probe is illustrated in Fig. 12.

Using wedge probe or any other probe but Prandtl or Pitot tube one it is essential to do probe calibration to find out dependence of differential pressure Δp on air flow velocity. Calibration for taken velocity interval must be done for each single probe. Important characteristic is also in this case the matter of flow velocity vector turning off at axe of total pressure off-take or differential pressure excess branch.

Wedge probe used for measuring in fluid boiler is of outside diameter 20mm and operation length approx. 4m. It is made of steel ČSN 17 153. Despite initial apprehension of negative effect of material stress due to fast temperature changes probe proved to be good. During measurement process cleaning up the probe must be done. Off-take holes must be blowed through. Measurements were done for horizontal probe position. Vertical position would be better.

Velocity measurements in chutes under cyclones is very demanding because many solid particles trapped in cyclone flow alongside walls. Such a fact makes using common measuring instruments impossible. Due to dynamic effect of falling particles there is waste gases vertical flow alongside vertical chutes. On the contrary there is upward fluidization air (waste gases) flow from fluid closures on majority part of through section in middle part of chute.

Output waste gases flow from cyclones is highly swirled in agreeing rotation of waste gases in cyclone. Waste gases swirling results in significant velocity field unevenness however it is not shown until it reaches additional areas.

3.1.4. VELOCITY MEASUREMENTS IN II. DUCT AND IN ADDITIONAL BOILER SURFACES

Prandtl tube can be advantageous to be used in case waste gases temperature is lower than 800°C . Measuring holes in membrane wall might be made only in flag. Tube curving does not need to be done.

Specially designed Prandtl tube with cooled supporting middle part was used for measurement of waste gases velocity in II. duct of fluid boiler 350 tph. Diagram of probe is illustrated in Fig. 13.

Example of velocity measurement in cyclone input channels cyclone of boiler 350 tph is shown in Fig. 14. Measurements were done for boiler output

350, 280 and 140 tph. Measurement results proved the fact that velocity field is highly affected by holes shape and their placing at waste gases exit at boiler combustion chamber. Channel geometry to combustion chamber is of fundamental influence. If there is lower output material sedimentation as a deposit at the channel bottom is apparent.

4. OFF-TAKE OF WASTE GASES ELEMENTS FROM BOILER WASTE GASES CHANNELS

Off-takes of waste gases gaseous elements from boiler waste gases duct can be divided into three groups:

- off-takes of waste gases samples from bottom part of fluid layer,
- off-takes of waste gases samples from boiler furnace chamber, cyclones and cyclones link channels,
- off-takes of waste gases samples from boiler II. duct up to exit to chimney.

4.1. BASIC PRINCIPLES FOR OFF-TAKE OF WASTE GASES GASEOUS SAMPLES FROM WASTE GASES DUCTS

To monitor fluid chamber operation process O_2 , CO , CO_2 , NO_x , SO_2 measurements can be taken into consideration. Other elements are usually monitored as far as exit from separator of solid particles in front of chimney.

To take emission samples probes with off-take routes heating or cooling or probes where temperature of off-take has no affect on final representative sample are most frequently used

4.1.1. OFF-TAKES OF WASTE GASES GASEOUS SAMPLES FROM STATIONARY FLUID LAYER OR FROM BOTTOM PART OF FLUID CHAMBERS WITH CIRCULATING FLUID LAYER

Fig. 16 illustrates cooled off-take probe that might be used to take waste gases gaseous samples (but SO_2). Probe has got identical construction as it is used for temperature taking. Therefore there are same principles valid for inserting probe into boiler fluid as it is described at *chapter 2*. Measurements found out that due to excess pressure of air (waste gases) in fluid layer and waste gases exhaustion it is necessary to protect front part of probe with protection guard of size approx. 2-3mm. Such a grid enables particles to penetrate to internal tube of probe and thus protect the probe against choking. Special tight radial fan linked to probe with rubber hose is used to exhaust the particles. During exhaustion gas is rapidly cooled down (from 800° to approx. 30°C) in cooled probe so as no other waste gases flammable elements reaction happens. Gas sample is then taken off to be analysed in mobile laboratory. Method went through trial operation process and fully proved to be good.

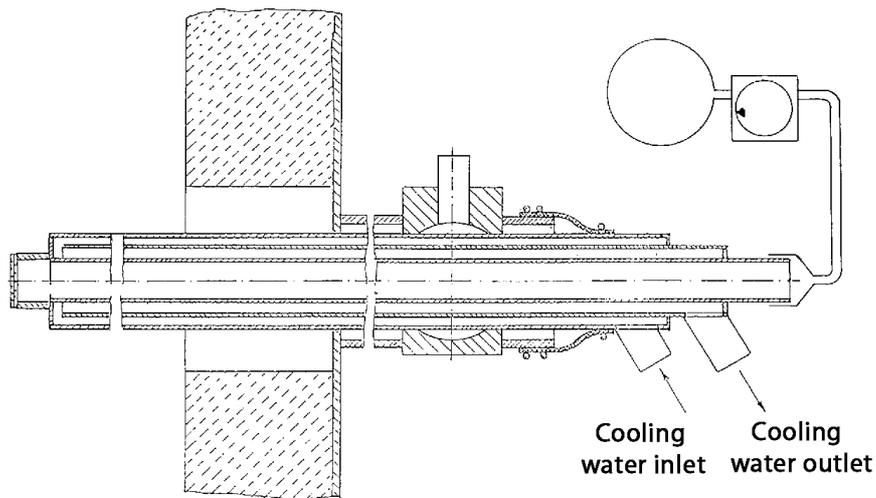


Fig. 15 Diagram of probe for waste gases gaseous samples off-take from fluid layer

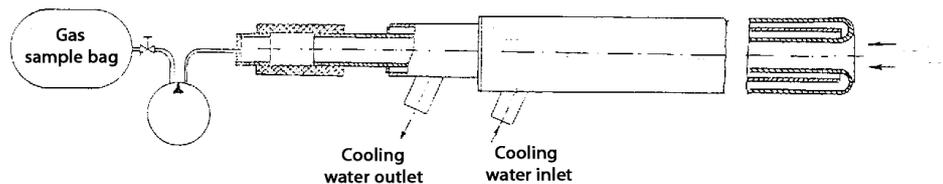


Fig. 16 Diagram of probe for waste gases gaseous samples off-take from furnace of fluid boiler

4.1.2. OFF-TAKES OF GASEOUS SAMPLES FROM FURNACE OF FLUID BOILER, CYCLONE AND CYCLONE LINKING CHANNELS

It is always recommended to use cooled probe to take samples. Diagram of such a probe is illustrated in Fig. 16. Probe is linked to tight radial exhaustion fan with rubber hose. Gaseous sample might be taken to off-take bags made of PE and thus can be distributed to laboratory for further analysis. Such an organisation of off-takes makes job more effective and helps to make net measuring at all fluid boiler through sections very quickly. Due to lower solid particles concentration it is necessary to protect probe mouth with protection grid. In case it is choked it is enough if probe is blown-through with compressed air.

4.1.3. OFF-TAKES OF WASTE GASES FROM II. DUCT OF FLUID BOILER IN AREA BETWEEN ADDITIONAL SURFACES AND AT BOILER OUTPUT

Mostly it covers waste gases off-takes of temperature safely below 800 °C. Due to such a temperature majority of taken gaseous sample is not able to oxidize quickly and thus it is possible to use off-take tube made of steel (e.g. 17153) or sintered corundum Al_2O_3 . To set concentrations (e.g. SO_2)

off-take channels must be heated up during sample taking operation so as reaction with water does not happen.

4.2. EXAMPLE OF SOME MEASUREMENT RESULTS - O_2 , CO A NO_x CONCENTRATION IN COMBUSTION CHAMBER OF FLUID BOILER

Figure 16 illustrates off-take probe used in detailed net measuring of O_2 concentration in boiler combustion chamber of output 125 tph of steam. There were convection heat-exchange areas in upper part of combustion chamber.

Measurement was taken at height level +13.4 m, +28 m a +32 m for two boiler output regimes (90 % a 60 % Nominal output).

Results of O_2 concentration measurements are shown at Figs. 17a – 17b.

As it is shown in Fig. 6c calculation of average concentration was calculated at height of fluid layer. O_2 average concentrations in every single point are illustrated in Fig. 18. It is interesting that picture is similar to temperature distribution in fluid layer where areas of high temperatures has got lower content O_2 and contrariwise.

Net method of measuring O_2 , CO a NO_x concentration was used. Measurement was taken in

measuring holes in the middle of sidewalls of combustion chamber. Results of CO a NO_x concentration measurements for output 90 % Nominal output are illustrated in Fig. 19. Results of CO a NO_x concentration measurements for output 60 % Nominal output are illustrated in Fig. 20.

Based on results of measurement we can say that there is intensive suppression of NO_x originating in reducing area. However NO_x originating is getting higher in areas of secondary and after-combustion air supply. CO concentration has got expected course. Fast lowering happens if after-combustion air supply is gradual.

4.3. O₂ CONCENTRATION MEASURING IN FLUID BOILER CYCLONE

Due to fluid boiler 350 tph cyclone failure diagnostical measurements was done inside of cyclone. Mesuring points corresponded with temperature measuring points in this area. Fig. 16 illustrates off-take probe used in this measurement. Results for three different boiler output levels are shown in Fig. 21.

Exhibit proves apparent fact that higher concentration of solid phase goes hand in hand with lower O₂ concentration as it is in combustion chamber. Lowest values are taken for nominal boiler output in chute under cyclones. On the contrary if output is minimalised there is apparent excess of fluidization air in chute under cyclone.

O₂ concentration field is not homogeneous. Effect of unevenness is already apparent at cyclone input.

5. SOLID PARTICLES CONCENTRATION MEASUREMENTS IN BOILER WASTE GASES CHANNELS

5.1. BASIC METHODS TO DETERMINE SOLID PARTICLES CONCENTRATION AND FLUID LAYER DENSITY

To determine solid particles concentration in airflow czech norm ČSN ISO 9096 is obligatory. It is gravimetric detrmiation of concentration based on isokinetic off-take of solid particles from airflow. Basic principles that the above-mentioned norm covers can be applied to gravimetric measurements in boiler. If both solid and gaseous flow direction is identical such a method can be used.

Concerning fluid chambers it is aim to determine solid particles concentration in lower part of fluid layer and in fluid boiler furnace. Therewise isokinetic off-takes cannot be taken into concideration because airflow direction is frequently different from particles flow direction. Moreover fluid layer in furnace is not usually homogeneous and its density is variable at through sections. Due to bigger and smaller (heavier and lighter) particles separation fluid layer density varies at furnace height as well. Concerning density for lower part it is interval 500 ÷ 800 kg.m⁻³, for upper

part of furnace with circulating layer it is interval 0.1 ÷ 0.5 kg m⁻³.

5.1.1. DETERMINATION OF SOLID PARTICLES CONCENTRATION IN BOILER FURNACE

There are general qualities valid for fluid layer. Fluid layer applies hydrostatic pressure on furnace walls. General ratio for hydrostatic pressure is:

$$p = h \cdot \rho \cdot g \quad (\text{Pa})$$

where: h - fluid layer height (m)
 ρ - fluid layer density (kg.m⁻³)
 g - acceleration of gravity (m.s⁻²)

by modification we get basic ratio to calculate average fluid layer density

$$\rho = \frac{p}{h \cdot g} \quad (\text{kg.m}^{-3})$$

Fluid layer density varies at height and to more precise density determination at furnace height marginal concentration values must be determined.

Pressure in fluid layer is always measured for various height levels. Taken pressure data are continuously monitored by operation measuring instruments. There is basic ratio

$$\rho = \frac{\Delta p}{\Delta h \cdot g} \quad (\text{kg.m}^{-3})$$

where: Δp (Pa) - static pressure difference between two measured points of height difference Δh

Thus we can credibly determine average fluid layer density at furnace height.

5.1.2. DETERMINATION OF SOLID PARTICLES CONCENTRATION IN BOILER WASTE GASES CHANNELS BEHIND FLUID COMBUSTION CHAMBER

To determine solid particles concentration in waste gases gravimetric method with solid particles isokinetic off-takes can be used.

Gravimetric measurement unit with specially designed cooled off-take probe is used. Fig. 23 illustrates measurement unit for solid particles isokinetic off-take.

At the begining of measurement process flow velocity for steady output is determined at measurement points by net method. We can use for example wedge probe as it is illustrated in Fig. 12. According to taken values of dynamic and differential pressures on velocity probes off-take velocity is set for each single measuring point. It is also necessary to know static pressure and temperature in measuring points.

To determine concentration in measuring points disposable off-take probe is used. Diagram of

disposable probe for isokinetic off-take in channels at cyclone input is illustrated in Fig. 22. Probe is based on its internal diameter of size 13mm. Steel tube ϕ 10×1 made of material 17153 or if need be 15128 is inserted in. Thread is cut out at the end of tube to install off-take tubes of various through sections. Inserted tube through section ϕ 10×1 is chosen to avoid waste gases water vapour condensation at cold probe walls and temperature of waste gases was safely above dew point. Short rubber hose links probe to catcher. Catcher consists of basic cyclone with output through glass microfibrils of diameter 300 mm. It is supported by grid. Free from solid solid phase waste gases are distributed to condenser where they are cooled down to 20 ÷ 40 °C and goes on to measuring blanket line. Waste gases through flow is set and measured at blanket line.

Solid phase concentration is calculated as a ratio of trapped solid phase volume and exhausted waste gases volume

$$c_{solidphase} = \frac{m_{solidphase}}{V_{exhaustedwastegases}} \quad (\text{kg}\cdot\text{m}^{-3}), (\text{g}\cdot\text{m}^{-3})$$

where: $m_{solidphase}$ - trapped solid phase weight (kg), (g)
 $V_{exhausted waste gases}$ - exhausted waste gases volume (m^3)

Exhausted waste gases volume in measuring point is:

$$V_{exhausted waste gases} = k \cdot \left(\frac{\Delta p_{cl}}{\rho_{cl}} \right)^{0.5} \cdot \tau \quad (\text{m}^3)$$

where:

k -blanket constant
 Δp_{cl} -differential pressure at blanket
 ρ_{cl} - waste gases density at saturation limit for temperature at blanket ($\text{kg}\cdot\text{m}^{-3}$)
 τ - exhaustion time [min]

Density at blanket must be determined based on O_2 analysis and CO_2 a N_2 calculation. H_2O content is determined based on temperature at blanket and trapped condensate volume.

Concerning boiler 350 tph steam concentration at cyclones input was determined following above mentioned methods and arrangements.

Other variant of combine off-take probe is cooled probe as it is illustrated in Fig. 24. Probe is used for combine measurements of flow velocity and off-take of solid particles of temperature up to 1400 °C. Probe has got graduated cooling jacket where cooled part reaches probe peak. Interchangeable head cooling is thus managed. Tube with internal heat insulation is inserted into graduated cooling jacket. This tube distributes mixture of solid and gaseous phase to catcher. Tube is telescopic with possibility of extension. Measure of extension determines cold heat-exchange area size that cools down exhausted sample.

Therefore measure of extension can be used to lower sample temperature at probe output no matter how high the input temperature was. It can guarantee that output temperature would be set above waste gases dew point. There are off-takes of static pressure along both sides so as probe can be used even for velocity measurements for very high temperatures.

Other variant is off-take probe with cooled supporting part as it is illustrated in Fig. 25. Probe was developed to measure solid particles through hole in membrane wall flag. Off-take part touches cooled parts only by its part to avoid waste gases cooling below dew point during off-take process.

5.2. RESULTS OF MEASUREMENTS OF SOLID PARTICLES CONCENTRATION AT HOT CYCLONE INPUT

As an example of taken results solid particles concentration measurements at hot cyclone input can be illustrated at. Measurement was taken at boiler 350 tph with circulating fluid layer.

Solid particles concentration measurements happens in environment with high temperature of surroundings and demands skilled staff in good physical shape to manage such a measurement operation. Moreover there is permanent danger of being burned by measuring instruments and waste gases. Under these circumstances measurement itself is burden with bigger error than it is in more friendly conditions. That is why measurement was done for various regimes only once and was not repeated.

Results are illustrated in Fig. 26.

Based on measurement results we can draw following conclusions: common verification measurements of fluid boilers in cyclone area leads to following pieces of knowledge:

- Big area and cyclone volume shows as significant element in keeping solid and gaseous phase in a range of temperatures from 800 to 900 °C.
- due to different velocity of solid and gaseous phase there is intensive after-combustion of combustible residues in solid and gaseous phase in cyclone,
- desulphurization process runs the same way as after-combustion process,
- last but not least recirculated solid phase is important source of inert material for fluidization of crude particles in bottom part of fluid layer and at the same time it helps to transfer mass and temperature all around of furnace and cyclone,
- solid and gaseous phase mixture is not homogeneous all around cyclone area; significant temperature and concentration differences effect flow and cyclone functions,
- solid phase blown by waste gases stream can be found in higher concentration in bottom part of transition channels. Concentration is lowering with upward direction. Concentration around 0.1

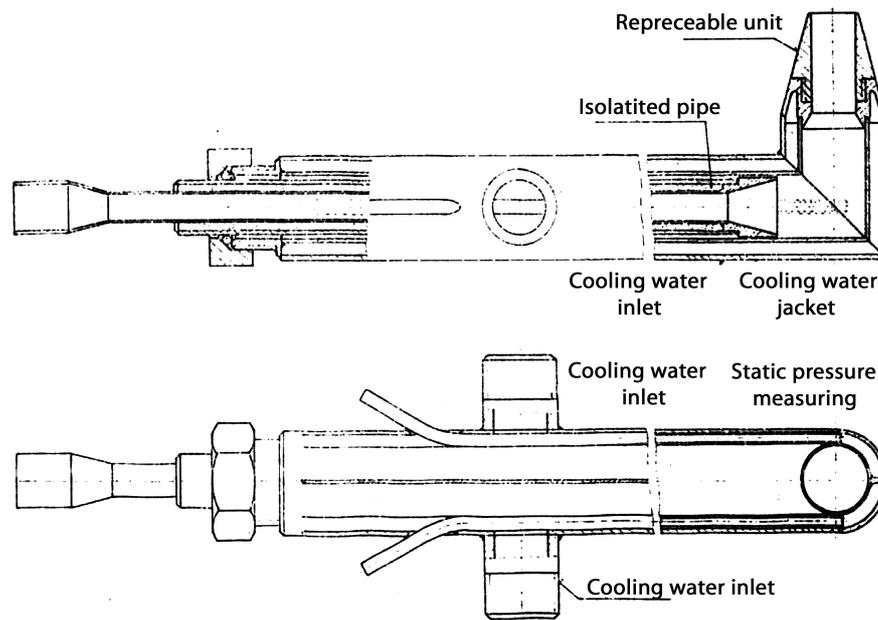


Fig. 24 Diagram of cooled off-take probe

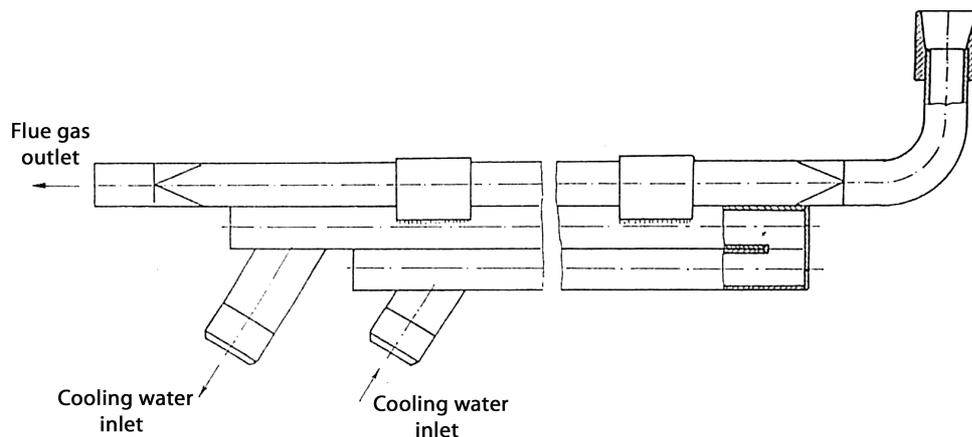


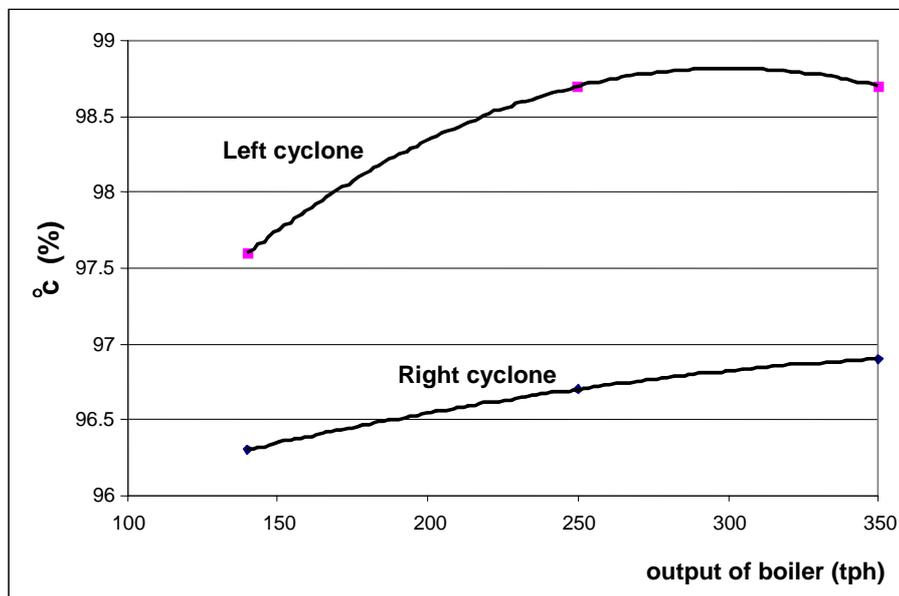
Fig. 25 Diagram of off-take probe with cooled supporting part

kg.mN^{-3} was monitored under both channels ceilings. On the contrary values in interval from 3 to 5 kg.mN^{-3} were monitored in bottom part of transition channels. This effect is connected by sorting out of fluid layer cruder particles when particles sediment with stalling velocity. This effect is typical for boilers of lower outputs where for 70 % boiler output inert deposit up to 1000mm height was at the bottom of transition channel and for 40 % P_{Nom} . Boiler output deposit was up to 1500 – 1700 mm in both transition channels and thus it happened that measuring hole in bottom part of chammel was not

acesible. This effect is general for all transition channels between combustion chamber and boiler in case they are led horizontally. Concerning boiler of output 350 tph these deposits are about 20 m^3 particles of medium diameter from 0.1 to 0.2 mm if the boiler output is low. As soon as boiler output increases these particles move quickly to cyclones and chutes and cause operation problems when regulating inert ratio in combustion chamber. This effect was later on elliminated by after-blow of pressure air. Different design of transition channels would be better solution,

Table 3 Circulation number results

Boiler output	40 %	70 %	100 %	
Medium concentration of solid particles – left side	841.9	3 308.5	4 427	[g.m ⁻³ _N]
Medium concentration of solid particles – right side	670.1	1 165.7	1 827	[g.m ⁻³ _N]
Mass flow of solid particles – left side	31.21	173.6	234.9	[kg.s ⁻¹]
Mass flow of solid particles – right side	20.14	65.91	100.12	[kg.s ⁻¹]
Total mass flow of solid particles	51.35	239.51	335.02	[kg.s ⁻¹]
Lower heating value	11 860	11 950	11 870	[kg.s ⁻¹]
Fuel consumption	10.041	16.72	23.283	[kg.s ⁻¹]
Volume of ash and limestone supply to boiler	2.447	5.677	6.995	[kg.s ⁻¹]
Circulation number of solid phase – left side	42	81	77	[1]
Circulation number of solid phase – right side	27	31	32	[1]
Circulation number of solid phase through cyclone and chute	34.5	56	54.5	[1]
Distribution of bed ash and light ash	40:60	25:75	13:87	[%]

**Fig. 27** Cyclone efficiency of boiler 350 tph

- point of transition channels linking to combustion chamber effects solid phase concentration at channel through sections. Solid phase keeps same flow direction as it has got at the end of combustion chamber. Concerning testing boiler field of maximal concentration of solid phase is closer to both internal walls of transition channels (toward boiler axe). It corresponds with average velocities in channels. From the point of optimization of solid phase flow at cyclone input reverse direction sense of both cyclones would be better,
- solid phase concentration in transition channels at cyclone input corresponds with temperature distribution taken in both channels. Measurement proved fact that solid phase average temperatures are higher than the gaseous one. This effect was also found valid for temperature measurements in cyclones where is no heat exchange with surroundings,
- such a measurement can be used to determine volume of solid phase that circulates round combustion chamber, cyclones and chute under cyclones. Circulating material volume is shown at Table 3 – both in absolute value and as a circulation number (ratio of solid phase mass flow at cyclone input and volume of blow-off boiler ash). Circulation number was also basis to calculate cyclone efficiency using ratio:

$$\eta_c = \left(1 - \frac{1}{O_c} \right) \cdot 100 \quad (\%)$$

where O_c is circulation number.

Based on measurements we can drive into conclusions that burning chamber of boiler 350 tph is not symmetrically loaded. Both power output and velocities are higher for left side of the boiler. Solid phase through flow through both cyclones is

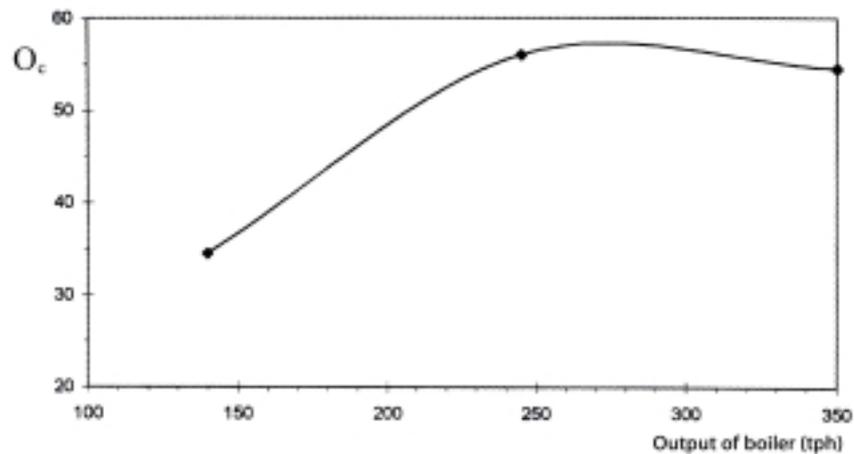


Fig. 28 Circulation number of inert material through cyclones of boiler 350 tph

significant as well. Volume of left cyclone loading is much higher than the right one. This is highly probably caused by unevennesses that already originates in bottom part of furnace. Assymetrical air supply to area under the grate, variable output of coaling plants to left and right side, heterogenous granulometrics of fuel in storage bin etc. All these variabilities were tested for all boiler outputs and can be taken as their characteristics.

Results are illustrated in Table 3 for output 100 %, 70 % and 40 % Nom. output. Circulation number is quite high but this fact corresponds with very low content of combustible particles taken off in chutes under cyclones (snub approaches to 0). Circulating material is not important in snub ratio lowering but it is inert particles source for development of fluid layer in combustion chamber.

Generally we can say that hot cyclones of fluid boiler has got high separation ability. Results of cyclone effectiveness for various boiler outputs are illustrated in Fig. 27.

Graphical illustration of results of cyclones fluid layer average circulation number for various boiler outputs is shown in Fig. 28.

6. SUMMARY AND FINAL CONCLUSIONS

Since 1996 there were 28 big fluid boilers with desulphurization ability during combustion operation process put into operation in the Czech Republic. Differences in design and various conceptions of these units helped us to gain a number of valuable data and experience. There was no such a possibility until these units were builded up.

Based on the fact that development of the boilers was controlled by foreign supplier authorities it was not possible to get acquainted with technical parameters of boilers in the Czech Republic until the

units were put into operation. First operation hours of majority of these boilers were affected by atypical characteristics of czech coal. Highly abrasive ash matter, high humidity, clay impurity of fuel and higher content of other elements in raw fuel (stone, wood, metal) made it necessary to modify fuel feed channels, crushers, separating plants and fuel in-take to fluid channels. It happened many times that these problems ended up in total unit reconstruction or of need be their exchange. Frequent fuel supply discharges led to shortening of durability of combustion chamber heavy lining especially cyclone bricking and chutes under cyclones. Some problems are caused by ash off-take from fluid layer, its cooling down, granulometrics finishing and further manipulation. Other problems are in area of fluid particles sintering when combustion temperatures are safely below 900 °C. Despite this fact mass sintering happens in various parts of boiler. Last but not least there is a trend to lower desulphurization costs if molar ratio Ca/S is in interval from 2.5 to 3 that means higher operation costs compare to wet tailings.

Quite new area of fluid boilers is combined combustion of coal and biomass or co-combustion of sorted fuel from renewable sources.

Thanks to building up 28 fluid boilers in the Czech Republic a lot of pieces of knowledge was gained in this interesting branch. Measurement diagnostics both brought a number of valuable data and many questions to be answered to. Despite inhibition process in extensive development in energetics there are further projects in area of applicable research focused on operation process optimalization, efficiency improvements and operation costs minimalization. These are the areas where these pieces of information based on measurement results on various boiler types can be used up.

APPENDIX:

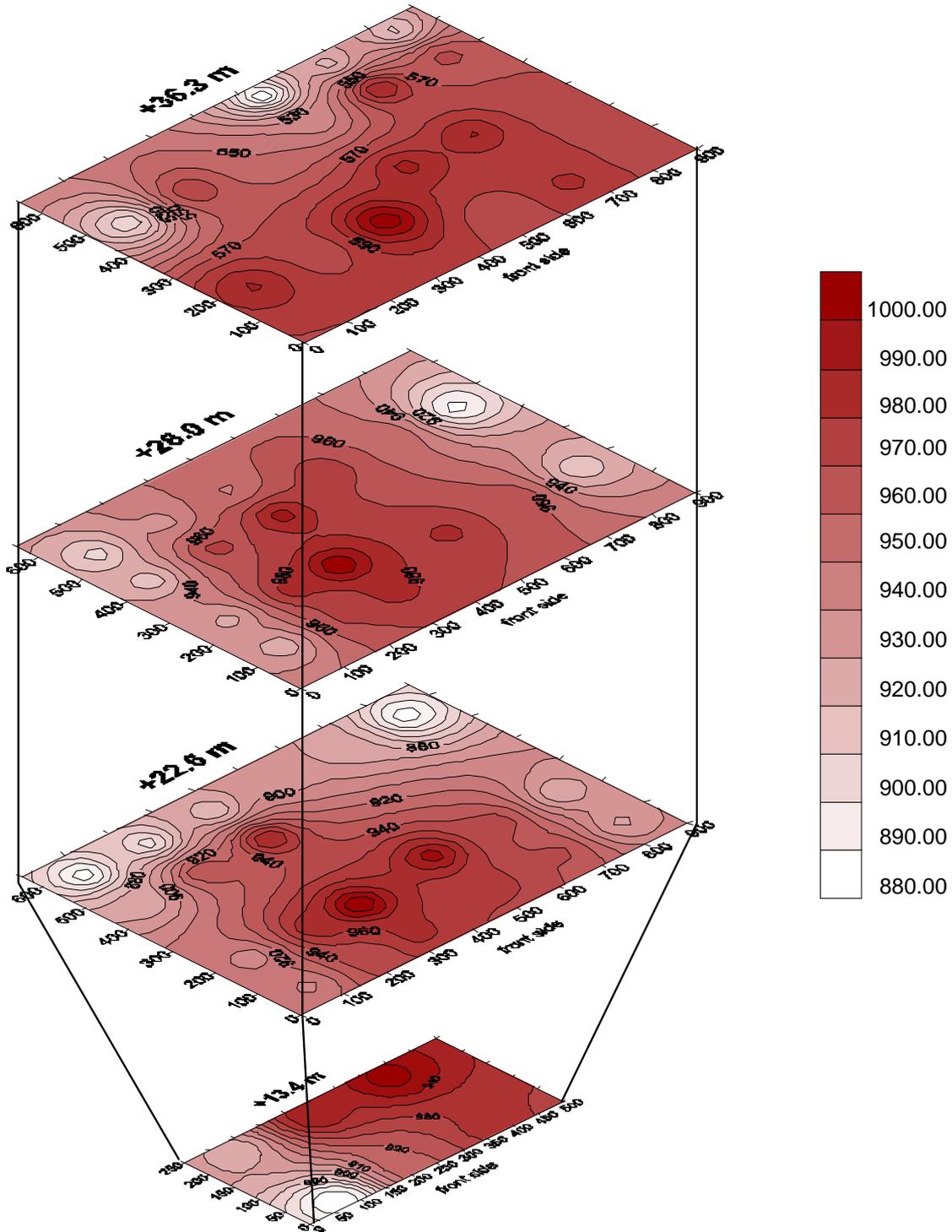


Fig. 6a Temperature distribution concerning height of furnace chamber 60 % Nominal output

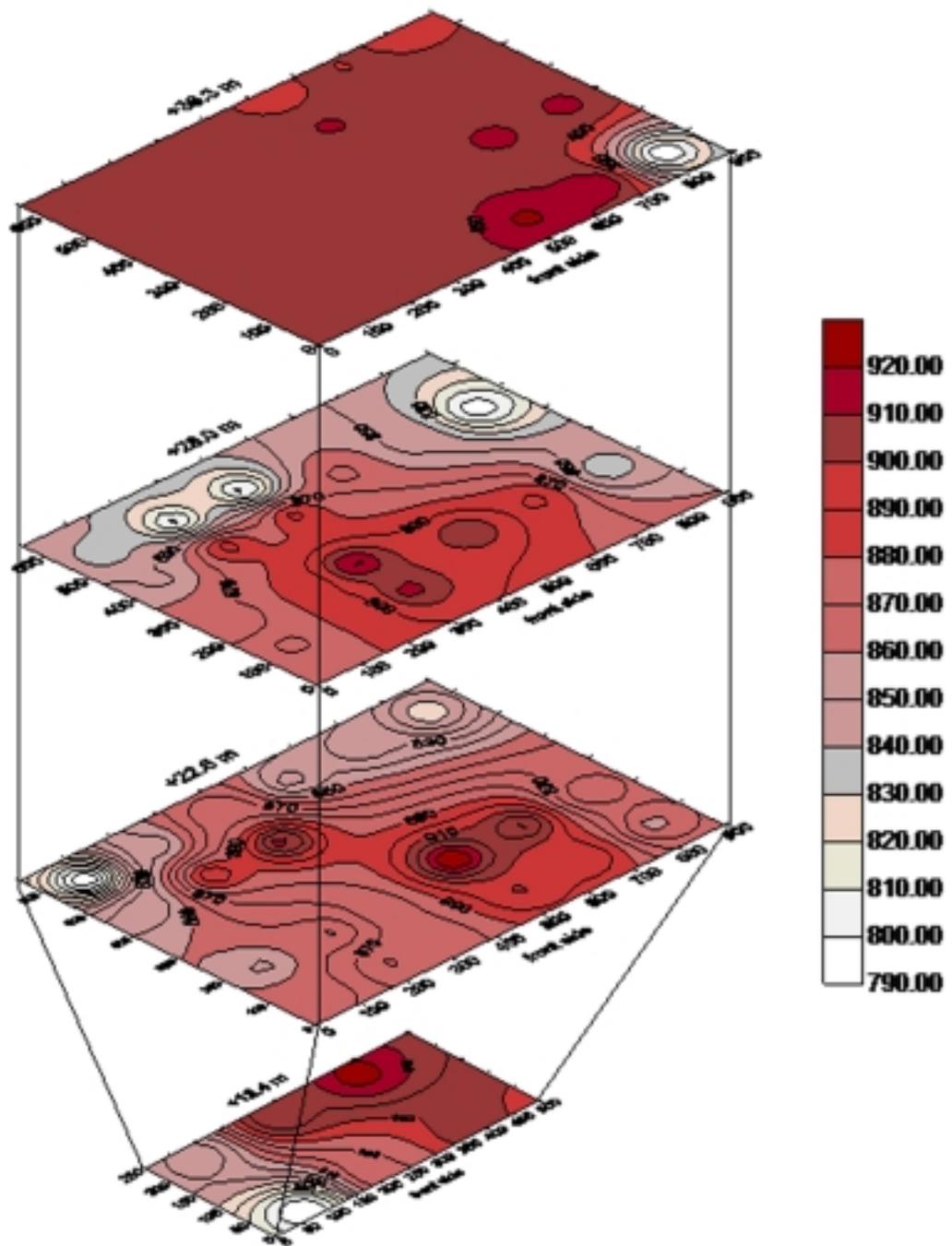


Fig. 6b Temperature distribution concerning height of furnace chamber 90 % Nominal output

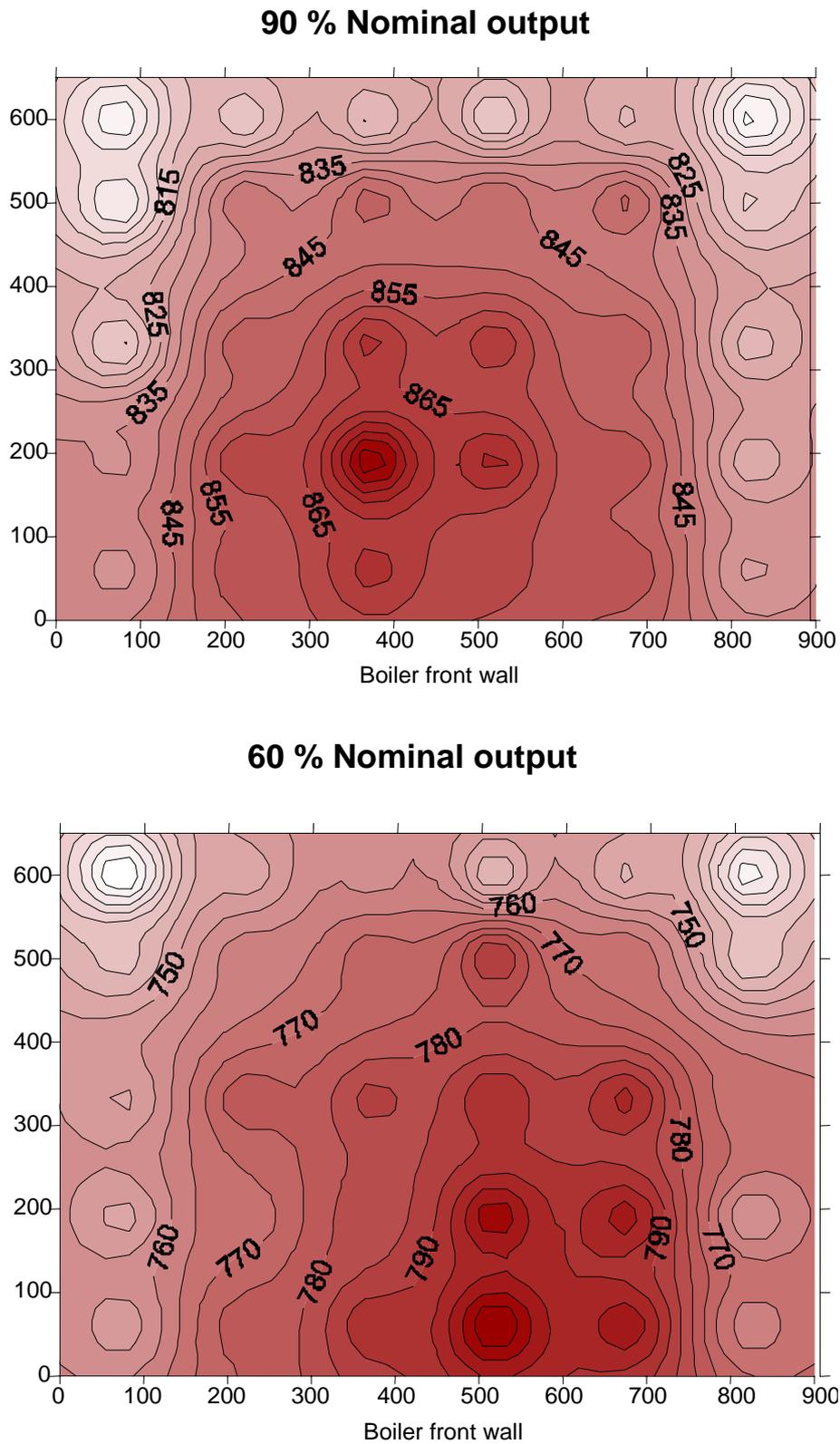


Fig. 6c Average temperature distribution concerning height of furnace chamber

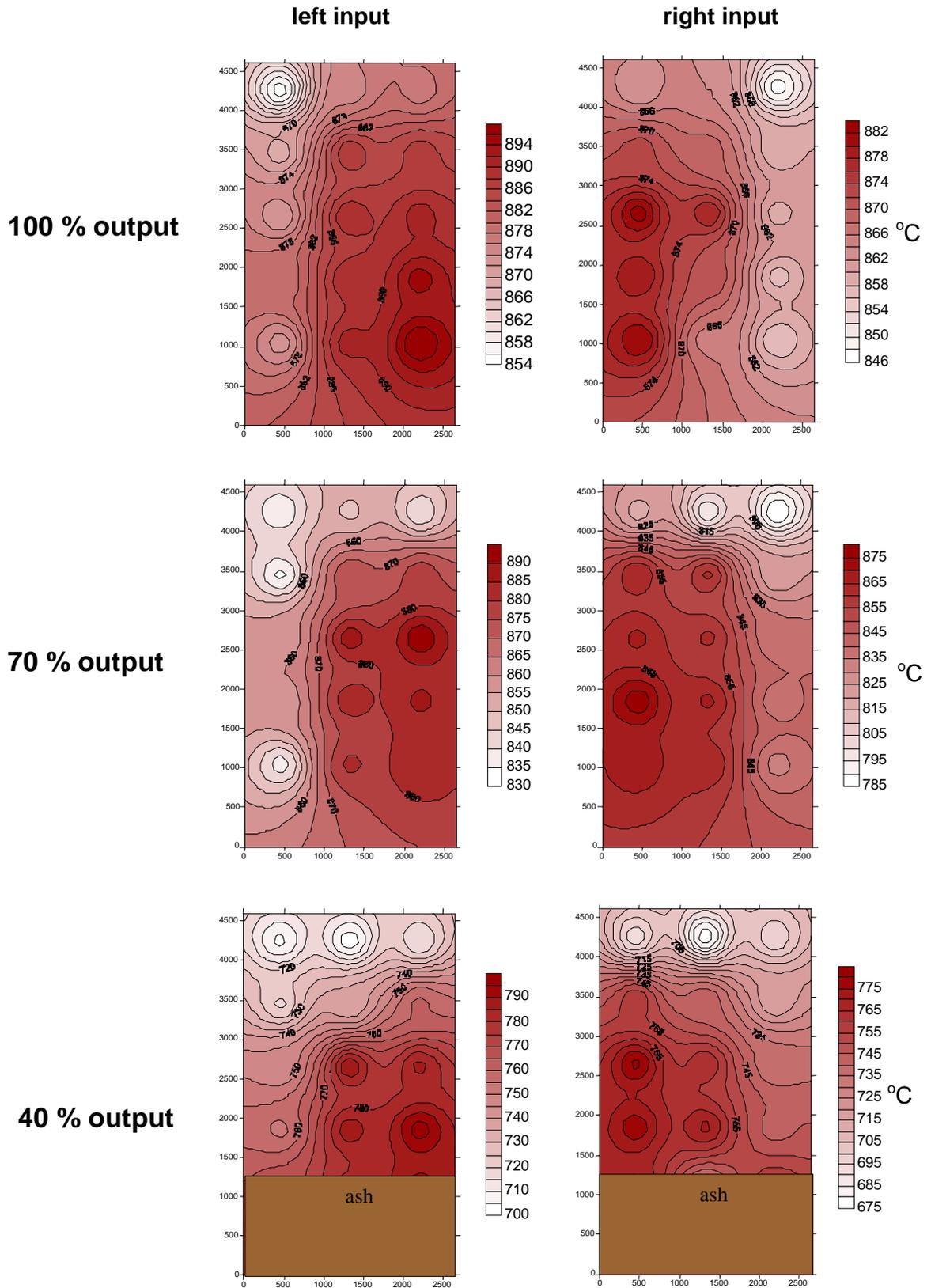


Fig.7 Temperature field distribution in input channels to cyclone

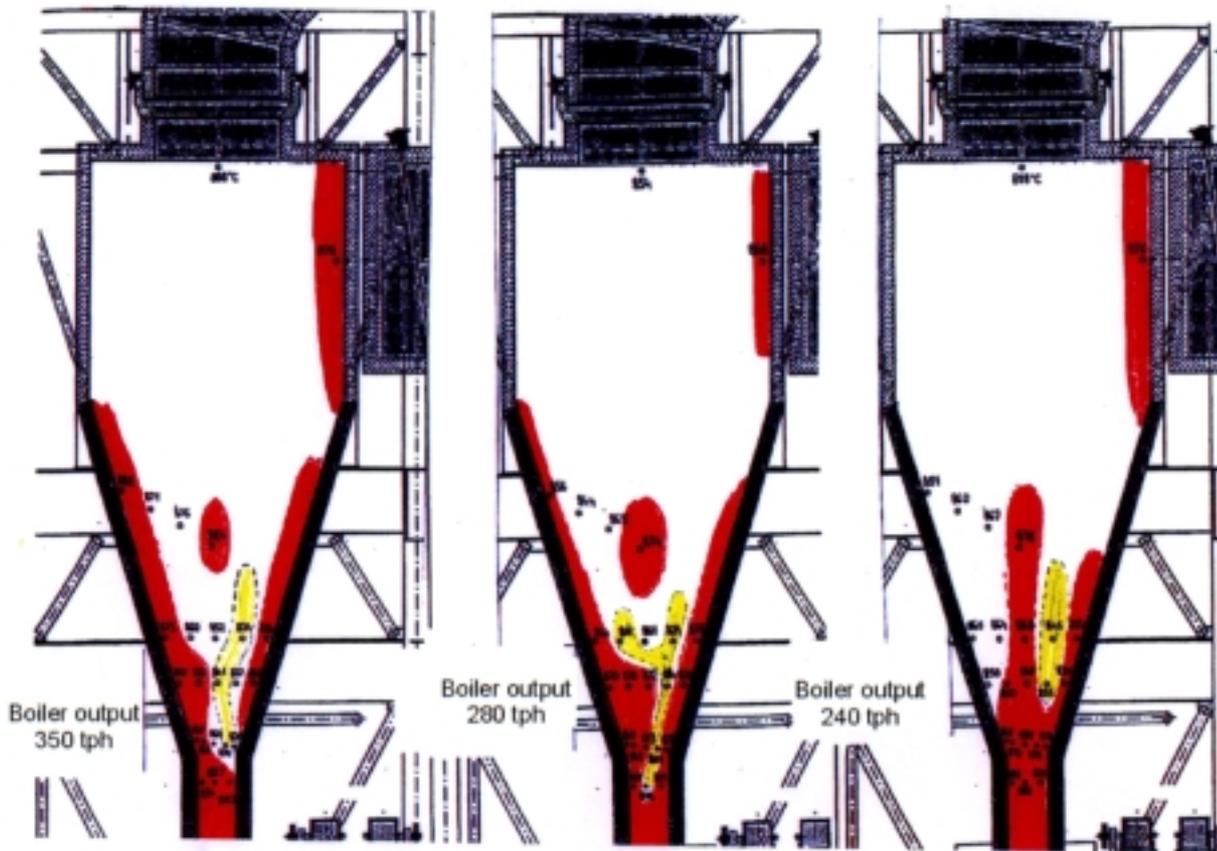


Fig. 8 Cyclone temperature field for outputs 350 tph, 280 tph and 140 tph

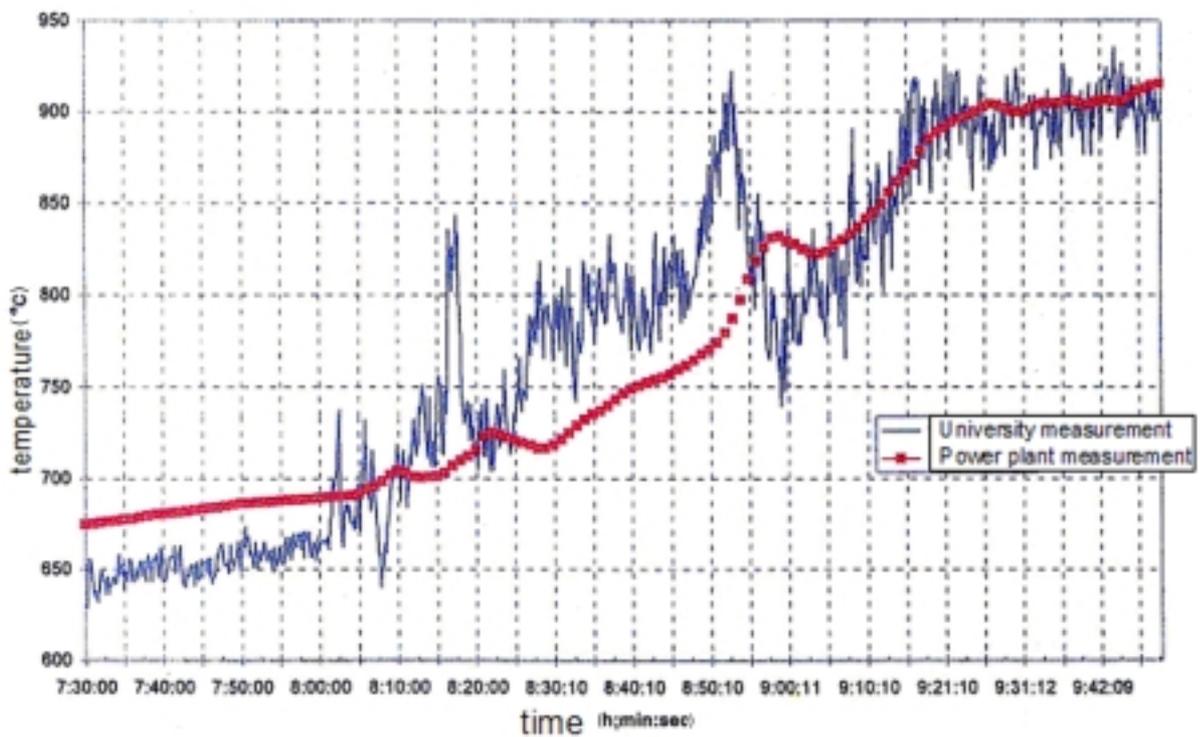


Fig. 9 Comparison of values taken by VŠB-TU Ostrava and ETI operating instruments

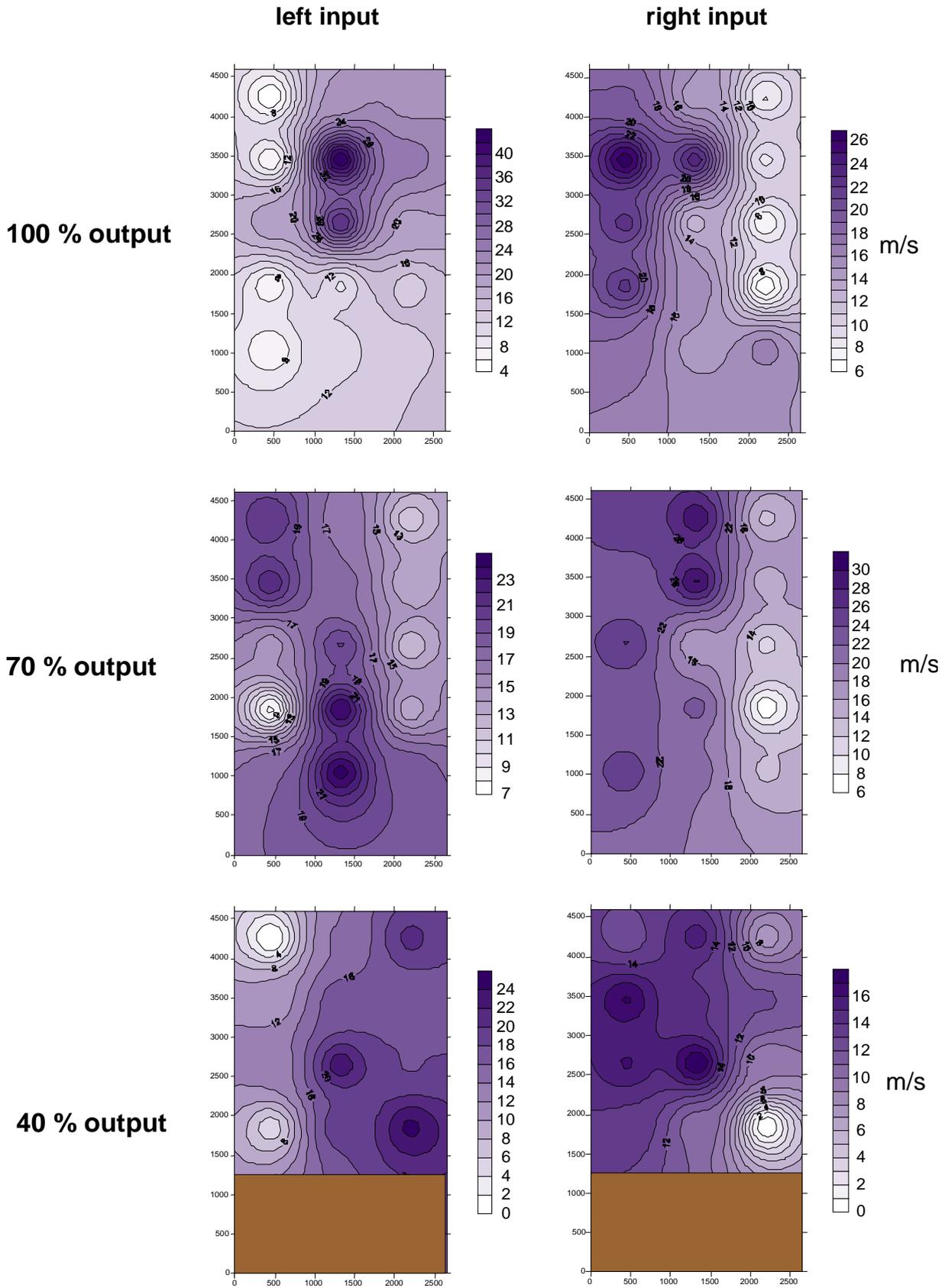


Fig. 14 Velocity field distribution in input channels to boiler cyclone 350 tph

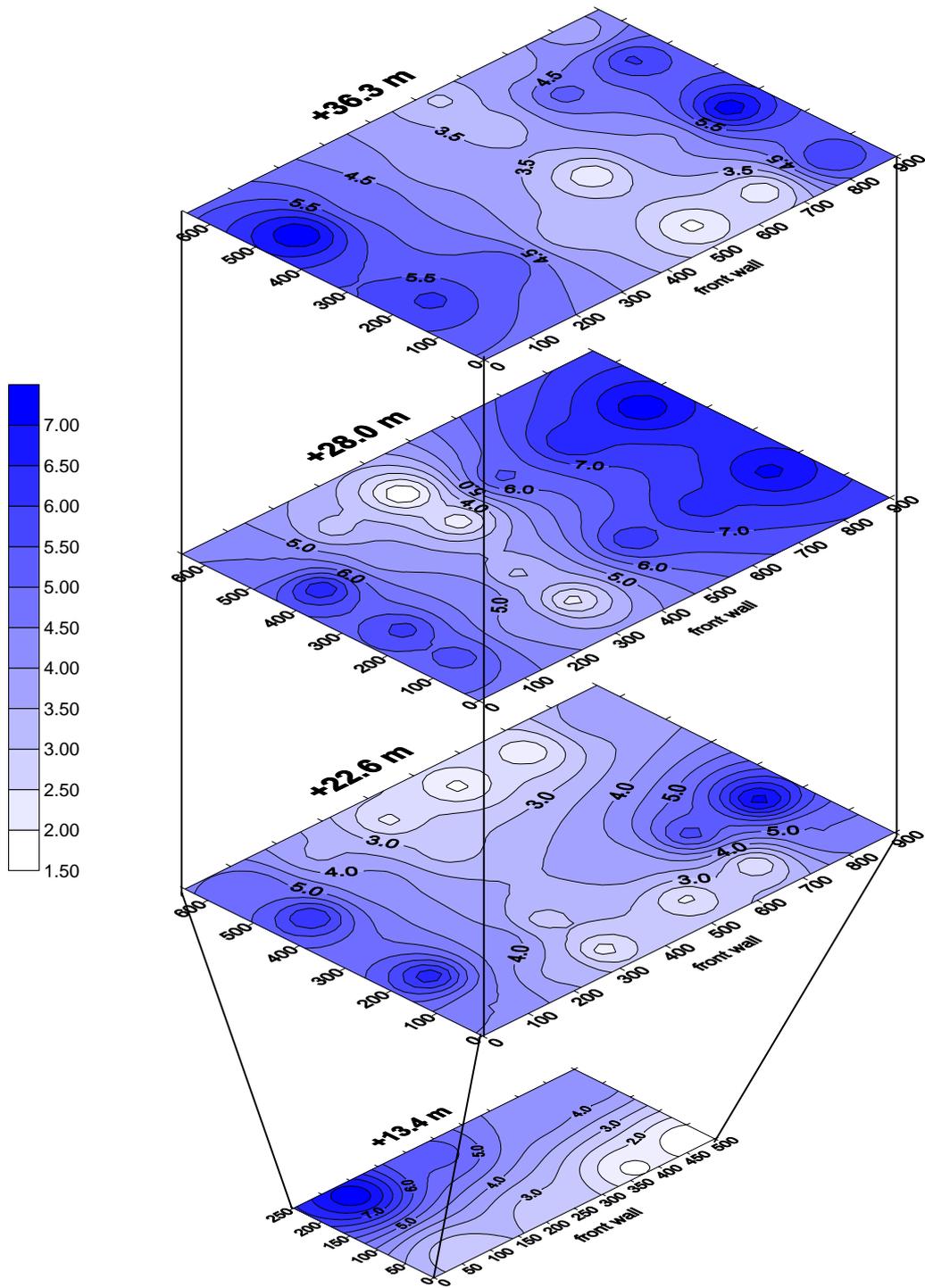


Fig. 17a Results of O₂ concentration measurements concerning height of furnace chamber 90 % nominal output

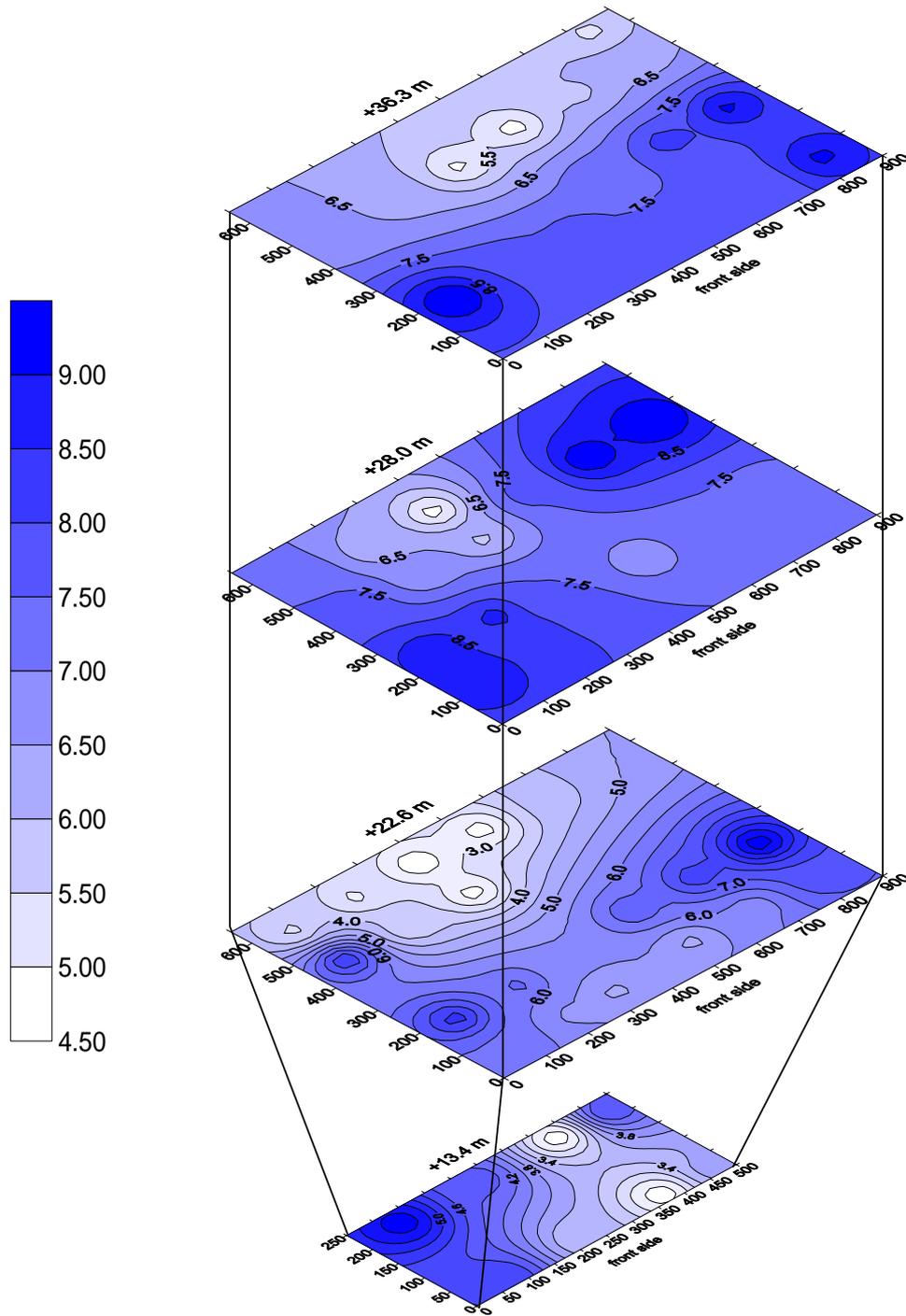


Fig. 17b Results of O₂ concentration measurements concerning height of furnace chamber 60 % Nominal output

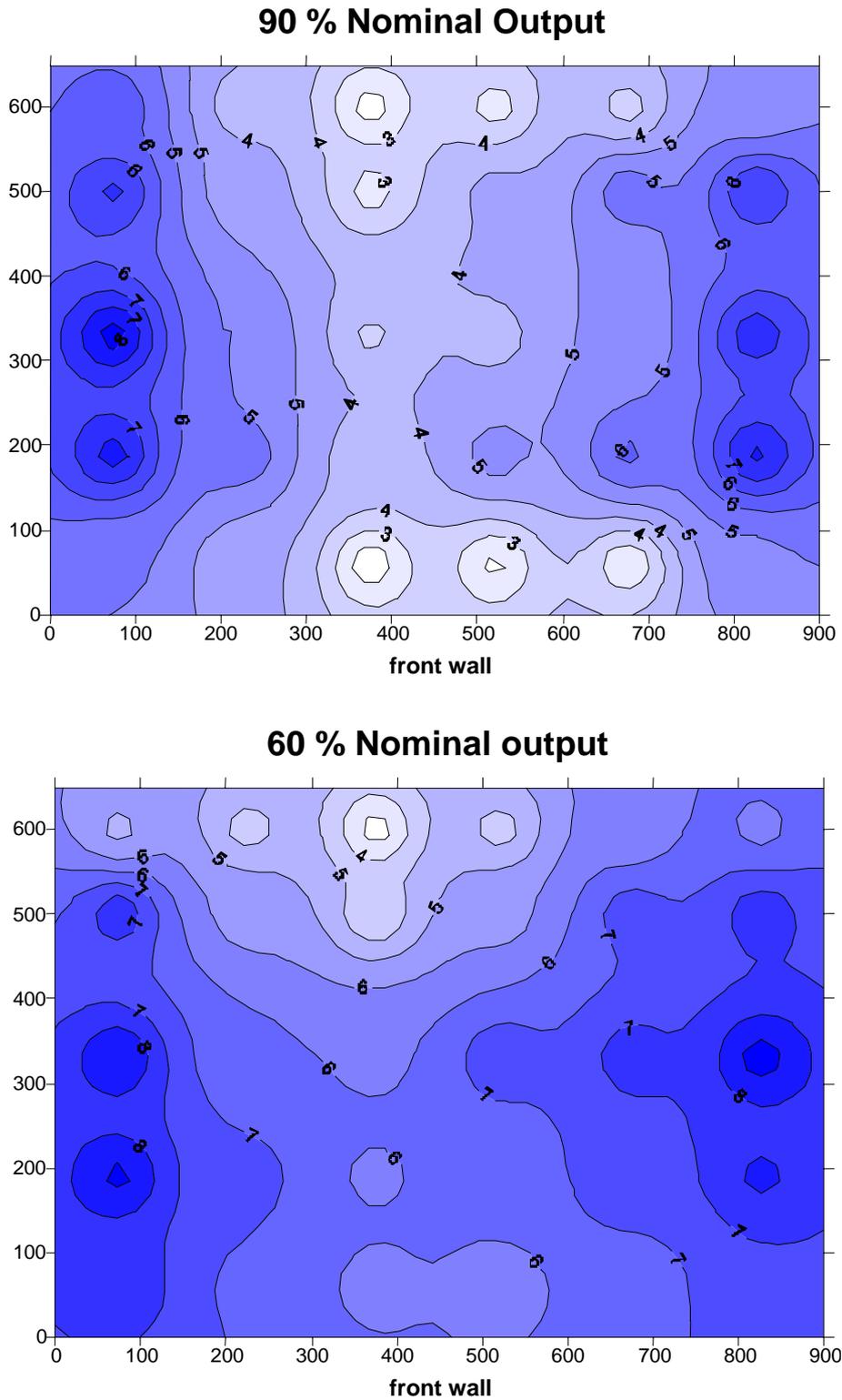


Fig. 18 Average O₂ concentration distribution concerning height of furnace chamber

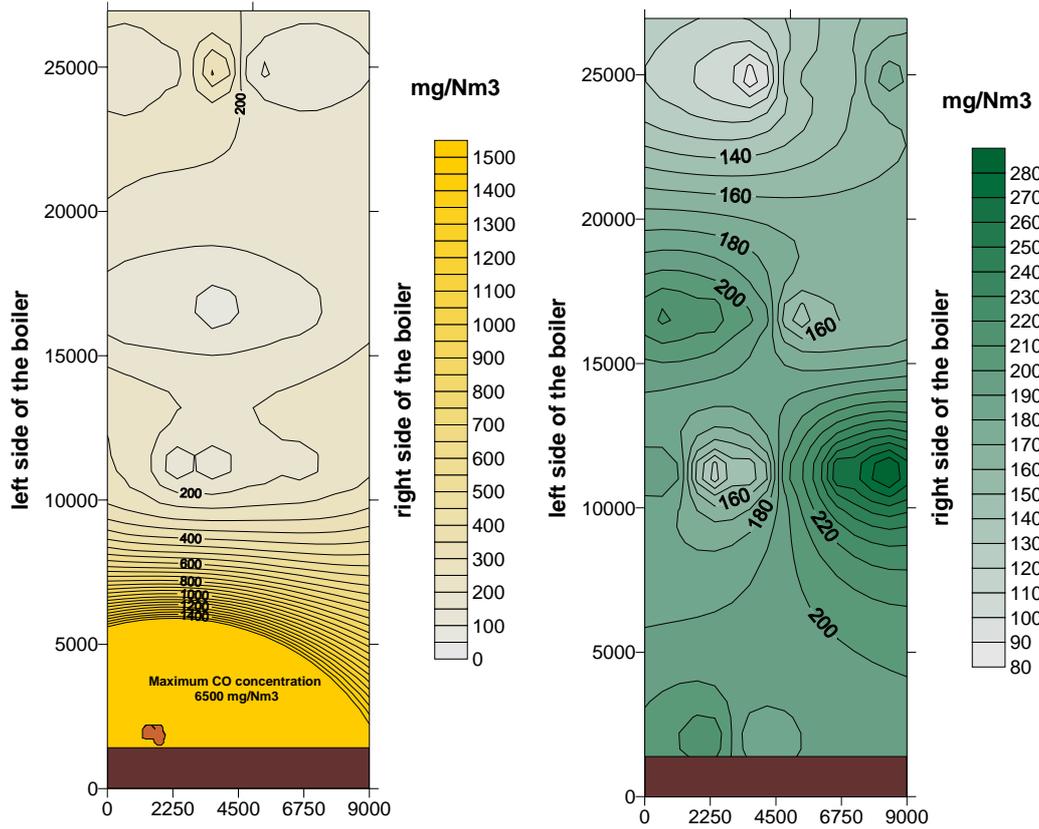


Fig.19 Average CO and NO_x concentration distribution at height of combustion chamber of boiler for output 90% Nominal output

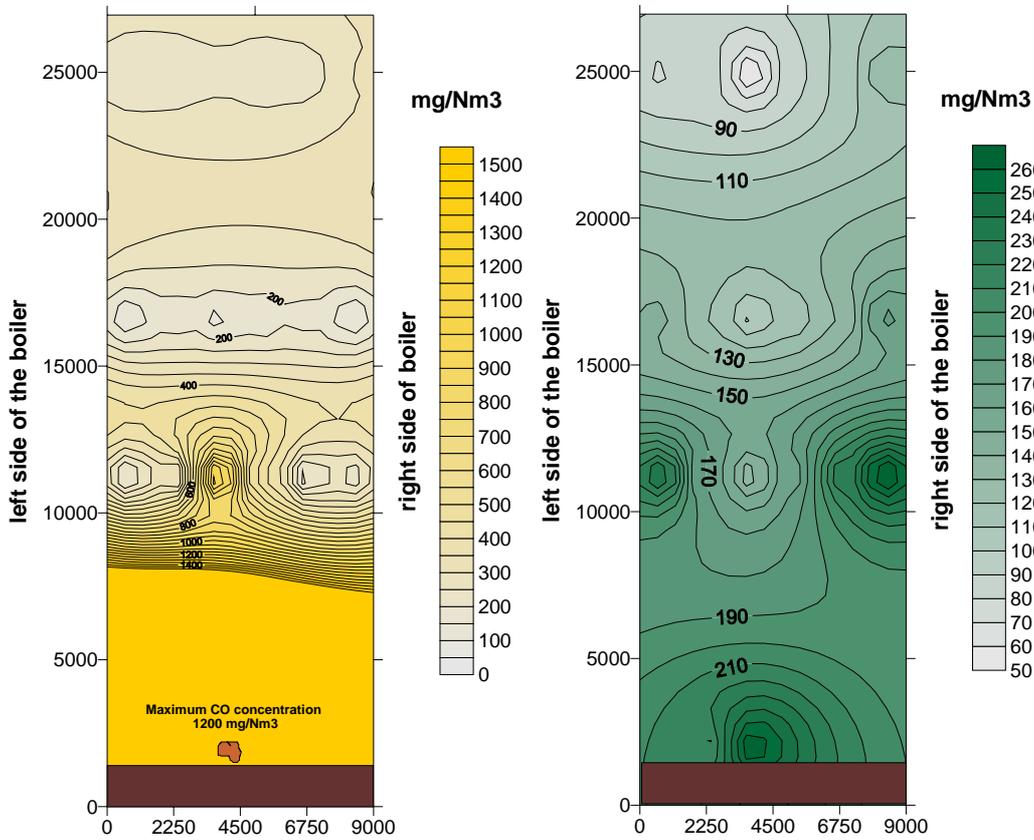


Fig. 20 Average CO and NO_x concentration distribution at height of combustion chamber of boiler for output 60% Nominal output

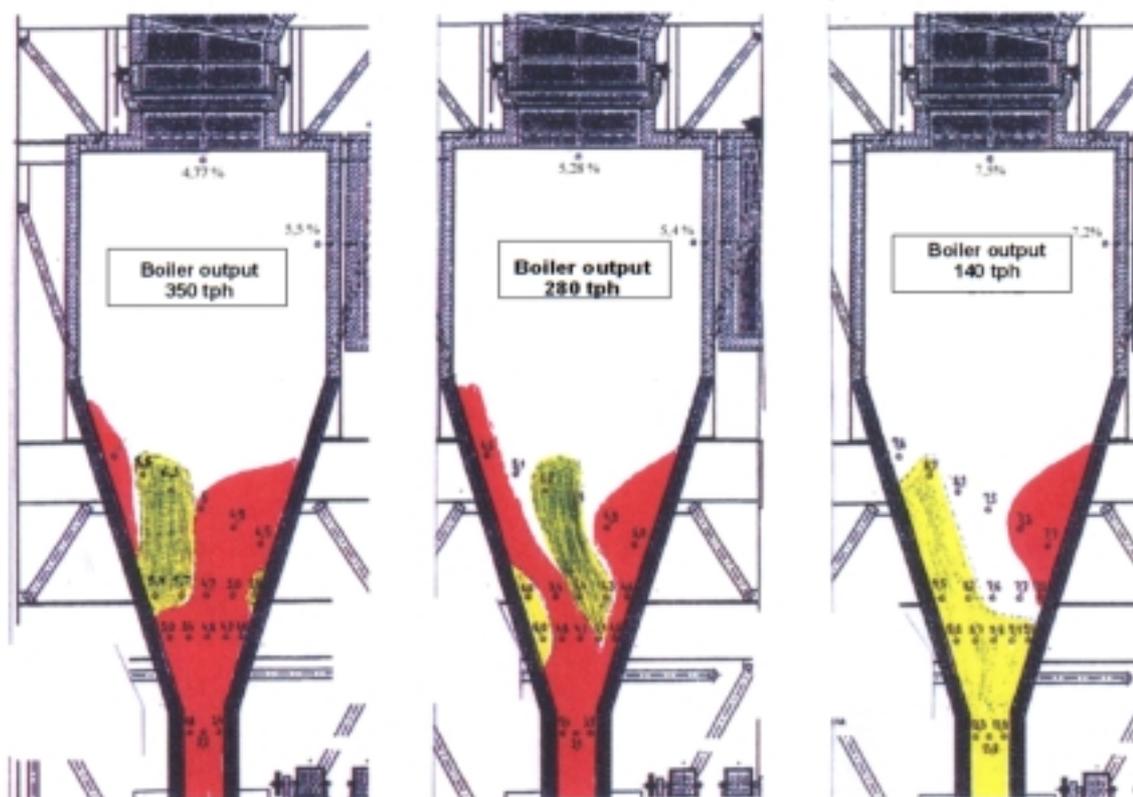


Fig. 21 O₂ concentration field in cyclone for output 350, 280 and 140 tph of steam

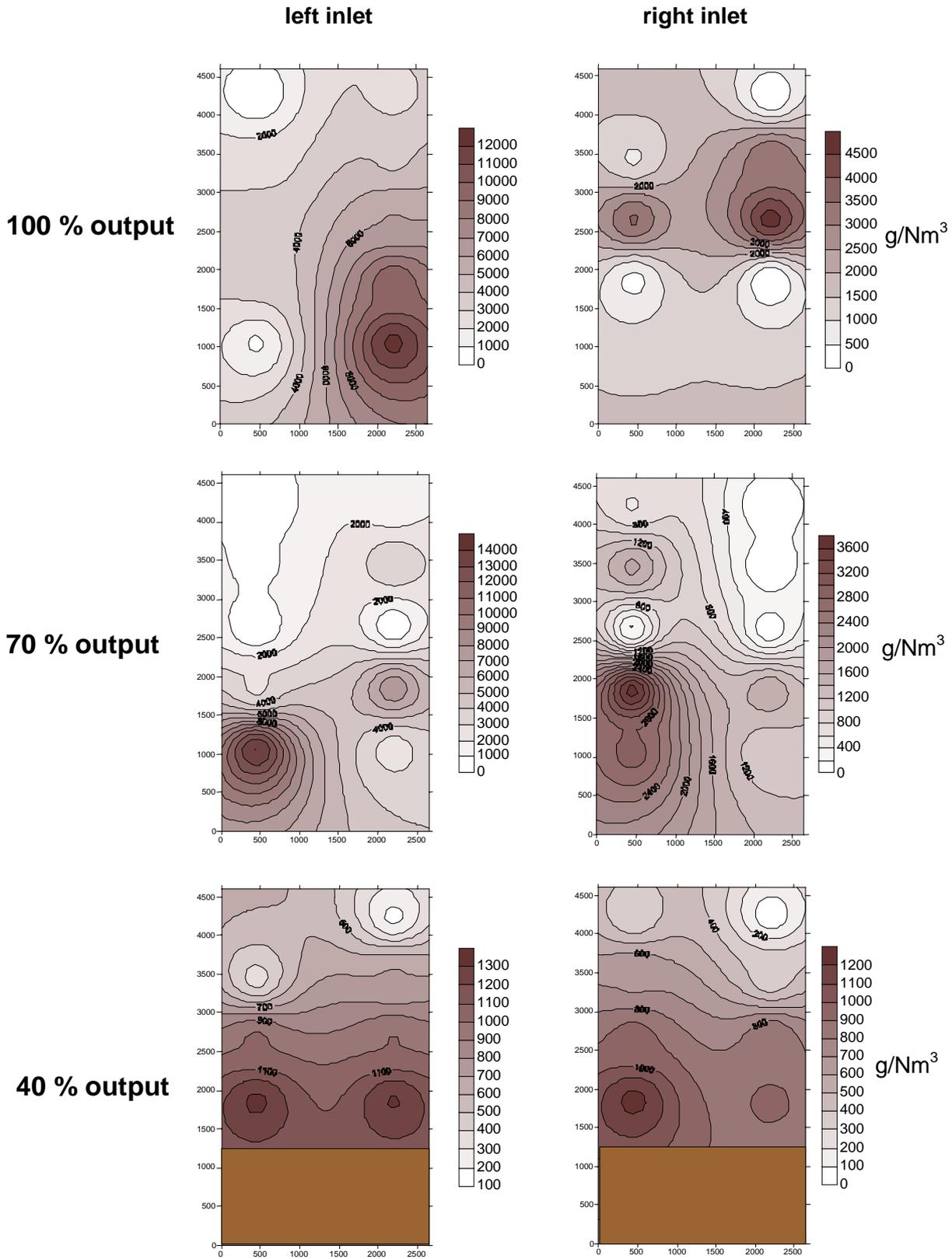


Fig. 26 Distribution of solid particles concentration at cyclone input channels of boiler 350 tph