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Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd. Engineering & Products Marine Machinery Devision Marine Boiler Section	**TECHNICAL REPORT**	No. BZM-Z02563_R1 Date Apr. 27, 2016

Order No.	F0H11	Project Name	**Marine Boilers for "FSRU TOSCANA"**
Subject	**Report on Boiler NOx Reduction Feasibility Study**		

MHI-MME has carried out the feasibility study of upgraded NOx emission reduction, aiming to achieving 100 mg/Nm3 at 3% O2 base with gas firing for "FSRU TOSCANA" required by the new emission regulations as follows.

Abbreviation in this document

CFD	Computational Fluid Dynamics
FGR	Flue Gas Recirculation
FS	Feasibility Study
FSRU	Floating Storage and Regasification Unit
MHI-MME	MITSUBISHI HEAVY INDUSTRIES MARINE MACHINERY & ENGINE CO., LTD.

1. Purpose of this feasibility study

Due to the new emission regulation in FSRU TOSCANA field, the requirements regarding NOx emission are upgraded to the range from 150 mg/Nm3 to 100 mg/Nm3 at 3% O2 base with gas firing. To analyze and confirm the feasibleness of new emission regulations, MHI-MME service engineer conducted the investigation of boiler NOx study on 9/Nov/2015 – 11/Nov/2015 onboard. As a result of this investigation, it was noted there would be a possibility to achieve 100 mg/Nm3 if the flue gas recirculation rate (FGR rate) is increased. But in high FGR rate conditions, further studies were required.

The purpose of this feasibility study for NOx emission reduction is to analyze and confirm the feasibleness of new emission regulations for 100 mg/Nm3 at 3% O2 base with gas firing.

Rev.	Content	Approve	Check	Drawn	Marine Boiler Section		Conferred
1	Corrected the description. 14/Jul/2016	K.M	S.S	M.A	Approved	for S. Sueno	
					Checked	-	
					Drawn	M. Amano	

[The major subjects to solve to satisfy new NOx emission regulations]

1) When FGR rate increases, O_2 deviation between two burners expands.
2) Due to the expansion of O_2 deviation, flame size may be expanded and NOx emission may increase.
3) In order to operate the boiler with high FGR rate, the modification will be required, for which the proposal is to be worked out.

Various evaluations and analysis using CFD were performed to address these subjects in this FS.

2. Results of previous investigation dated on 9/Nov/2015 - 11/Nov/2015

Following is summary of previous investigation data. FGR rate is adjustable using the parameter of “FGR bias ratio” in existing control system. When FGR rate is increased (FGR bias ratio is increased), NOx figure is below 100 mg/Nm3 at boiler normal load (48t/h). In following data, NOx figure is on an O2 3% base.

Table 2-1 Existing Boiler Data (measured on 9/Nov/2015);

Date	Time	Boiler Nor. Load [%]	STBD boiler / PORT boiler	FGR bias ratio	NOx [mg/Nm3]
9-Nov-15	14:20 - 15:30	35 (17t/h)	STBD	0.3	79.7
			PORT		95.1
	15:30 - 16:45	50 (24t/h)	STBD		87.1
			PORT		102.5
	16:45 - 17:50	75 (36t/h)	STBD		104.9
			PORT		122.2
	17:50 - 18:30	100 (48t/h)	STBD		125.2
			PORT		134.8

Table 2-2 Effect of FGR rate data (measured on 10/Nov/2015);

Date	Time	Boiler Nor. Load [%]	STBD boiler / PORT boiler	NOx [mg/Nm3] FGR bias ratio = 0	FGR bias ratio = 0.3	FGR bias ratio = 0.6	FGR bias ratio = 1	FGR bias ratio = equipvalent 1.3
10-Nov-15	8:40 - 11:25	35 (17t/h)	STBD	83.5	79.9	76.4	76.0	n/a
			PORT	101.1	92.6	90.9	84.4	n/a
	11:25 - 15:00	75 (36t/h)	STBD	n/a	104.0	103.0	101.0	96.1
			PORT	n/a	121.7	110.7	92.0	76.6
	15:00 - 17:25	100 (48t/h)	STBD	n/a	n/a	124.1	100.3	78.7
			PORT	n/a	n/a	109.6	79.4	n/a

Table 2-3 Effect of Steam Injection Data (measured on 10/Nov/2015)

Date	Time	Boiler Nor. Load [%]	STBD boiler / PORT boiler	FGR bias ratio	NOx [mg/Nm3] Steam Injection bias ratio = 0	Steam Injection bias ratio = 0.63	Steam Injection bias ratio = 1
10-Nov-15	17:25 - 18:30	75 (36t/h)	STBD	1.0	92.1	88.6	88.2
			PORT		91.2	88.4	85.5

* This data is flue gas recirculation plus steam injection.

The status of planning study items to confirm the feasibleness of NOx reduction at previous investigation stage is given in the following table. To satisfy new emission regulation, required analysis items were studied in this FS.

Table 2-4 Status of planning study items

Item	Status
Preliminary modification planning	Finished (Submitted plan regarding the flue gas mixing device and boil off gas lead pipe)
Measurement of existing boiler condition	Finished
Detail study of improvement for mixing device	Not carried out
Study of stable operation with high GR rate	Not carried out
Study of additional required modification according to the boiler data obtained this time	Not carried out

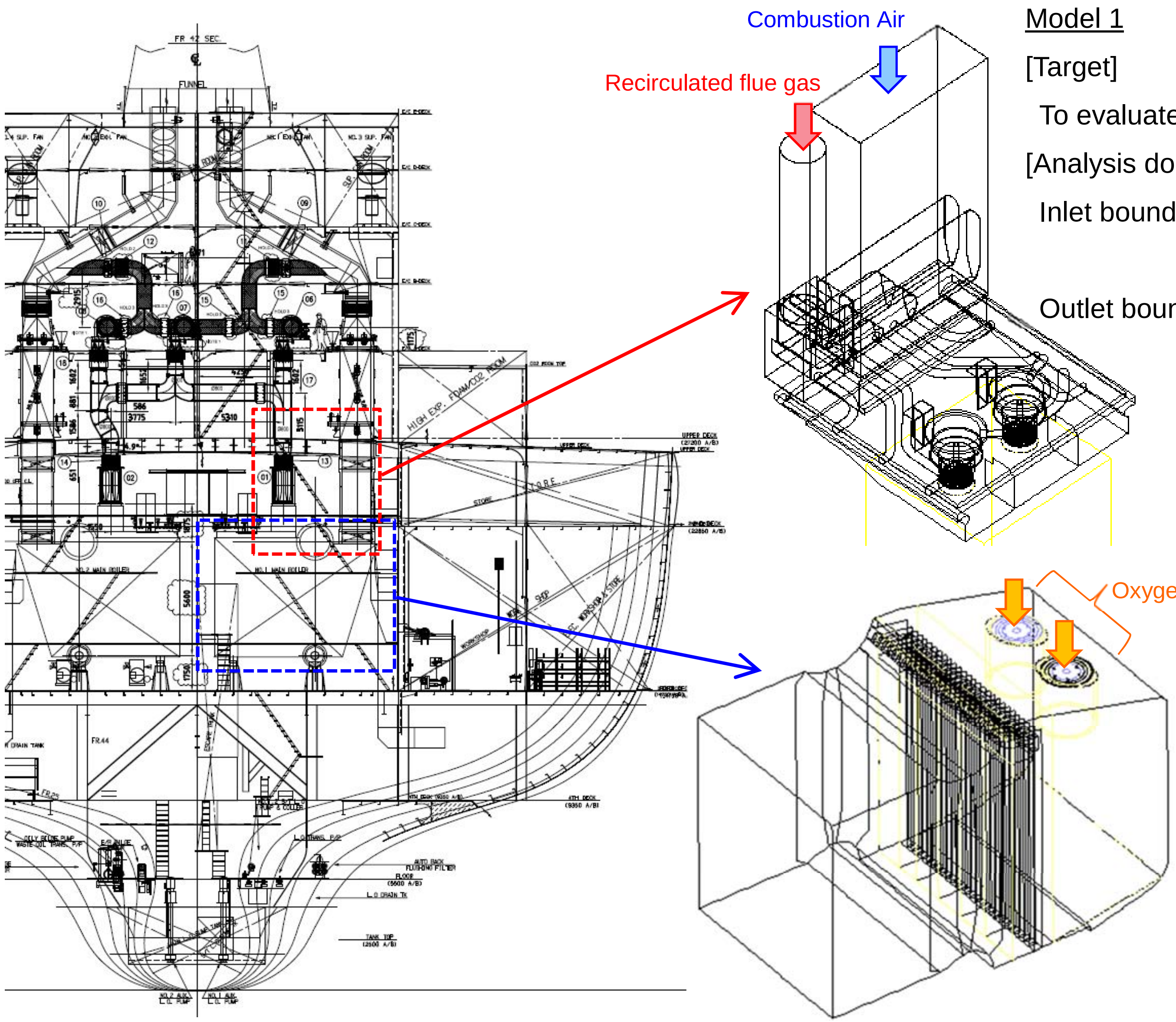
3. Outline of CFD Analysis

Two analysis evaluations as shown below were carried out. The outline of each analysis model is shown in Fig. 2-1.

[The aim of analysis evaluation]

Model 1
Target:
To evaluate flue gas mixing in the burner wind-box
Analysis domain:
Inlet boundary area: inlet area of the duct connecting to the wind-box
Outlet boundary area: outlet area of the burner

Model 2
Target: To evaluate the combustion flame regime under the oxygen bias condition
Analysis domain:
Inlet boundary area: outlet area of the burner
Outlet boundary area: cross-section area of bank tube outlet



Model 1

[Target]

To evaluate flue gas mixing in the burner wind-box

[Analysis domain]

Inlet boundary area: inlet area of the duct connecting to the wind-box

Outlet boundary area: outlet area of the burner

Model 2

[Target]

To evaluate the combustion flame regime under the oxygen bias condition

[Analysis domain]

Inlet boundary area: outlet area of the burner

Outlet boundary area: cross-section area of bank tube outlet

Fig. 3-1 The outline of each analysis model

4. Evaluation of O2 deviation formed between burners when increasing the FGR rate

When FGR rate is increased, mixing condition regarding the FGR gas and combustion air may change. Due to this factor, expansion of O2 deviation formed between burners is a concern.

4.1 Analysis model and analysis condition

Analysis model

The analysis model used for evaluating the mixing condition is shown in Fig. 4-1.

As an analytic area, FGR gas duct entrance and the wind-box duct entrance were made into the inflow boundary area, respectively. The domain which imitated the space of a combustion chamber was modeled and set up the outflow boundary area.

In addition, it was presupposed to the inflow boundary area that the 5 times as much run-up section as a duct diameter is prepared so that flow separation might not come out to the flow which flows into the inside of a wind box.

Analysis condition

The analysis conditions (inflow boundary condition) are shown in Table 4-1. Evaluation was carried out in two Steps.

Step 1: Reappearance calculation of the existing actual condition
Purpose: To evaluate the validity of an analysis model

Step 2: Evaluation of the change of O2 deviation in two burners in case that FGR gas mass flow is increased
Purpose: Quantification of the subject for NOx reduction in case that FGR rare is increased

In mixing calculation of FGR gas and combustion air at mixture, the temperature difference for FGR gas and combustion air was taken into consideration. For this reason, the influence of heat conduction through the mixture wall surface was considered.

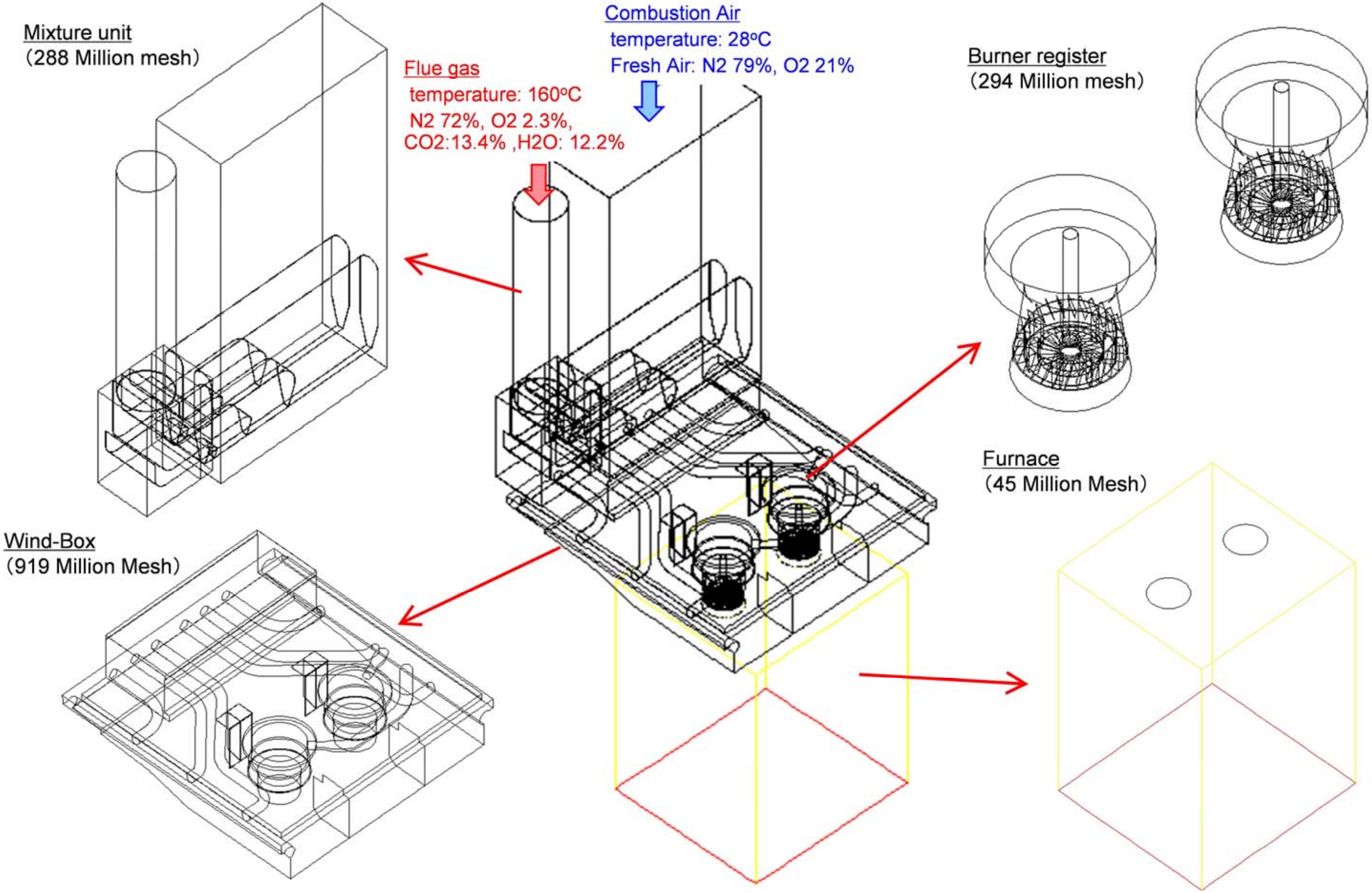


Fig.4-1 Mixed analysis model

Table 4-1 Analysis condition

		Base	Case 1	Case 2	Case 3
		2013/9/6			
		14:30			
		FGR 1.3			
target boiler	–	NO.1	NO.1	NO.1	NO.1
O2 concentration_boiler front	%	17.2			
O2 concentration_boiler rear	%	19.0			
O2 concentration_boiler total	%	18.1	17.2	16.3	15.4
Excess Air Ratio	–	**1.12**	**1.12**	**1.12**	**1.12**
O2 concentration at boiler outlet	%	2.2	2.2	2.2	2.2
FGR ratio_boiler front	%	20.2			
FGR ratio_boiler rear	%	10.6			
FGR ratio_boiler total	%	15.4	20.0	25.0	30.0
Combustion gas					
Economizer outlet gas temperature	**℃**	**160.0**	**160.0**	**160.0**	**160.0**
fuel flow	kg/h	2310	2310	2310	2310
combustion air temperature	**℃**	**29**	**29**	**29**	**29**
combustion gas flow／fuel flow	kg/kg	20.67	20.67	20.67	20.67
combustion air flow	**kg/h**	**45438**	**45438**	**45438**	**45438**
combustion gas flow	kg/h	56458	59685	63664	68211
GR gas flow	**kg/h**	**8710**	**11937**	**15916**	**20463**
specific heat of combustion gas	kcal/kg℃	0.327	0.327	0.327	0.327

4.2 Flow evaluation inside a mixture

1) Evaluation on system reappearance conditions

Regarding the mixture condition, the contour figure of temperature, absolute flow velocity and O2 concentration are shown in Fig. 4-2 - Fig. 4-4.

Moreover, O2 concentration contour (contour range is changed) in mixture is shown in Fig. 4-5 from the viewpoint of the impact evaluation by the condensation inside a mixture.

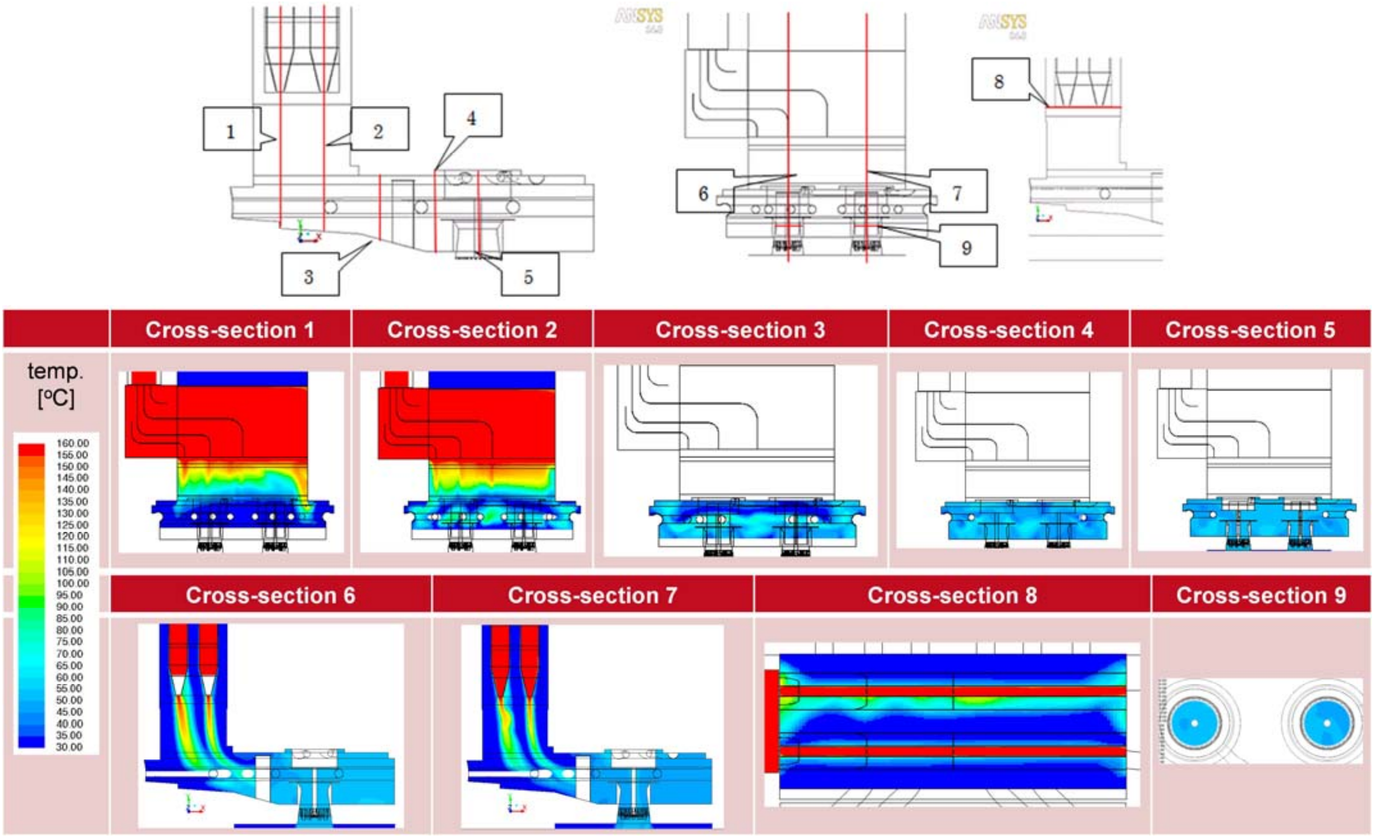


Fig.4-2 The temperature contour figure in a mixture

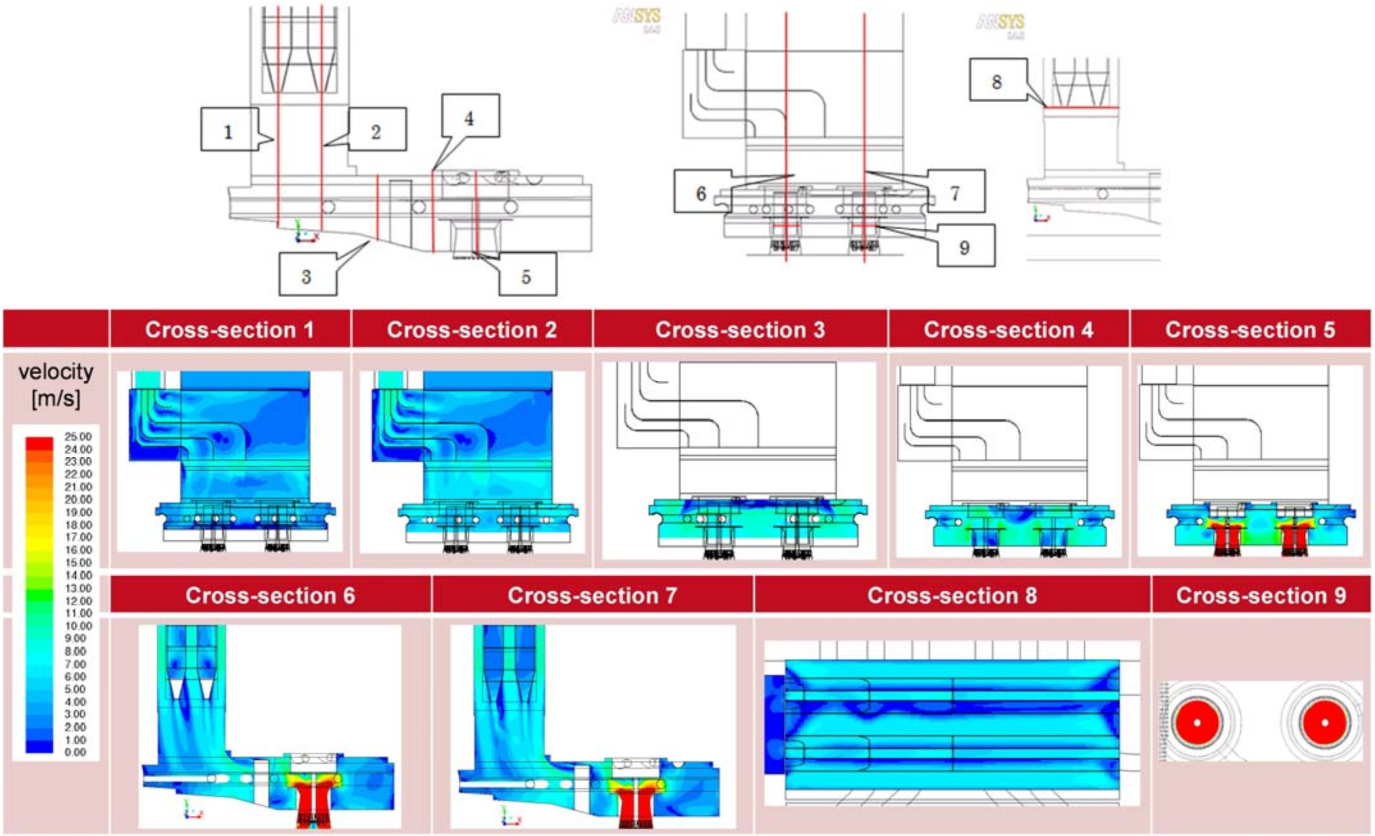


Fig.4-3 The absolute flow velocity contour figure in a mixture

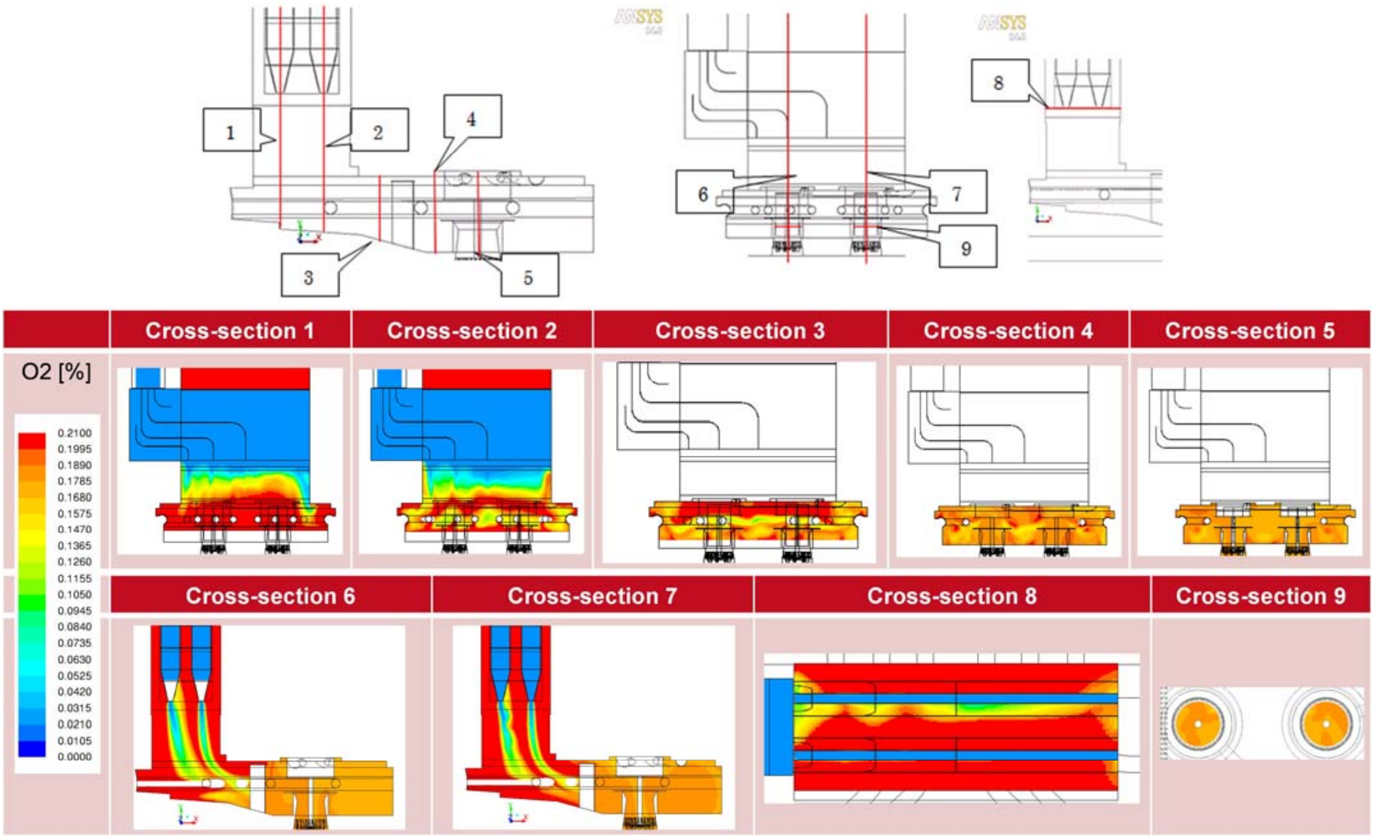


Fig.4-4 The O2 concentration contour figure in a mixture

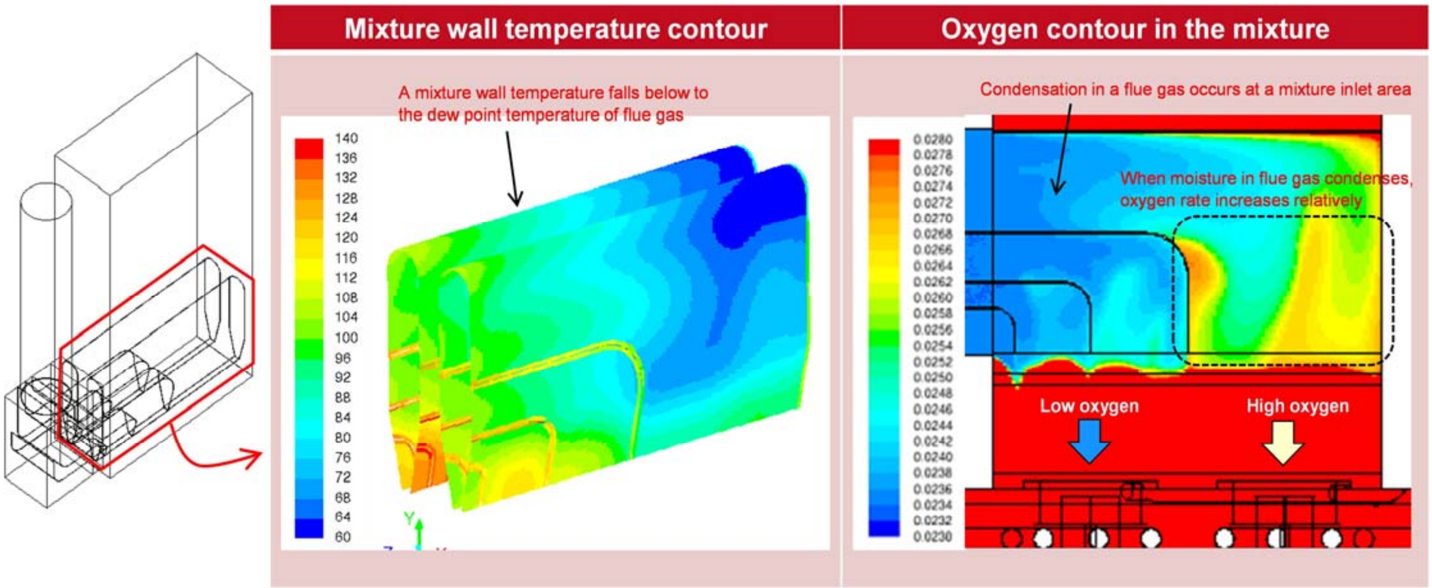


Fig.4-5 Evaluation of the mixed form in the inside of a mixed vessel

In this section, following are confirmed.

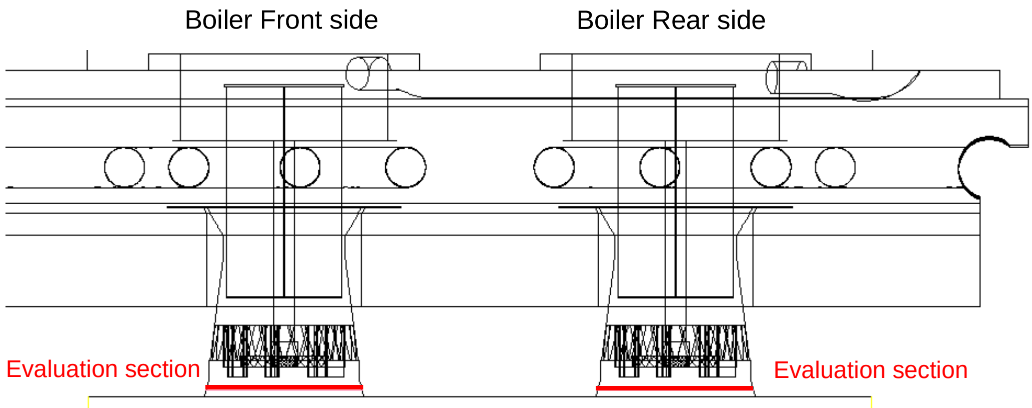
- With a flow of FGR gas, progress of mixture of temperature and O2 concentration slows near the central part in a wind box by narrowing the FGR gas exit area in the mixture. However, it was confirmed that mixture is promoted by the T type baffle fitted at the inlet of windbox.

- During the mixture, wall is cooled by the combustion air with ambient temperature which flows through the external surface, and wall temperature is decreased below the saturation temperature. This means that environment in the mixture generates the condensation.

- Moreover, since the condensation occurs near the mixture entrance, it was confirmed that a deviation of O2 concentration is formed between boiler front side and boiler rear side.

2) Evaluation of a condensation model

About the flow analysis including condensation in the mixed vessel described above, the O_2 concentration and the H_2O concentration of burner register cross section are shown in Fig. 4-6. In addition, the result without the consideration of condensation is also shown in order to compare the flow analysis result.



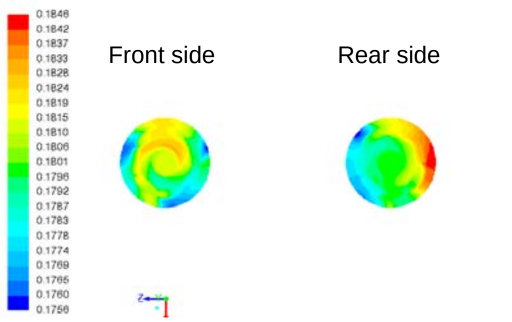
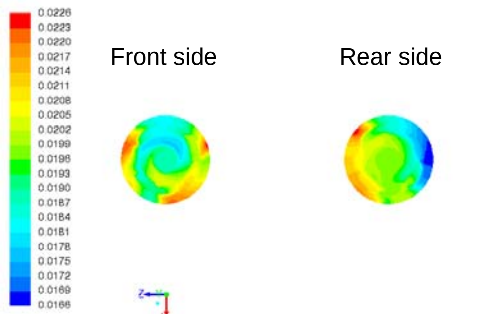
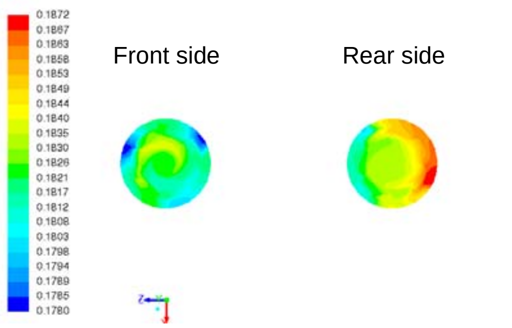
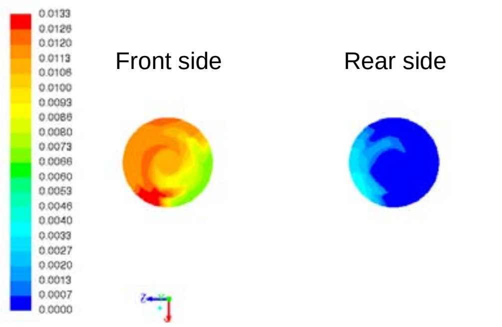
	O_2 Concentration [%]	H_2O Concentration [%]
Not including condensation	 Cross-sectional average : 18.0%(Front)、18.0%(Rear)	 Cross-sectional average : 1.96%(Front)、1.95%(Rear)
including condensation	 Cross-sectional average : 18.2%(Front)、18.4%(Rear)	 Cross-sectional average : 1.05%(Front)、0.07%(Rear)

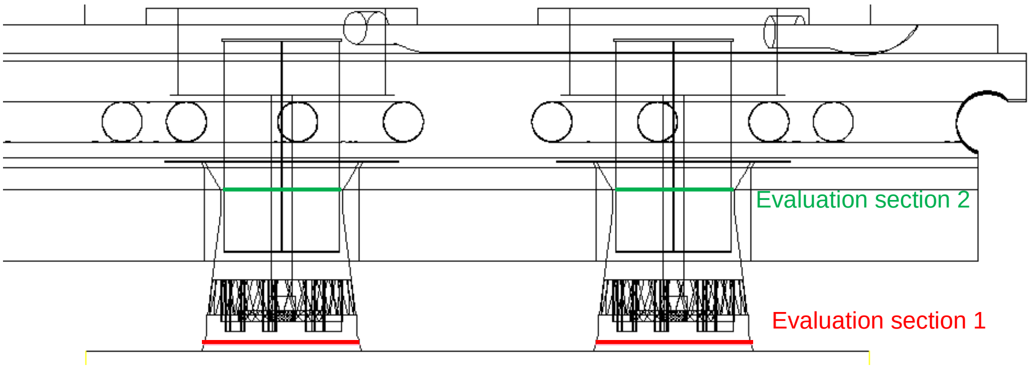
Fig.4-6 the O_2 concentration and the H_2O concentration of burner register cross section

- The O_2 deviation did not appear between two burners in the analysis which does not include condensation, but the O_2 deviation is formed between burners in the analysis when including condensation.

3) Consideration about the phenomenon with existing actual system

Based on the results shown above, the phenomenon with existing actual system is supposed to be as follow:

"O2 deviation confirmed with the existing system is a just local value (near a register entrance, near cross-section 2 of the following figure) by using the gas sampling meter inserted from the burner part, and O2 deviation is not formed as a cross-sectional average."



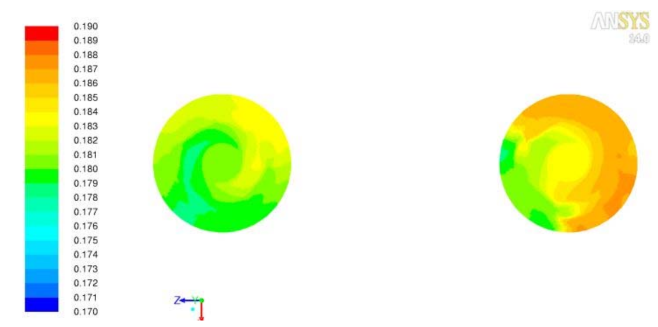
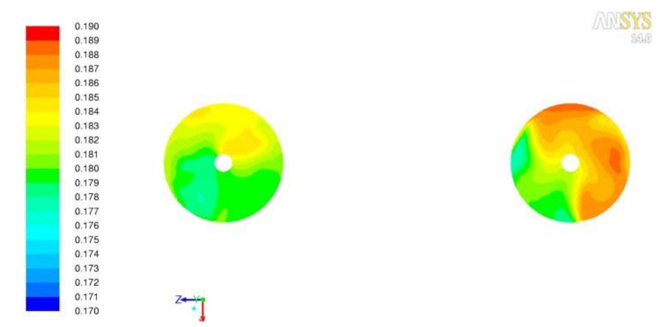
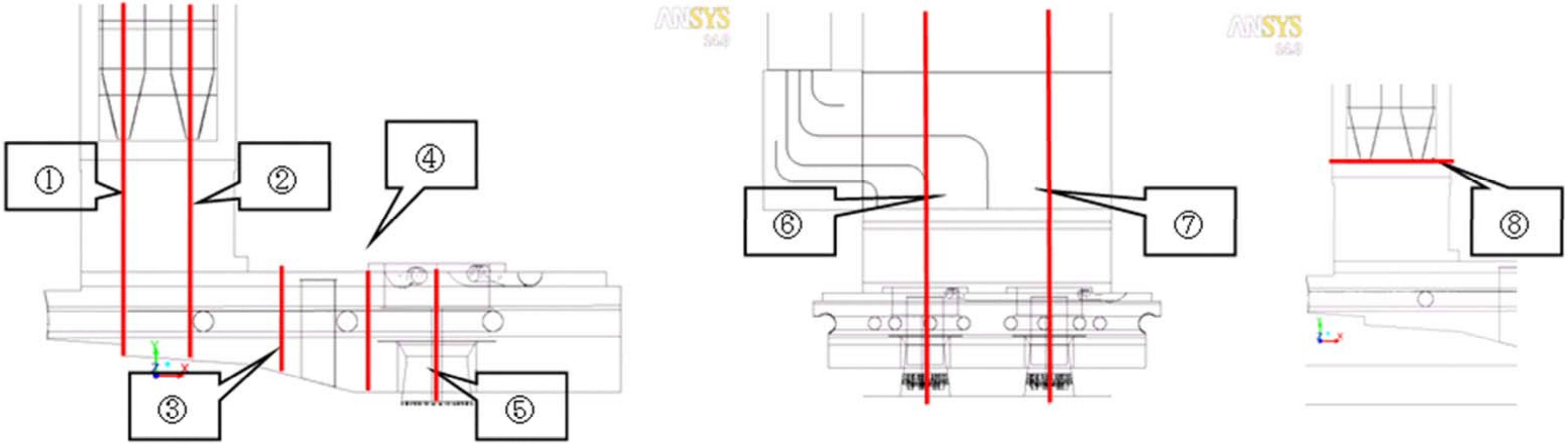
O2 Concentration in evaluation section 1 [%]	O2 Concentration in evaluation section 2 [%]
	
Average : 18.2%(Front)、18.4%(Rear) Local MAX : 18.7%(Rear) Local MIN : 17.8%(Front)	Average : 18.1%(Front)、18.4%(Rear) Local MAX : 19.1%(Rear) Local MIN : 16.7%(Front) It is 2.4% as O2 deviation

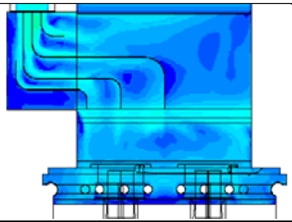
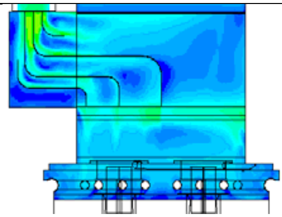
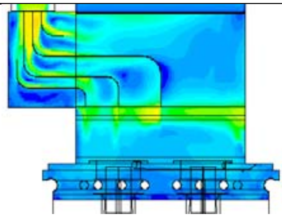
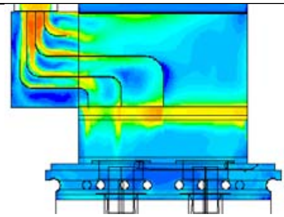
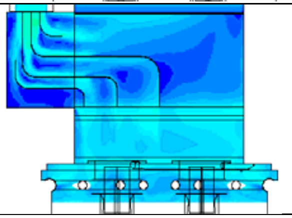
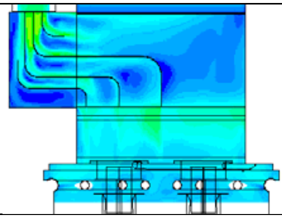
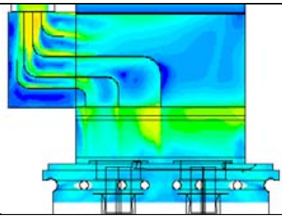
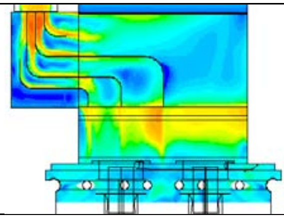
Fig.4-7 O2 contour in a burner register

4.3 Mixed evaluation in case of increasing the FGR rate

Next, to reduce the NOx emission, the result with further increasing FGR rate from the present condition is shown below.

About a flow inside a mixture and a wind box, the contour figure of the absolute flow velocity, static pressure, and O2 concentration is shown in Fig. 4-8 - Fig. 4-10. Moreover, it compares with Fig. 4-11 about the streamline inside a wind box as an aspect of a flow.



Cross section	range	FGR=15%	FGR=20%	FGR=25%	FGR=30%
section (1) Mixed vessel center #1	Absolute flow velocity [m/s]				
section (2) Mixed vessel center #2					

section (3) Between a mixed vessel to burners #1	
section (4) Between a mixed vessel to burners #2	
section (5) Burner center	
section (6) Boiler front side Burner center	
section (7) Boiler rear side Burner center	

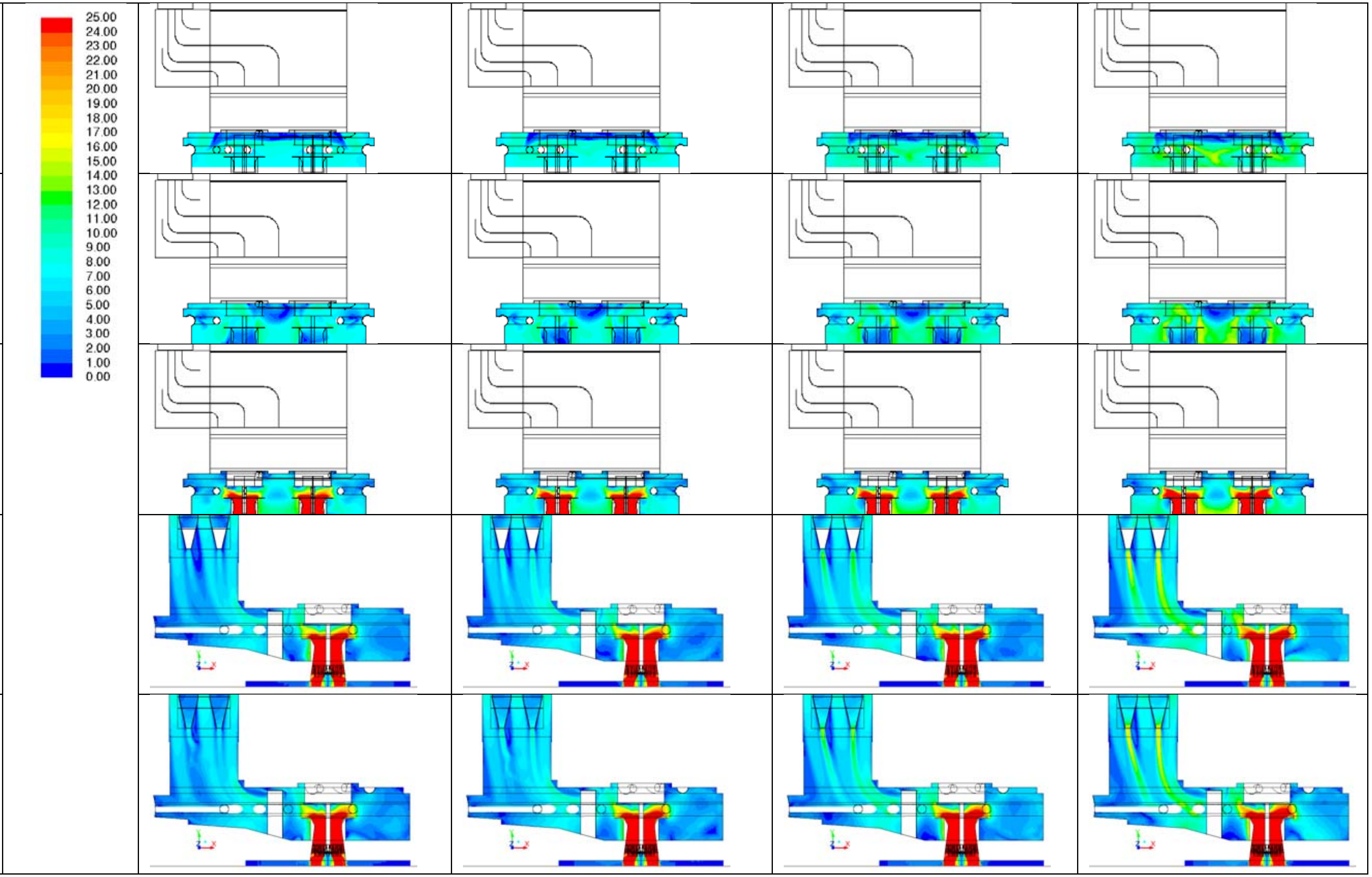
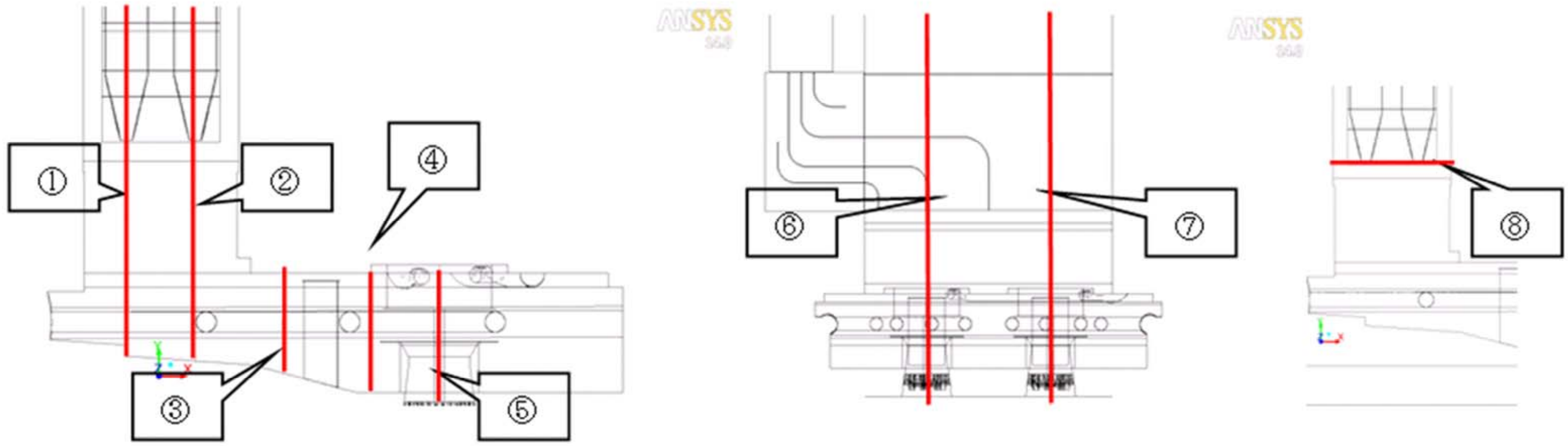
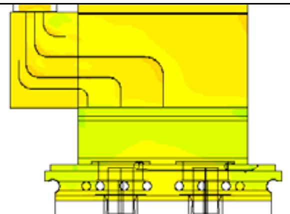
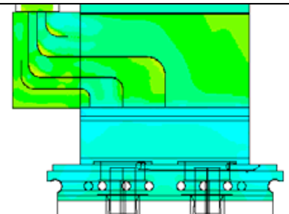
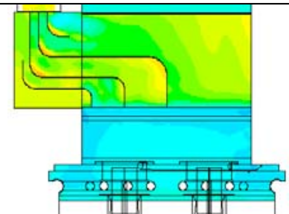
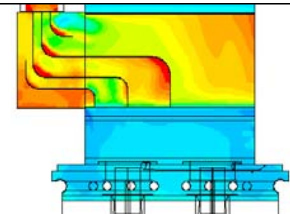
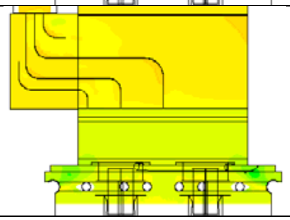
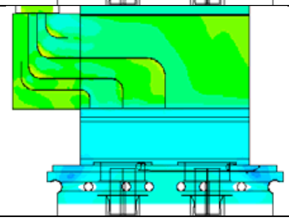
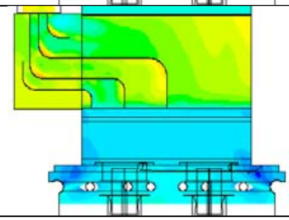
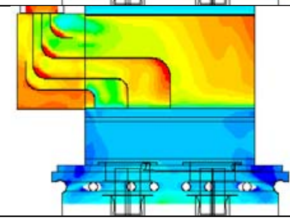


Fig.4-8 Comparison of the absolute flow velocity



Cross section		FGR=15%	range	FGR=20%	range	FGR=25%	range	FGR=30%
section (1)	Static pressure [Pa]		Satic pressure [Pa]		Static pressure [Pa]		Static pressure [Pa]	
section (2)								

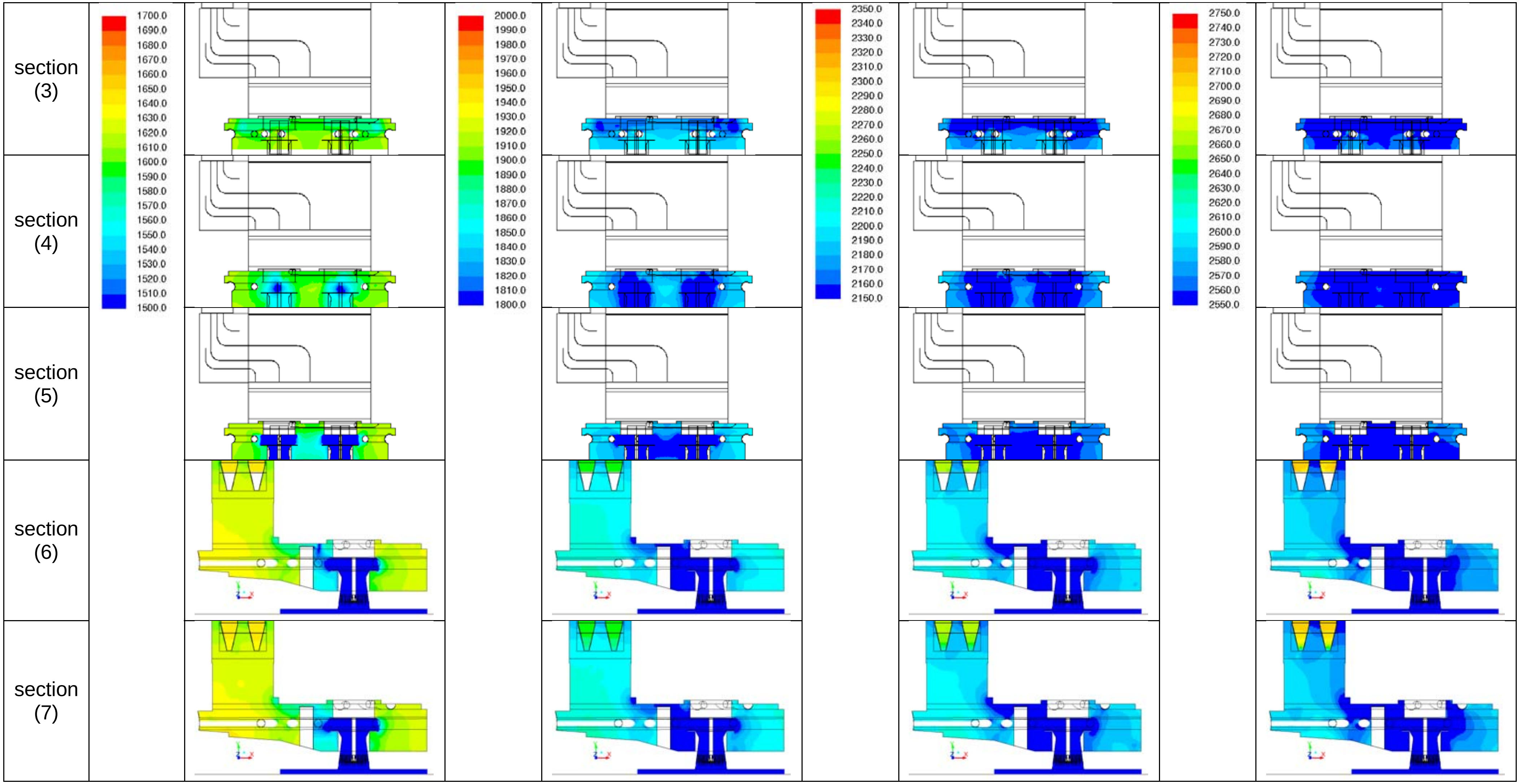
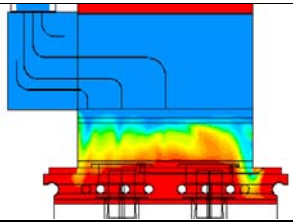
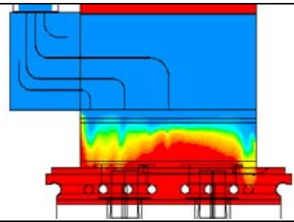
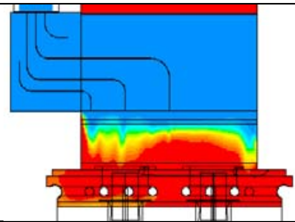
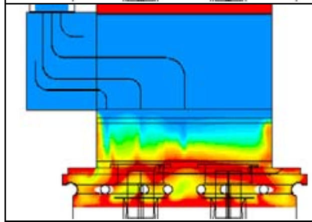
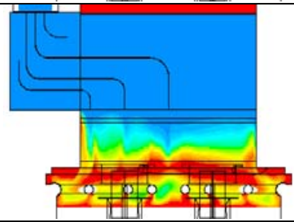
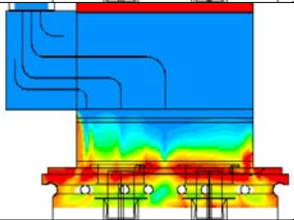
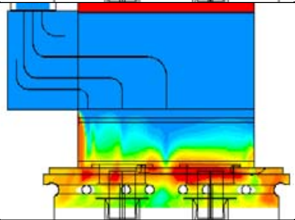
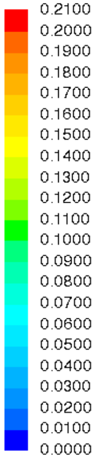
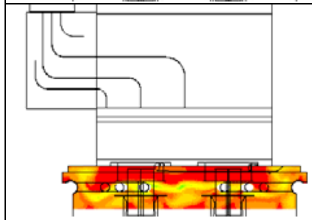
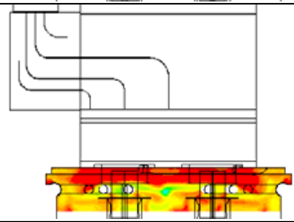
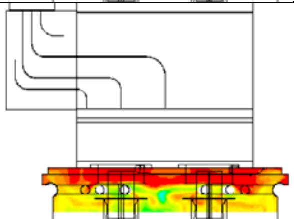
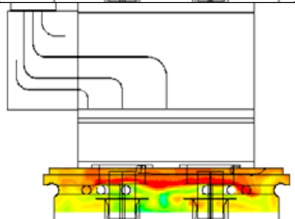
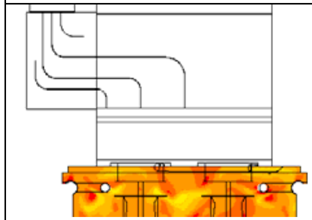
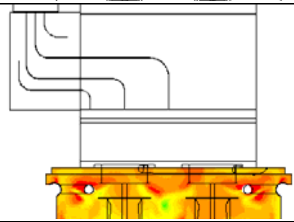
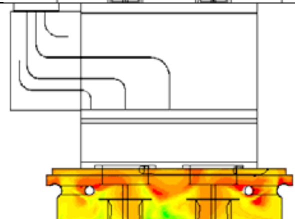
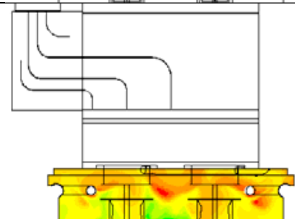
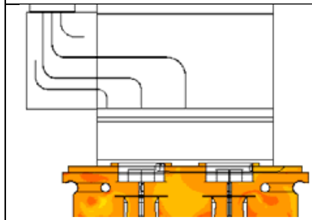
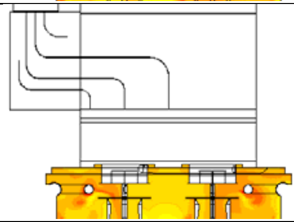
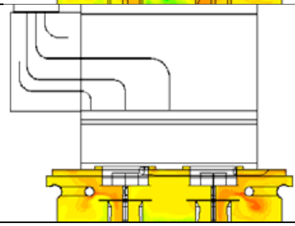
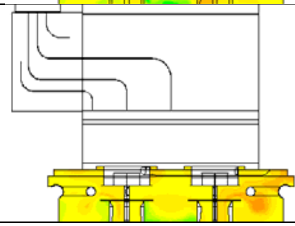
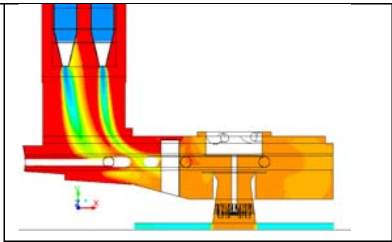
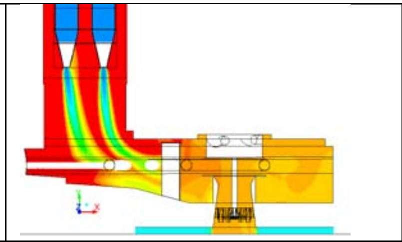
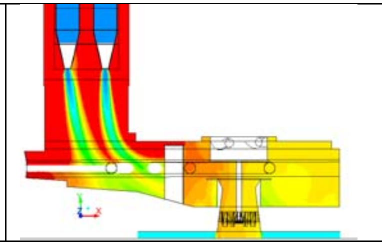
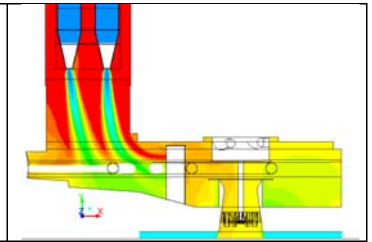
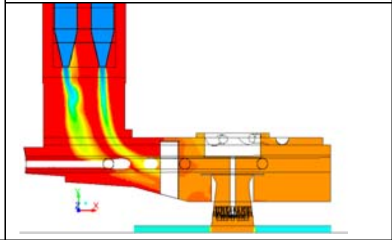
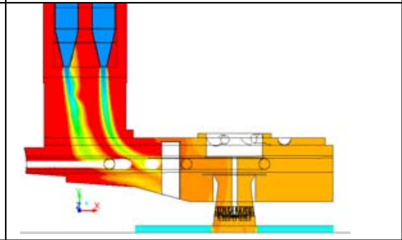
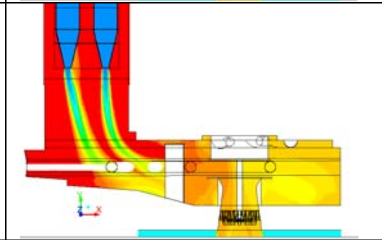
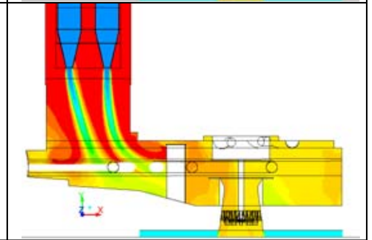
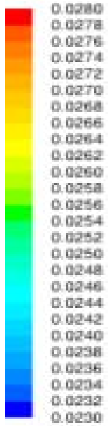
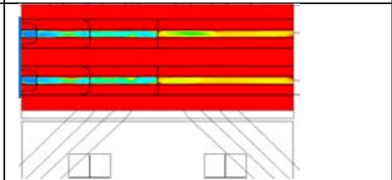
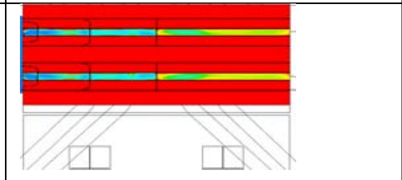
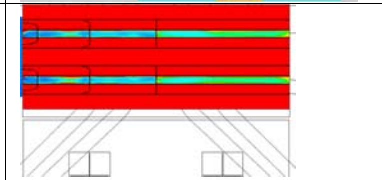
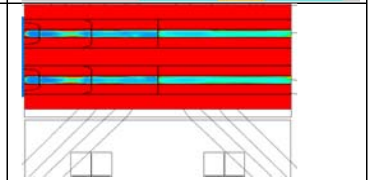
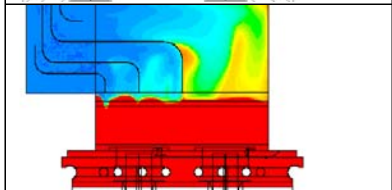
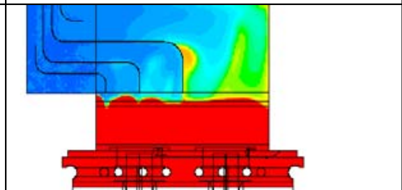
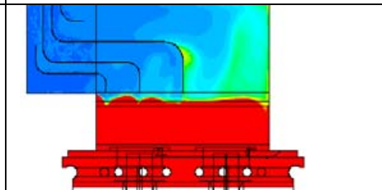
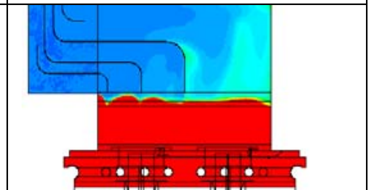
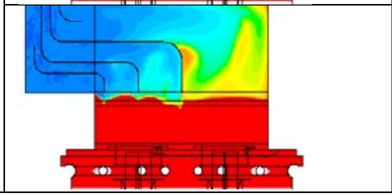
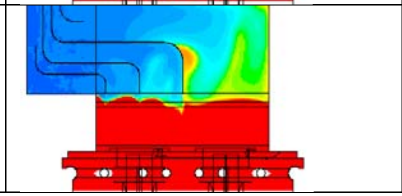
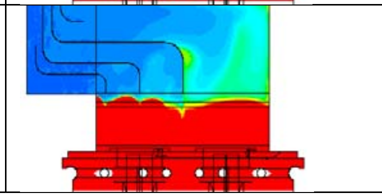
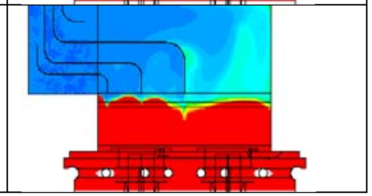


Fig.4-9 Comparison of the static pressure

Cross section	range	FGR=15%	FGR=20%	FGR=25%	FGR=30%
section (1) Mixed vessel center #1					
section (2) Mixed vessel center #2	O2 concentration [-]				
section (3) Between a mixed vessel to burners #1					
section (4) Between a mixed vessel to burners #2					
section (5) Burner center					

section (6) Boiler front side Burner center					
section (7) Boiler rear side Burner center					
section (8) outlet of the mixed vessel					
section (1) Range expansion					
section (2) Range expansion					

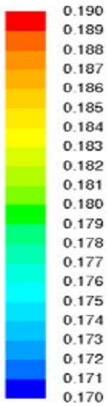
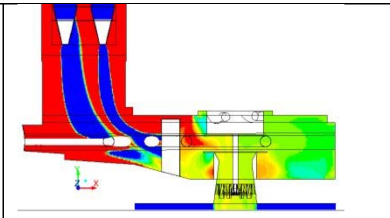
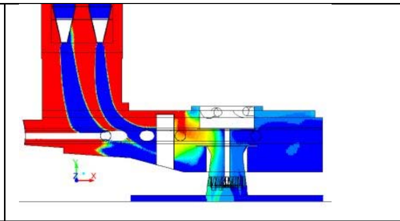
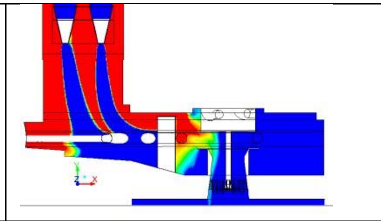
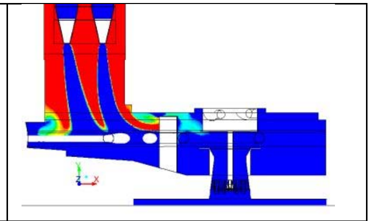
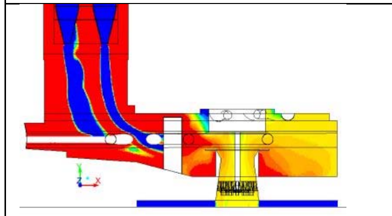
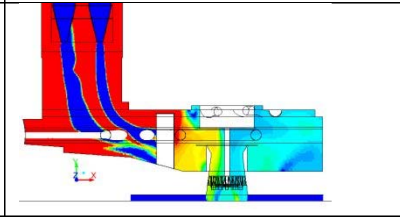
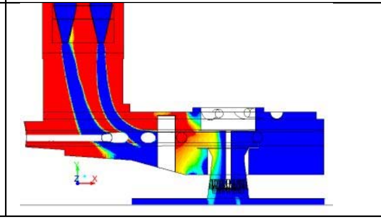
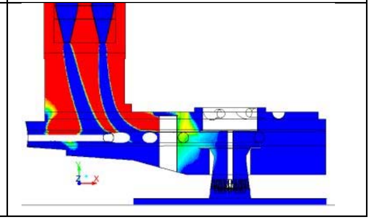
section (6) Range expansion					
section (7) Range expansion					

Fig.4-10　Comparison of the O2 concentration

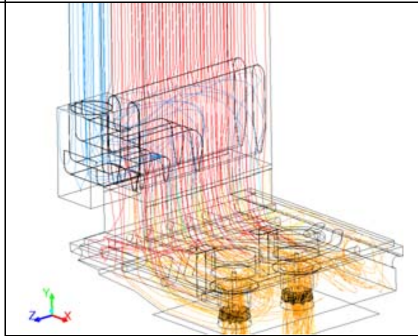
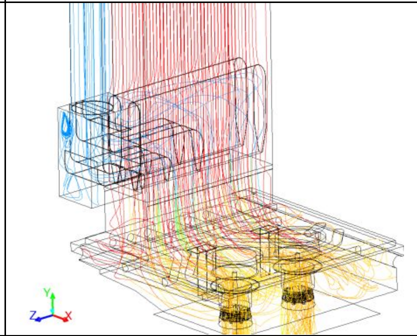
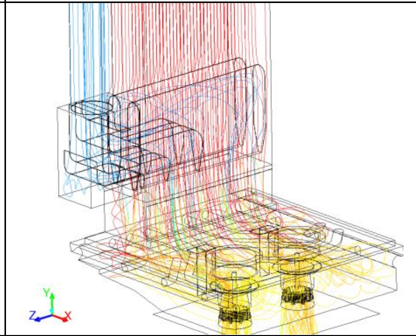
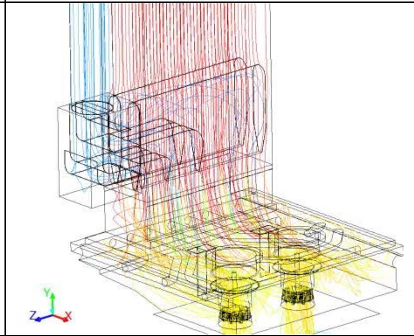
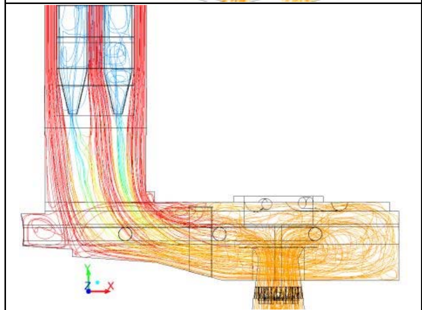
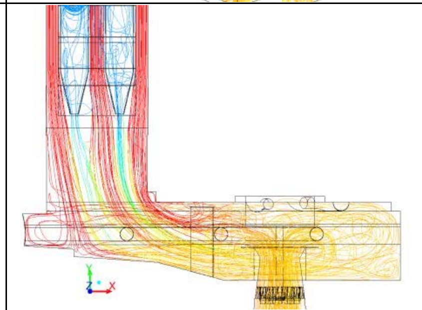
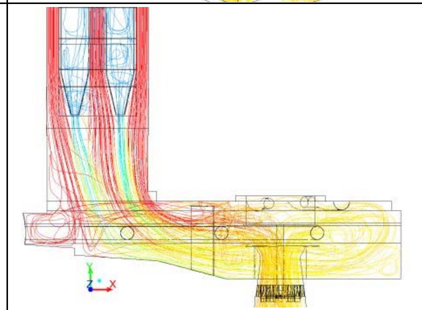
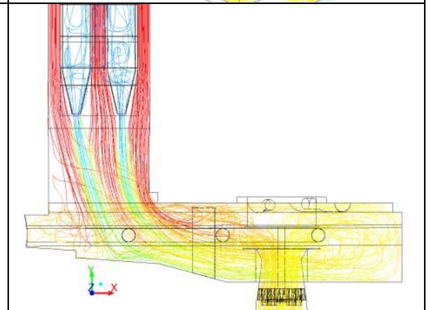
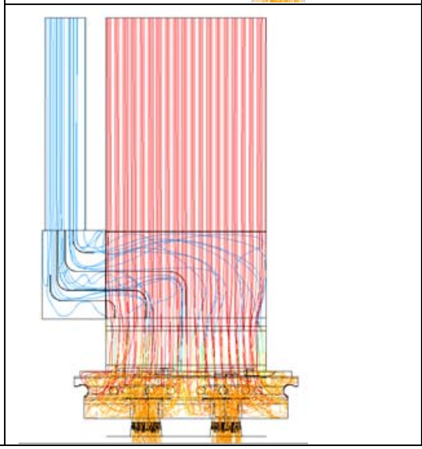
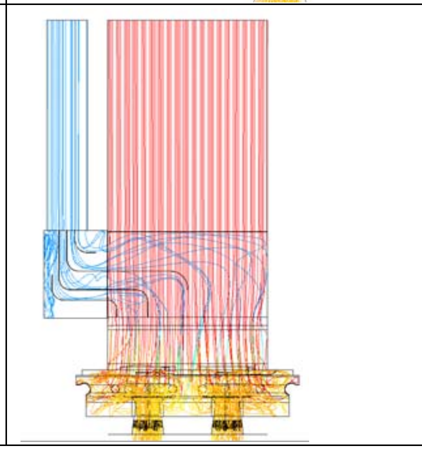
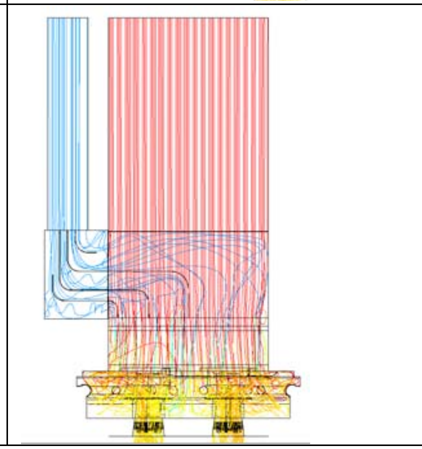
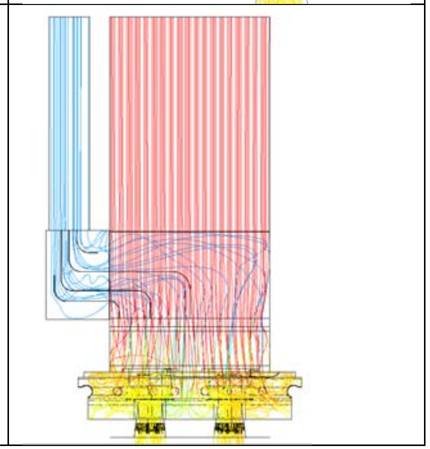
view	range	FGR=15%	FGR=20%	FGR=25%	FGR=30%
Bird's-eye view	O2 concentration [-] 0.2100 0.2000 0.1900 0.1800 0.1700 0.1600 0.1500 0.1400 0.1300 0.1200 0.1100 0.1000 0.0900 0.0800 0.0700 0.0600 0.0500 0.0400 0.0300 0.0200 0.0100 0.0000				
From boiler front side					
From boiler right side					

Fig.4-11 Comparison of the streamline inside a wind box

From these results, O2 deviation between two burners is shown in Fig. 4-12 as a factor which mostly influences boiler operation.

As mentioned above, local concentration distribution is formed in the burner register section, and O2 deviation is shown both register section average value and a local value.

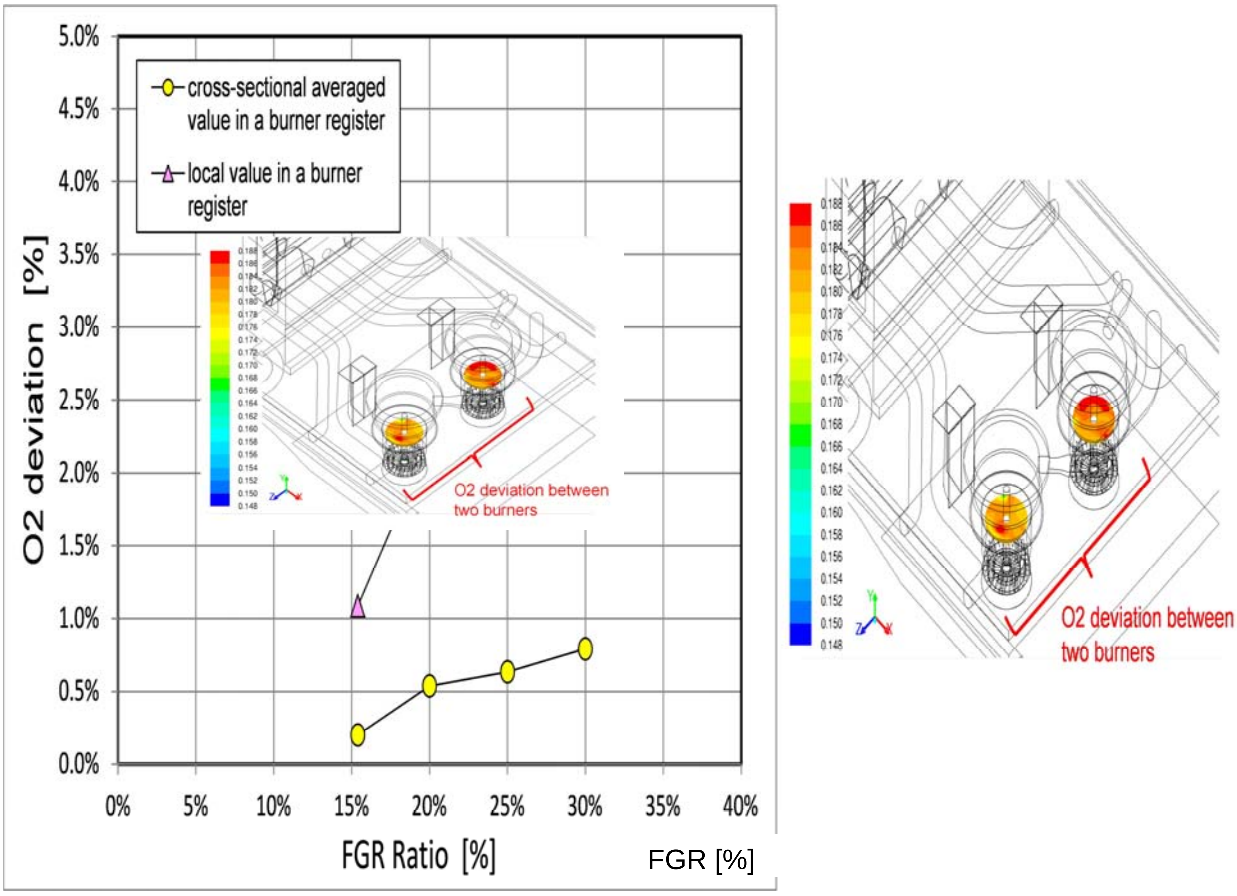


Fig.4-12 Change of O2 deviation between the burners in relation to FGR

- Although 1% or more of O2 deviation is formed as a local value, register section average value is 1% or less (about 0.8%) also in 30% of FGR. From this, it is considered that this O2 deviation range at average value is acceptable for boiler operation

5. The influence evaluation when O2 deviation is formed between burners
The combustion CFD evaluation was carried out with O2 deviation applied, considering the influence on the flame size and NOx characteristic.

5.1 analysis model and analysis condition

Analysis model

The outline of an analysis model is shown in Fig. 5-1.

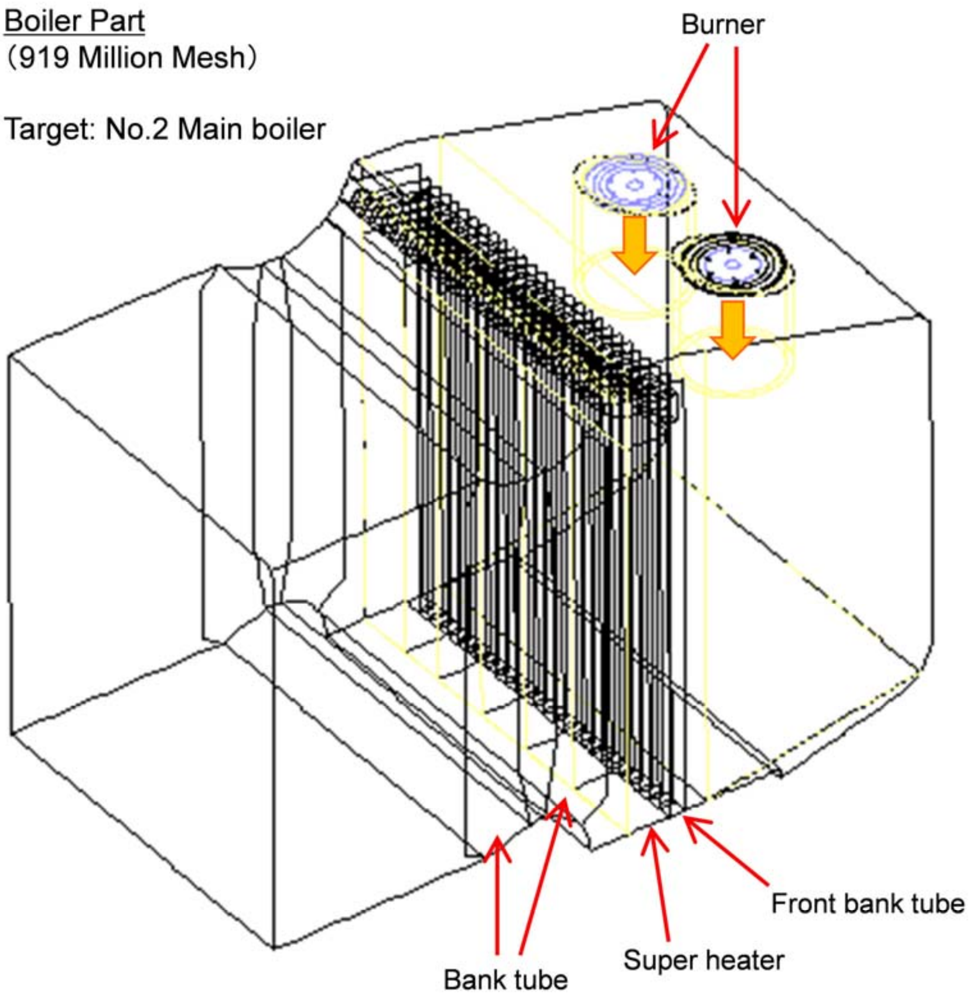


Fig. 5-1 the outline of analysis model

Analysis condition

The conditions are shown in Table 5-1.

In addition, the following assumption conditions are applied in calculation.

[assumption conditions in the analysis]

- Fuel gas chemical composition is CH4 100% base.
- Air mass flow distribution of a burner part is defined, using the actual measured profile.

- Combustion air temperature is 45 degrees-C of boiler planning conditions.
- Heating surface temperature is defined by boiler planning conditions.

Table 5-1 The evaluation conditions at the time of O2 deviation

[Analysis condition]

Fuel: CH4 100%
Boiler Load: 100% Normal Load
(Evaporation: 48t/h)
FGR: 15%

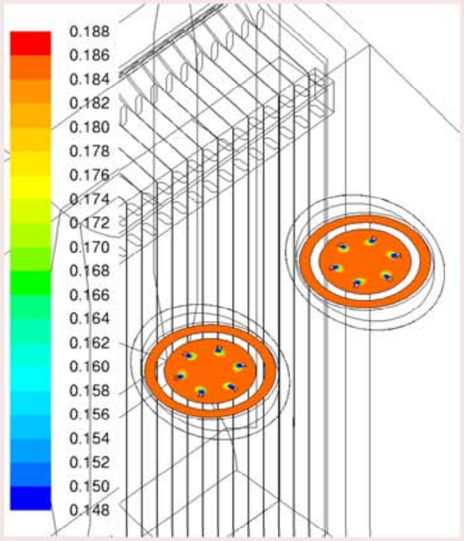
	Analysis condition	Front side [%]	Rear side [%]
Case1	● No Oxygen bias	18.5	18.5
Case2	● Oxygen bias condition (large deviation) ● With no O2 distribution in the burner register	17.7 (-0.75)	19.2 (+0.75)
Case 3	● Oxygen bias condition (small deviation) ● With no O2 distribution in the burner register	18.3 (-0.15)	18.6 (+0.15)
Case 4	● Oxygen bias condition (small deviation) ● With O2 distribution in the burner register	18.3 (-0.15)	18.6 (+0.15)

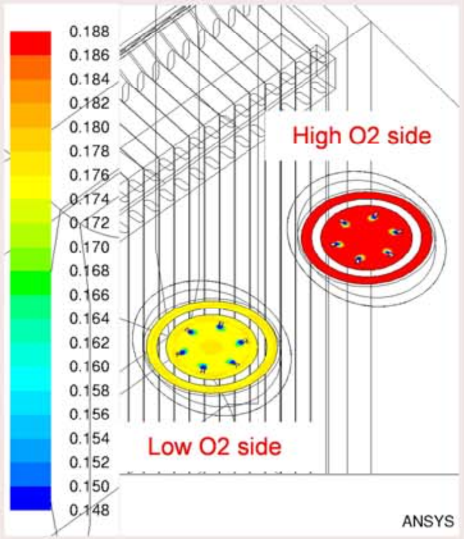
( ): the deviation from averaged value

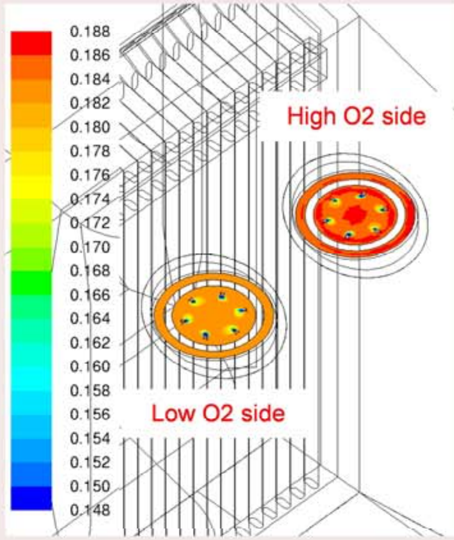
5.2 Analysis results

In analysis, O2 concentration contour defined at the burner register is shown in Fig. 5-2. The gas temperature contour and a NOx concentration contour in each section are shown in Fig. 5-3 and Fig. 5-4. The Isothermal temperature surfaces whose temperature of combustion gas is 1500 degrees-C as shown in Fig. 5-5 from a viewpoint of identifying a flame profile.

Case 1	Case 2	Case 3	Case 4
Boiler plan conditions (with no O2 deviation between burners) ・O2 deviation between burners : none ・O2 concentration at burber (A cross-sectional average) front side: 18.5% rear side: 18.5% ・Distribution in a section: none	1.5% of O2 deviation forms as a cross-sectional average between burners ・O2 deviation between burners : on ・O2 concentration at burber (A cross-sectional average) front side: 17.7% rear side: 19.2% ・Distribution in a section: none	0.3% of O2 deviation forms as a cross-sectional average between burners ・O2 deviation between burners : on ・O2 concentration at burber (A cross-sectional average) front side: 18.3% rear side: 18.6% ・Distribution in a section: none	2.4% of O2 deviation forms locally between burners (a cross-sectional average 0.3%) ・O2 deviation between burners : on ・O2 concentration at burber (A cross-sectional average) front side: 18.3% rear side: 18.6% ・Distribution in a section: on







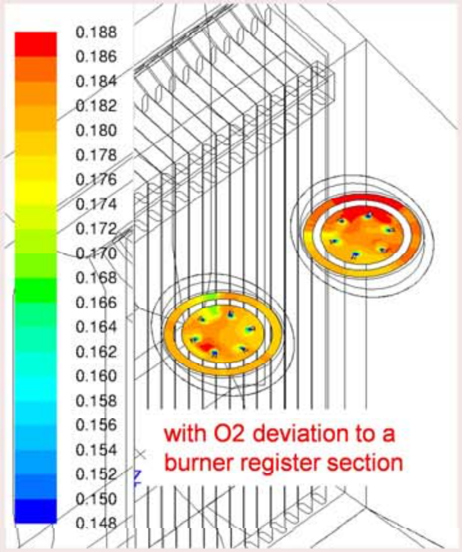


Fig.5-2 O2 concentration contour defined at the burner register

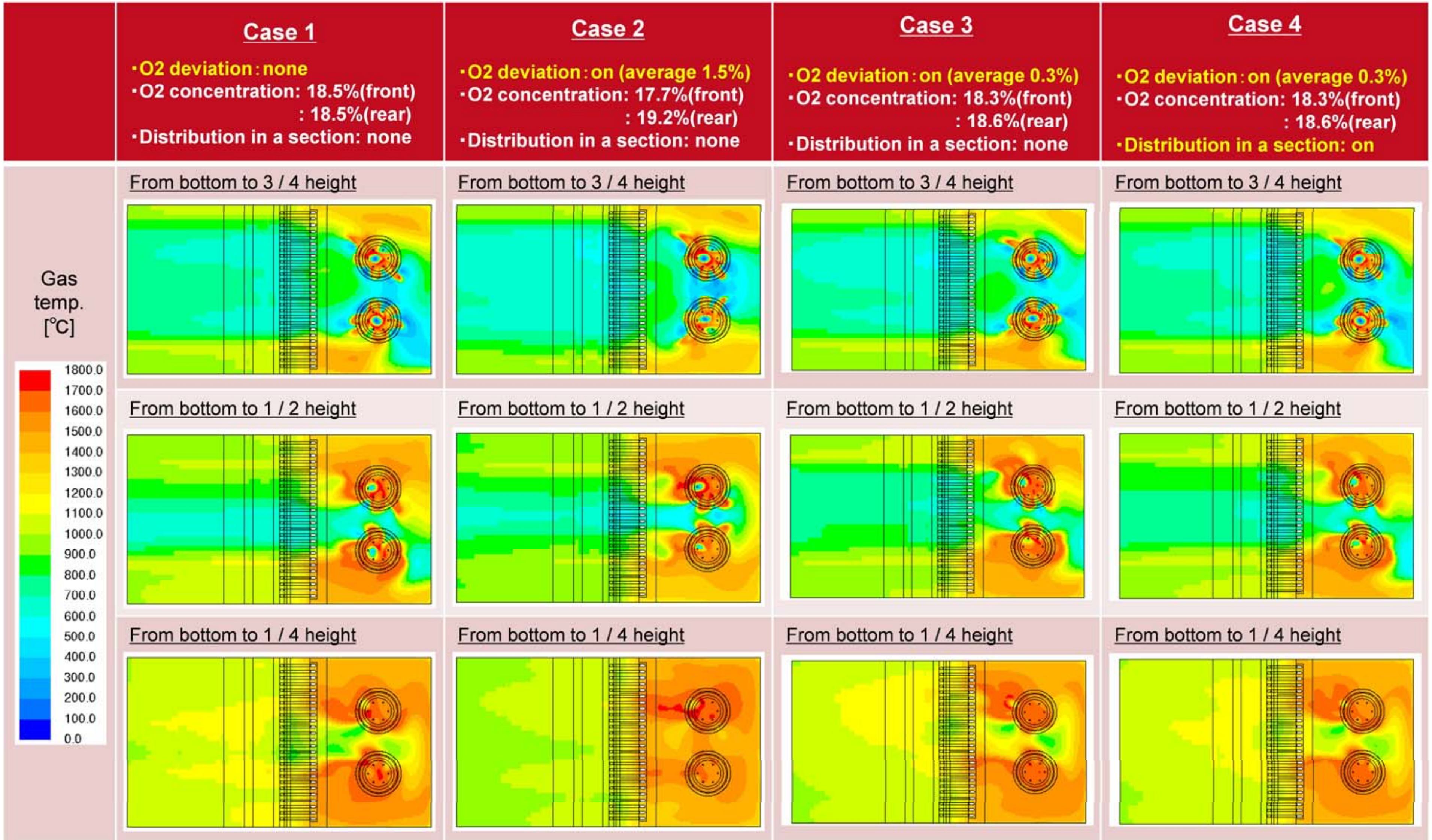


Fig.5-3 Gas temperature contour in the horizontal section

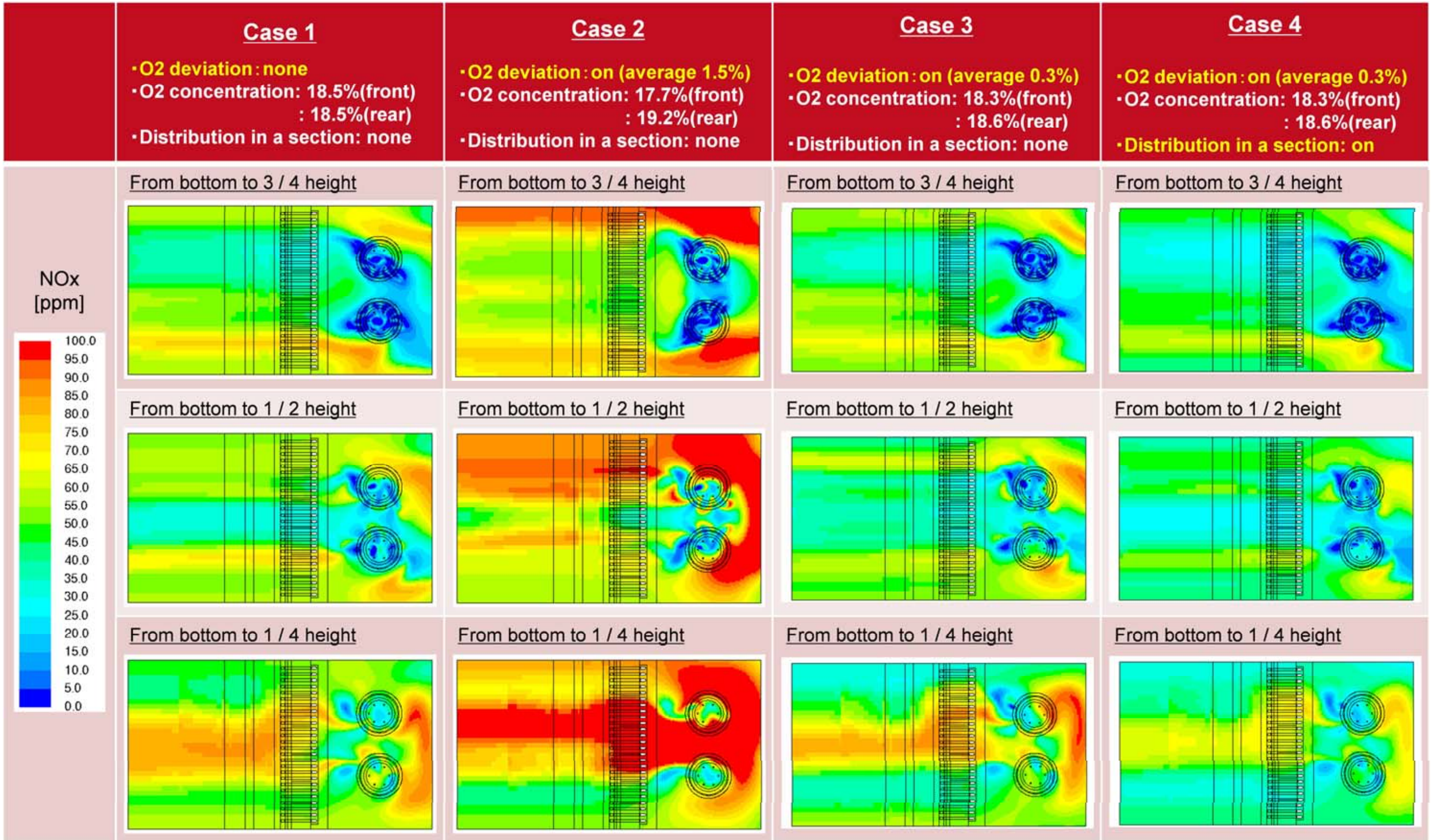


Fig.5-4 NOx concentration contour in the horizontal section

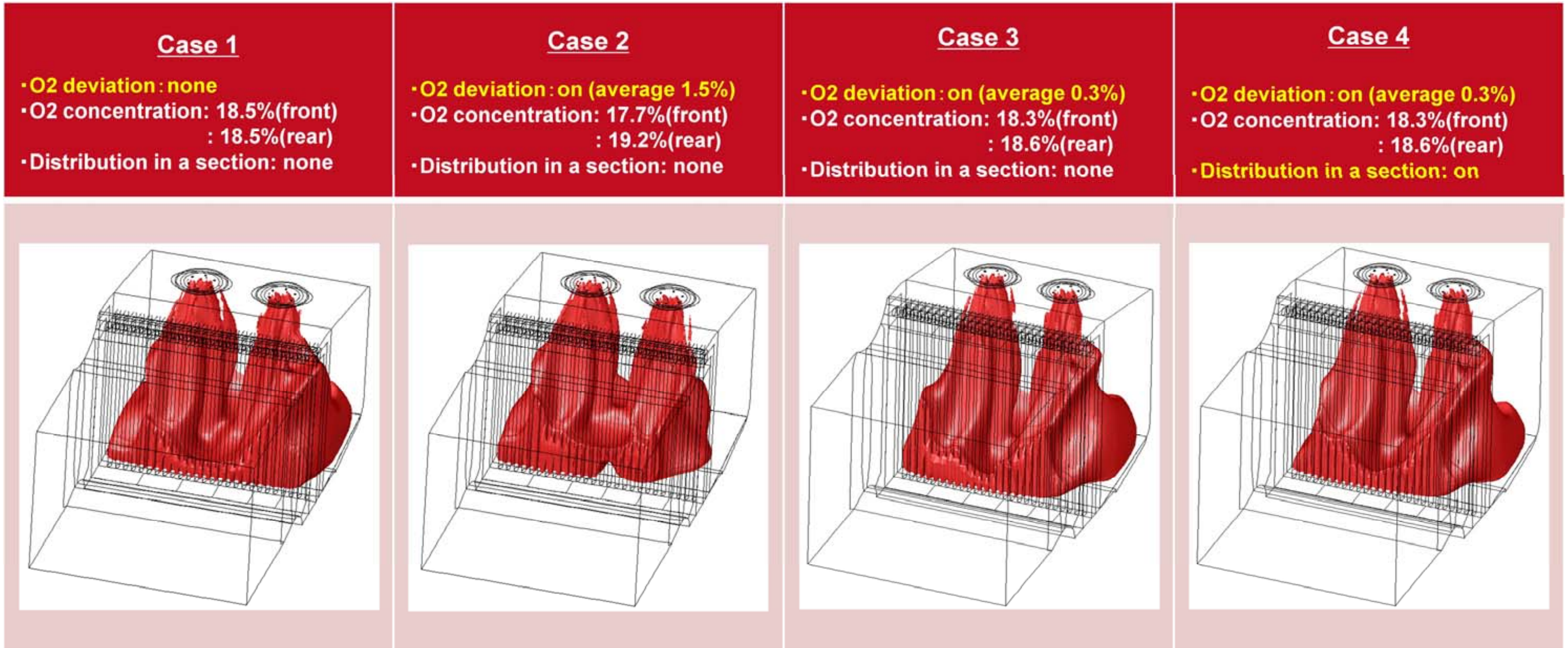


Fig.5-5 the Isothermal temperature surface whose temperature of combustion gas is 1500 degreesC

Comparison of the condition of a flame

According to the Fig. 5-6 about the condition of a flame, the followings were confirmed by comparing these results.

- By forming 1.5% of O2 deviation as a cross-sectional average between the burners, the stretch of a flame occurred at a high O2 side. This is concerned with hot combustion gas flowing into superheater tube section.
- On the other hand, if it is about 0.3% of O2 deviation as a cross-sectional average, the stretch of a flame did not occur at a high O2 side. In addition, in case of applying O2 local distribution, the stretch of a flame did not occur at a high O2 side. Hence, hot combustion gas does not flow into superheater tube section at 0.3% of O2 deviation on a cross-sectional average.

Comparison of the NOx characteristic

According to the Fig. 5-7 about the NOx value in a boiler exit, the followings were confirmed by comparing these results.

- When 1.5% of O2 deviation is formed by cross-sectional average between burners, the exit NOx increases. (about 38% increase)
- If it is 0.3% of O2 deviation in a cross-sectional average, NOx value is almost the same with case 1.
- When 1.5% of O2 deviation is locally formed between burners with 0.3% cross-sectional average condition, mixture of fuel and air is affected. According to these phenomena, gas temperature is decreased and NOx value is also decreased. (about 20% decrease)
- However, to identify the cross-sectional distribution at actual boiler operation is impossible, hence evaluation was carried out without O2 distribution as too severe side evaluation.

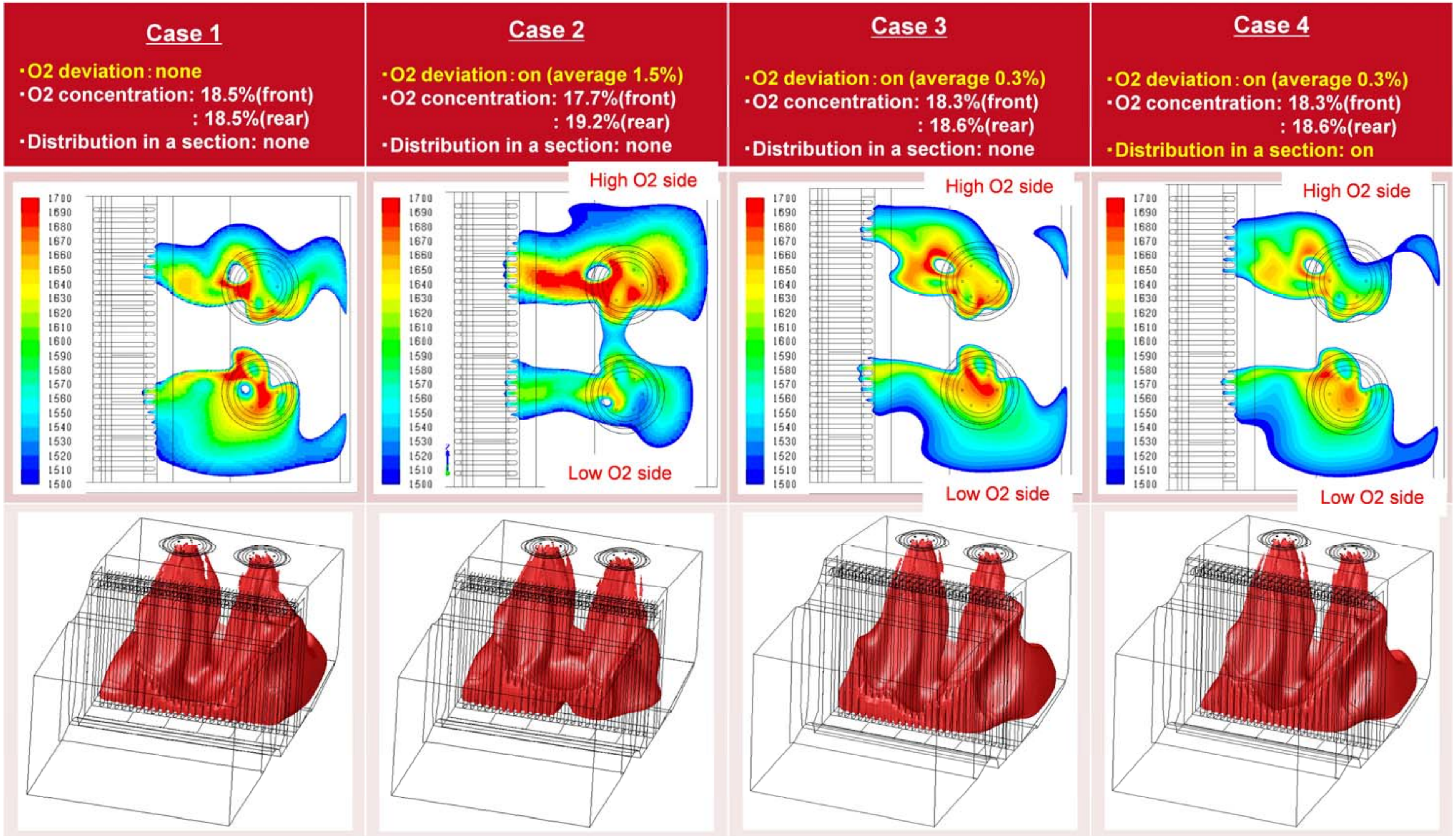
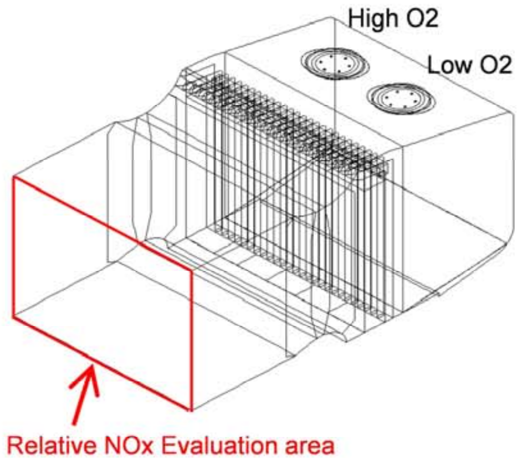


Fig.5-6 Comparison of the situation of a flame



	Analysis condition	Front side [%]	Rear side [%]
Case1	● No Oxygen bias	18.5	18.5
Case2	● Oxygen bias condition (large deviation) ● With no O2 distribution in the burner register	17.7 (-0.75)	19.2 (+0.75)
Case 3	● Oxygen bias condition (small deviation) ● With no O2 distribution in the burner register	18.3 (-0.15)	18.6 (+0.15)
Case 4	● Oxygen bias condition (small deviation) ● With O2 distribution in the burner register	18.3 (-0.15)	18.6 (+0.15)

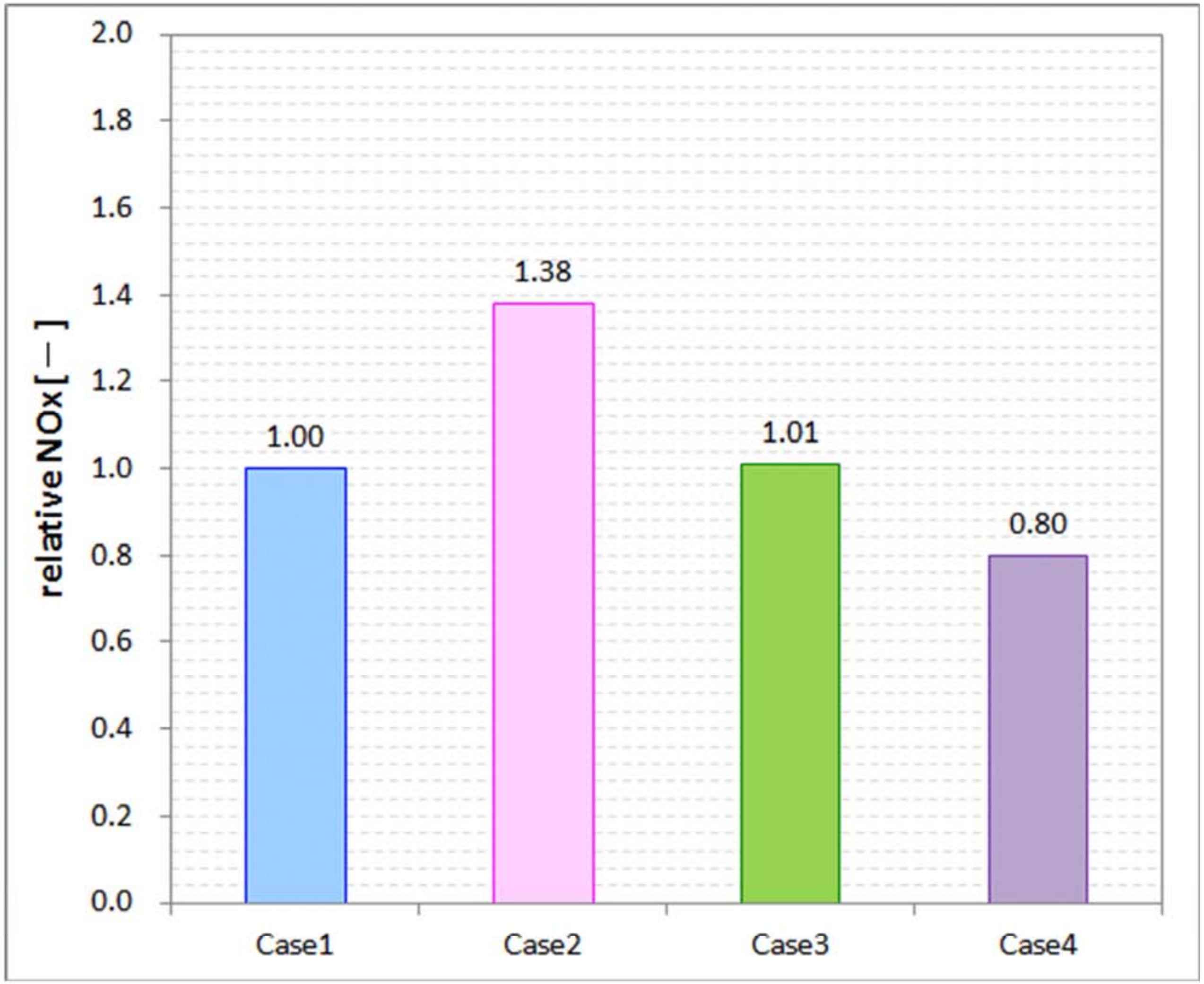


Fig.5-7 Comparison of the NOx characteristic

6. Impact evaluation of mixture modification

As mentioned above, during boiler operation, it is considered that there would be no big problem to increase FGR rate. However, the amount of water condensed inside a wind box increases with the increase of FGR gas volume. To prevent impact of the water condensation in the boiler, it is considered appropriate to fit the drain box in the duct.

Evaluation of this drain box was studied in this section.

6.1 Analysis model

The countermeasure structure for scuppering the drain generated inside the mixed vessel currently planned is shown in Fig. 6-1.

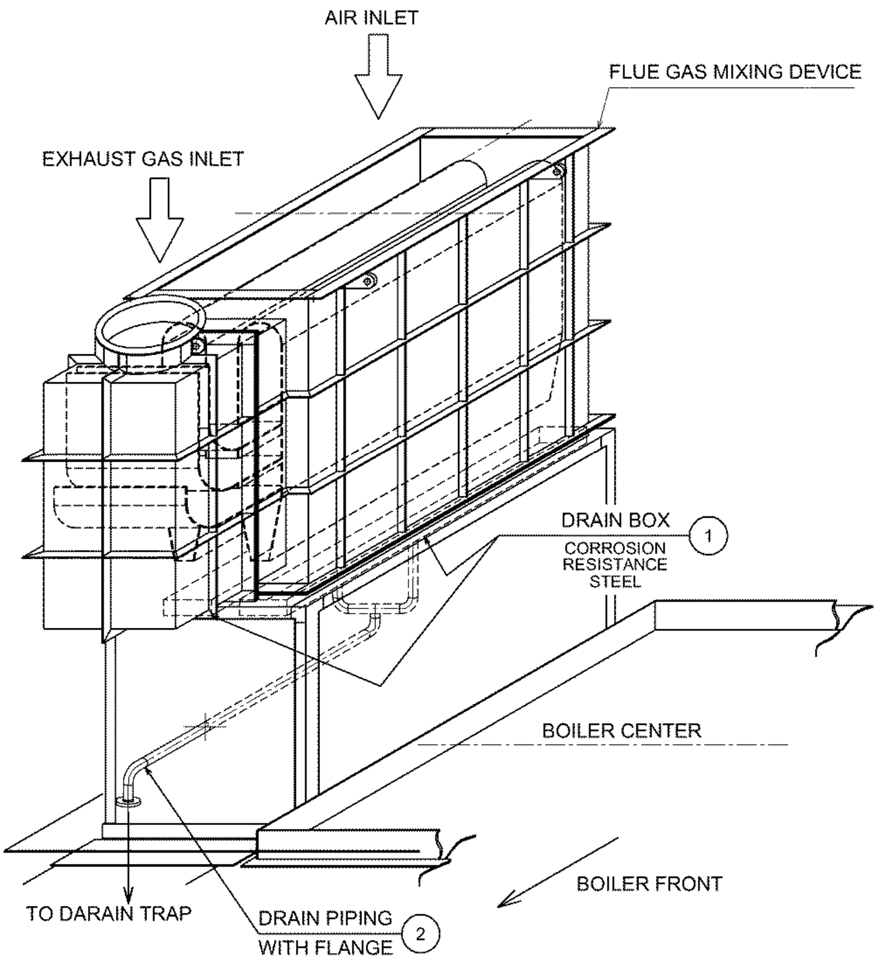


Fig.6-1 Drain scuppering structure proposal

The model in consideration of reconstruction structure is shown in Fig. 6-2 by contrast with the present mixed vessel structure.

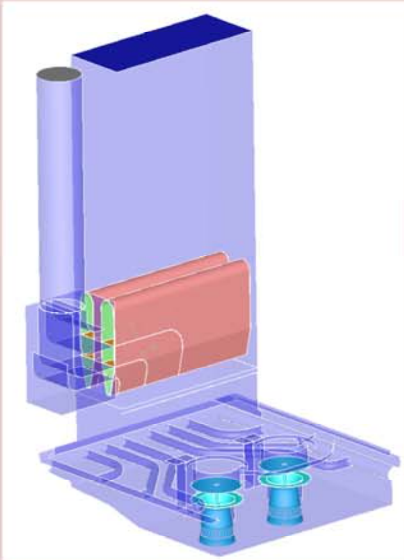
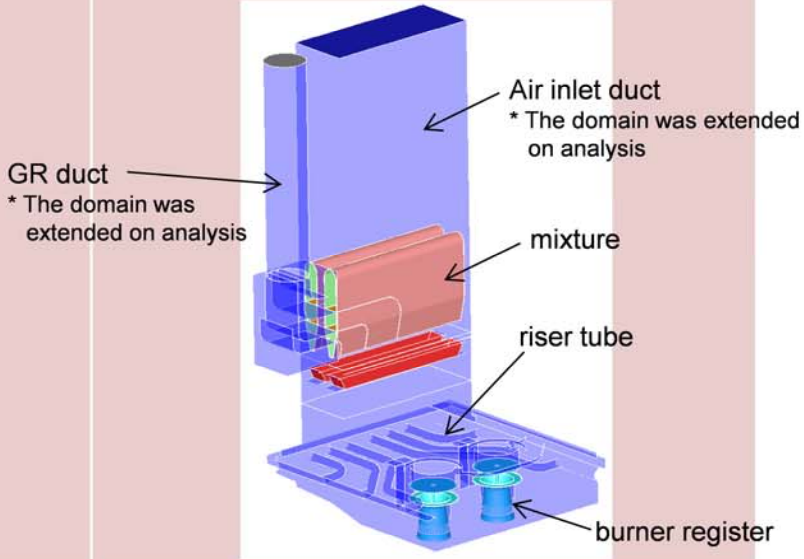
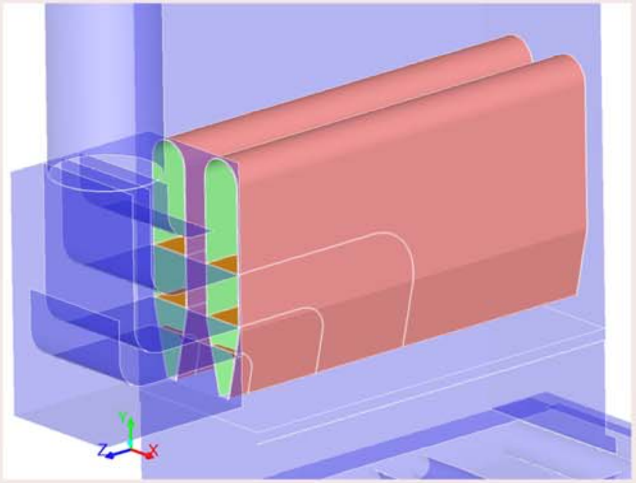
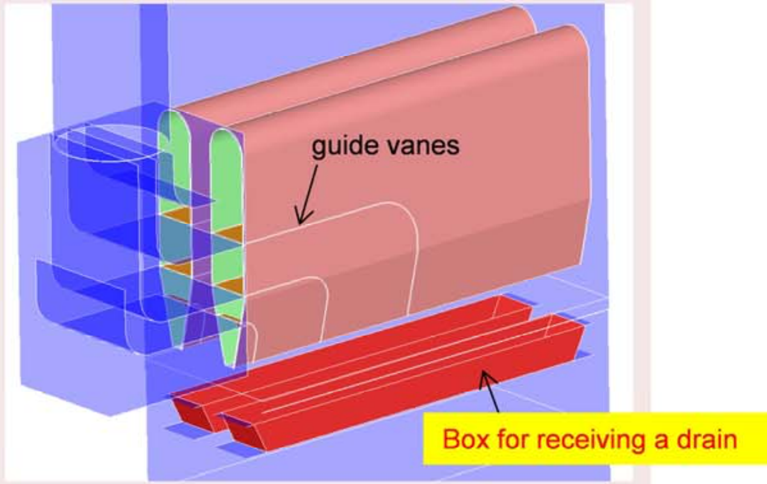
	Conventinal structure	Added drain BOX plan
General drawing of a mixture and a wind box		
The enlargement of measure structure		

Fig.6-2 The analysis model including countermeasure structure

6.2 Analysis results

<u>The flow pattern inside the wind box by drain BOX installation</u>
The flow pattern inside the wind box in case of installing the drain BOX at the mixture exit is shown in Fig. 6-3. The flow comparison in the wind box by drain BOX installation is shown in Fig. 6-4.

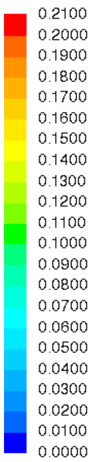
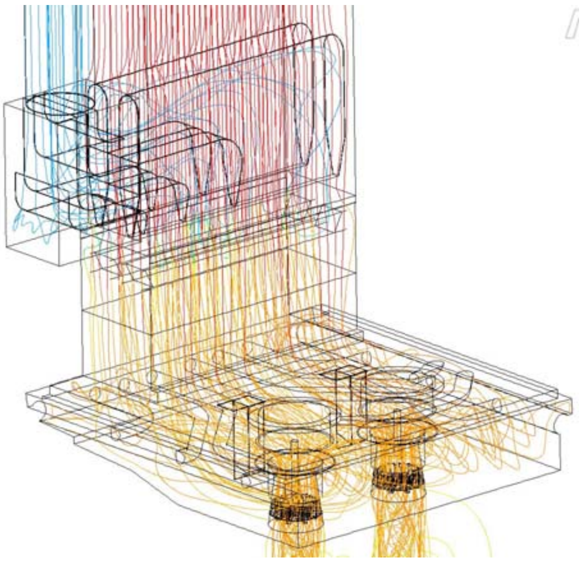
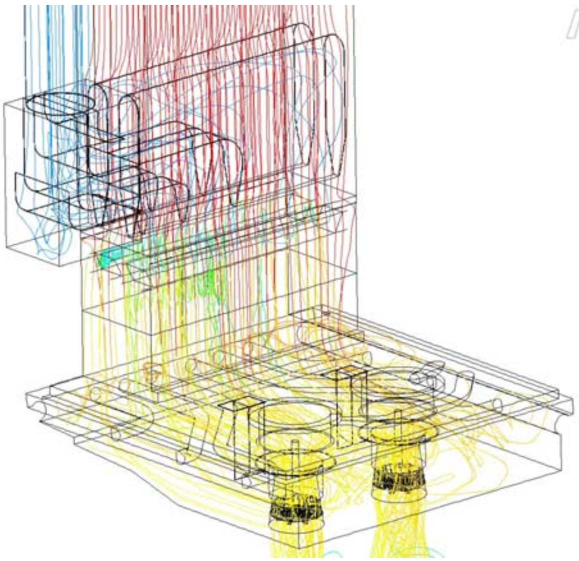
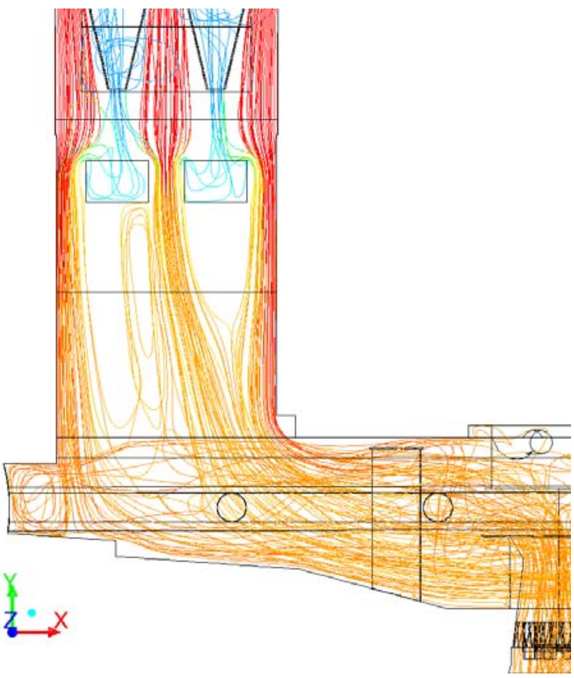
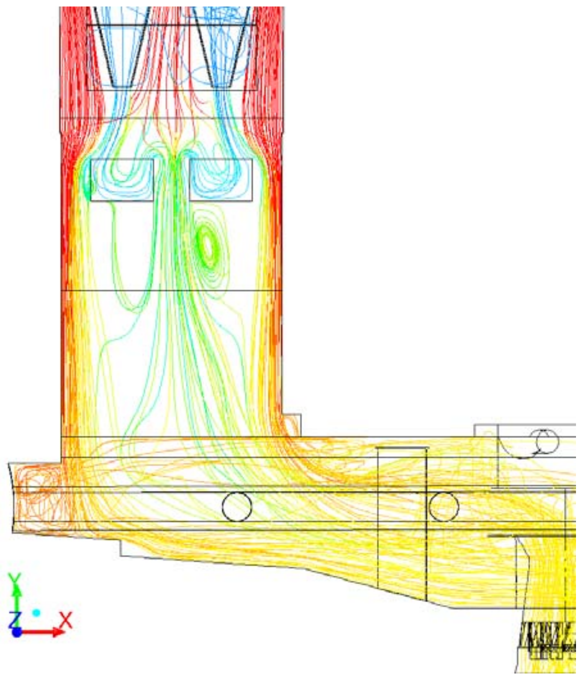
view	range	FGR=15%	FGR=30%
Bird Eye view	O2 [-] 		
from front side			

Fig.6-3 The flow pattern inside the wind box at the time of installing the drain BOX

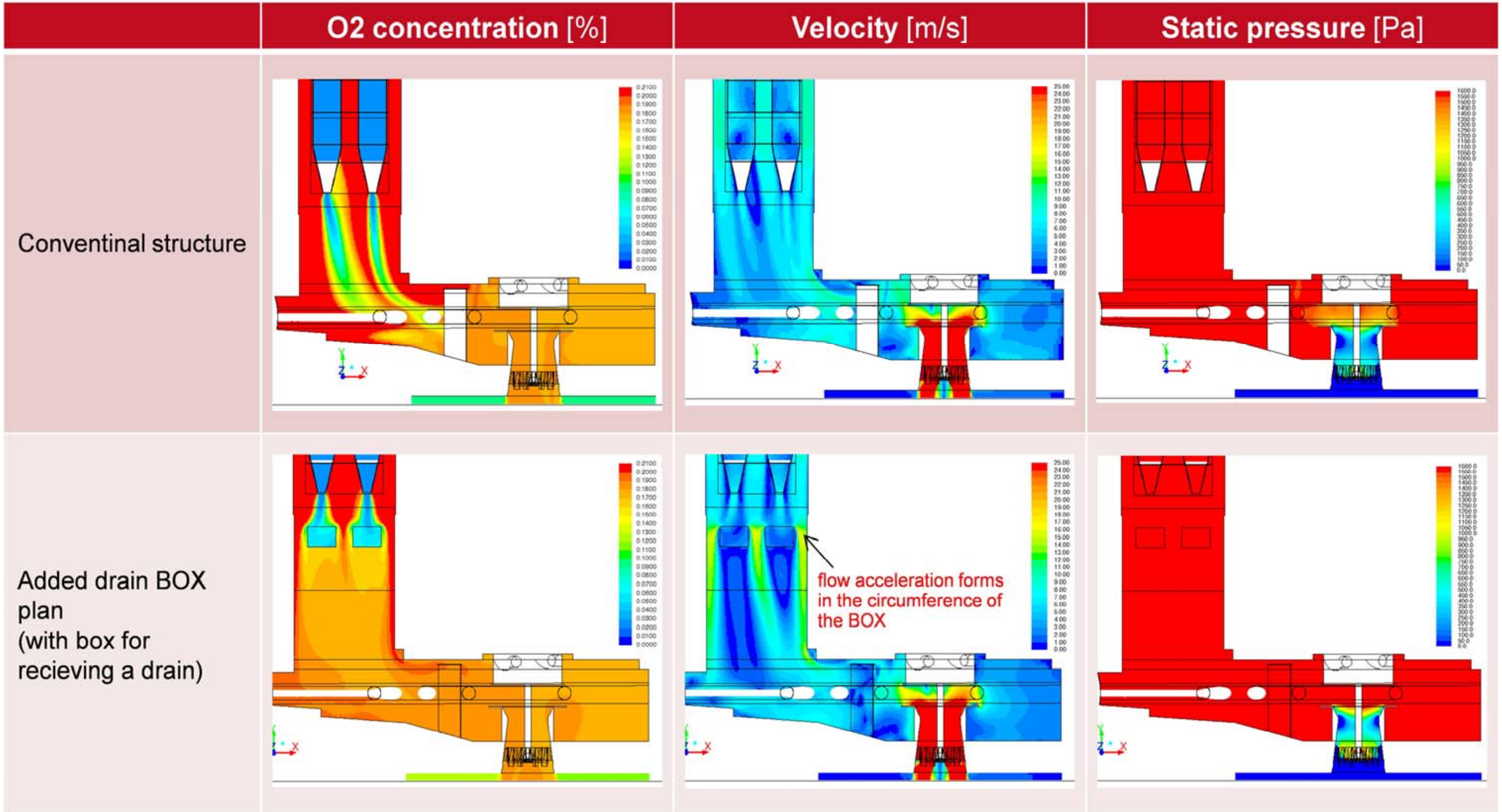


Fig.6-4 The flow comparison in the wind box by drain BOX installation

- When the drain BOX is installed in a wind-box duct, the flow which comes from the mixture is dammed up in the drain BOX, and flows into the circumference of drain BOX with the combustion air which has flowed from the upper part. Hence, it is confirmed that the flow is accelerated at the narrow area between the drain BOX and a wind-box duct.

The influence on the static pressure distribution by damming up a flow with the drain BOX is shown in Fig. 6-5.

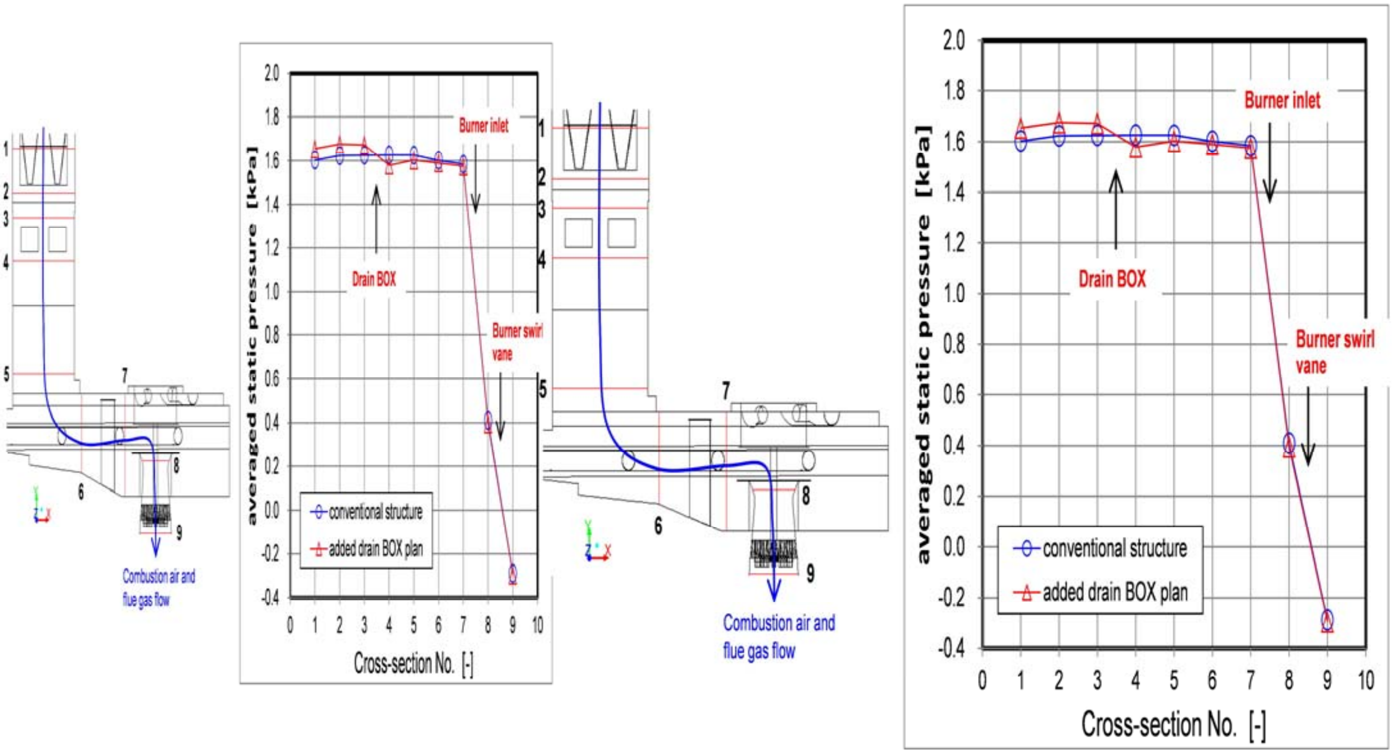


Fig.6-5 Static pressure distribution in the inside of a wind box from a mixed vessel

- From the viewpoint of the pressure loss inside a mixture and a wind box, the pressure loss in a burner part (a register entrance portion and a swirler part) is dominant, and the influence of drain BOX is little.

The influence of changing FGR rate is compared with Fig. 6-6 about the pressure loss in FGR gas and combustion air at the time of installing the drain BOX in a wind box. In addition, FGR was changed in 15 to 30% of range.

- As mentioned above, the influence of the pressure loss regarding the installation of drain BOX is small. In case of 30% of FGR, total pressure loss is increased about 6%. Moreover, the flow velocity of FGR gas blown into the drain BOX is about 10 m/s, and it is considered that the influence to the strength of drain BOX by fluid power is little.

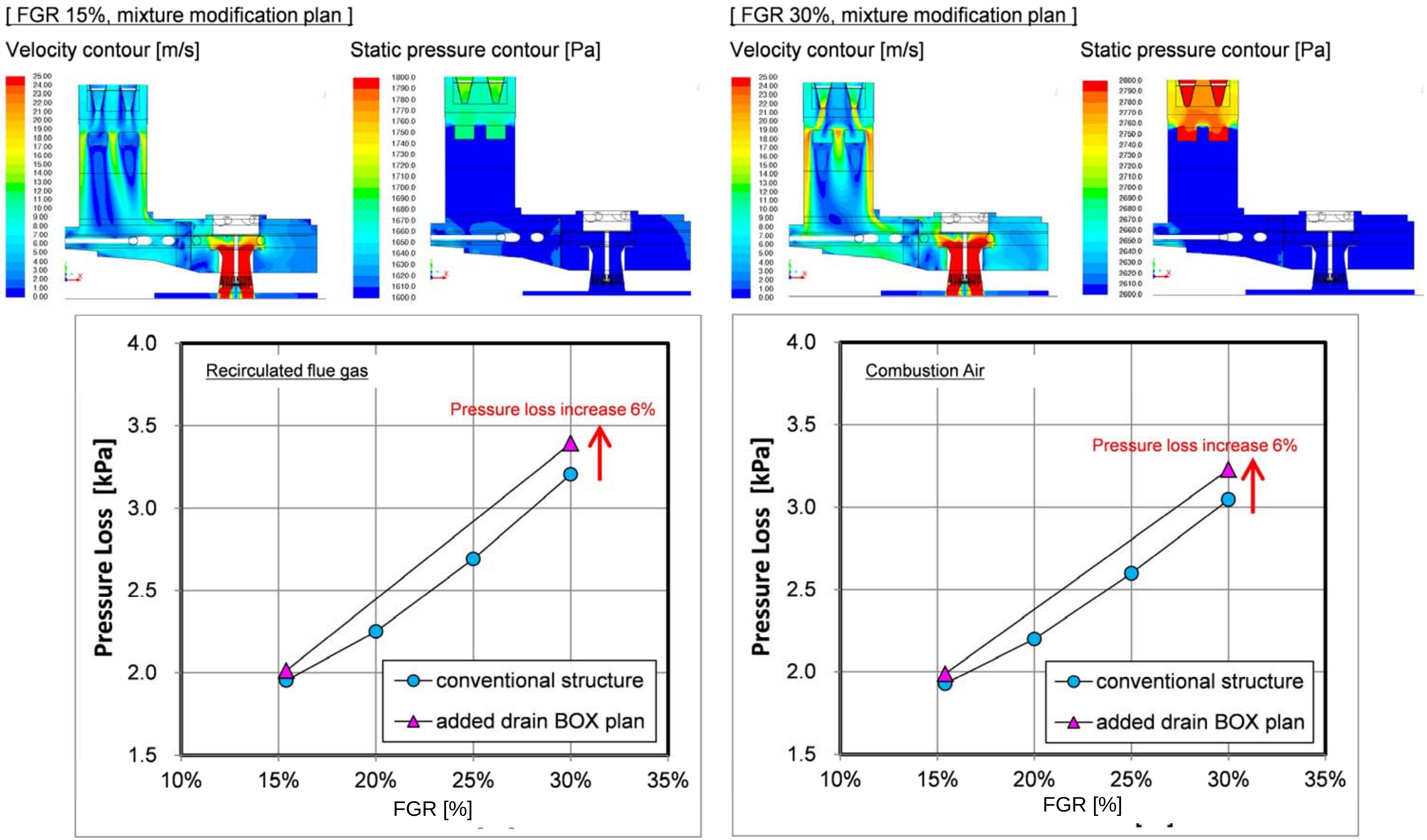
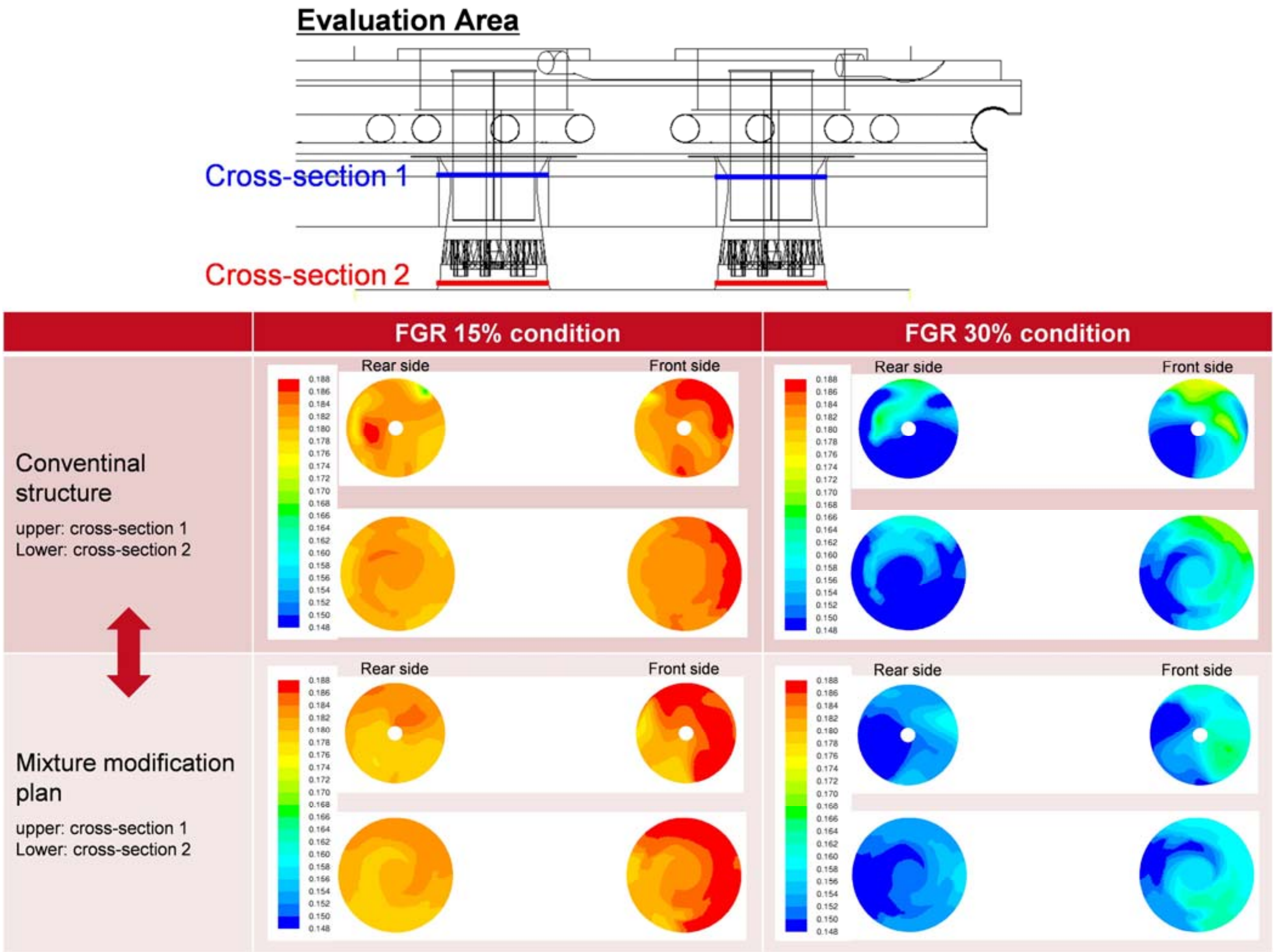


Fig.6-6 The influence of changing FGR rate about the pressure drop

Finally, the influence on O2 deviation regarding the installation of drain BOX is studied. A contour figure is shown for both section of a burner register entrance (section 1) and a burner jet (section 2).



FGR=15% Drain BOX: none	section (1)	section (2)	FGR=15% Drain BOX: on	section (1)	section (2)
Front side average O2(-)	18.2	18.1	Front side average O2(-)	18.1	18.1
Rear side average O2(-)	18.4	18.4	Rear side average O2(-)	18.4	18.4
Front side MAX O2(-)	18.4	18.8	Front side MAX O2(-)	18.2	18.4
Front side MIN O2(-)	**17.8**	16.7	Front side MIN O2(-)	**17.6**	17.5
Rear side MAX O2(-)	**18.7**	19.1	Rear side MAX O2(-)	**18.5**	18.7
Rear side MIN O2(-)	17.9	17.5	Rear side MIN O2(-)	17.4	17.3

Fig.6-7 Comparison of O2 concentration of the air which flows into a burner

- O2 deviation between the burners was almost the same. But it was confirmed that O2 local deviation was decreased in the burner register inflow part (section 2).

7. Conclusion of CFD analysis

[Mixing characteristics in a mixture and a wind box]

- A mixture wall temperature falls below the dew point temperature of flue gas by cooling with the combustion air.
- Condensation in a flue gas occurs at a mixture inlet area, and oxygen deviation is formed in the mixed gas which flows into two burners.
- As a local value, 1% or more of O2 deviation is formed. This appeared in the data of boiler commissioning period.
- In a burner register section on an average, O2 deviation is 1% or less at FGR 30% case.

[Burner flame regime under oxygen bias condition]

- Combustion flame is extended and hot gas flows into the superheater section on the high oxygen side.
- Generation of NOx increases in the domain between two flames, and relative NOx value increases in case of oxygen bias condition.

[Verification of drain countermeasure structure]

- From the viewpoint of the pressure loss in a mixture and a wind box, most of pressure losses occurred at burner part and the influence on the pressure loss by drain BOX installation is slight.
- It was confirmed that a drain box does not have influence on oxygen deviation between two burners.

8. Conclusion of Feasibility Study

MHI concluded that NOx figure 100 mg/Nm3 at 3% O2 base with gas firing is feasible by increasing the flue gas recirculation rate. Required conditions are as follow.

Condition;

- O2 content in exhaust gas is 3% reference base
- Kind of fuel is gas.
  Fuel gas chemical composition (clarified in MHI-MME e-mail dated 15/Apr/2016);
  Case 1
  Using natural boil-off only, the fuel gas composition is abt. 99% Methane.
  Case 2
  Using the forcing vaporizer (+ 3 tanks on natural boil off), the fuel gas composition depending on the cargo's aging and in general:
  Methane: 87% - 90%
  Ethane: 8 - 10%
  Propane: 1-2%
  Butane & Iso-butane: <1%
  Nitrogen: 0%
- Boiler load is 100% normal load (boiler evaporation : 48 t/h per boiler).

MHI FS study has been carried out using the analysis result dated on 9/Nov/2015 -11/Nov/2015 of ship's exhaust gas analysis system.

9. Modification Work Items

As a result of this feasibility study, modification work items to achieve 100 mg/Nm3 at 3% O2 base with gas firing is as follows.

- Add the cover to the existing boil off gas lead pipe with insulation. (Refer to Fig.9-1)

- Add the oxygen sensor to the each wind box to check the oxygen content.

- Add the cover to the riser pipe to prevent the corrosion of riser pipe due to the condensed water. (Refer to Fig.9-2)
  As a result of CFD analysis in this FS, in case that drain box is installed at the mixture outlet section, O2 local deviation decreases. This is good from the viewpoint of stabilization of combustion condition. Although the combustion condition is stable with existing condition, we are planning to confirm the effect of this drain box at actual boiler operation at boiler commissioning phase. In such a case as the emission regulation is further upgraded or the fuel gas chemical composition is changed in the future, the data with fitting the drain box will be useful for the study.
  Hence, we are planning to design this drain box with easy demounting at detail design stage. And final decision whether drain box is fitted or not will be made at the boiler commissioning phase with consideration of the boiler commissioning result for NOx reduction.

- Re-paint at the internal surface of mixture outlet and windbox to prevent the corrosion due to the condensed water. In case that FGR rate is increased, the amount of condensed water will be increased. Hence to operate the boiler with long term with high FGR rate, re-painting is required. To confirm the existing internal surface condition, please take pictures when boiler is stopped at general maintenance. There is a manhole at the air duct (boiler front side) to enter the windbox.

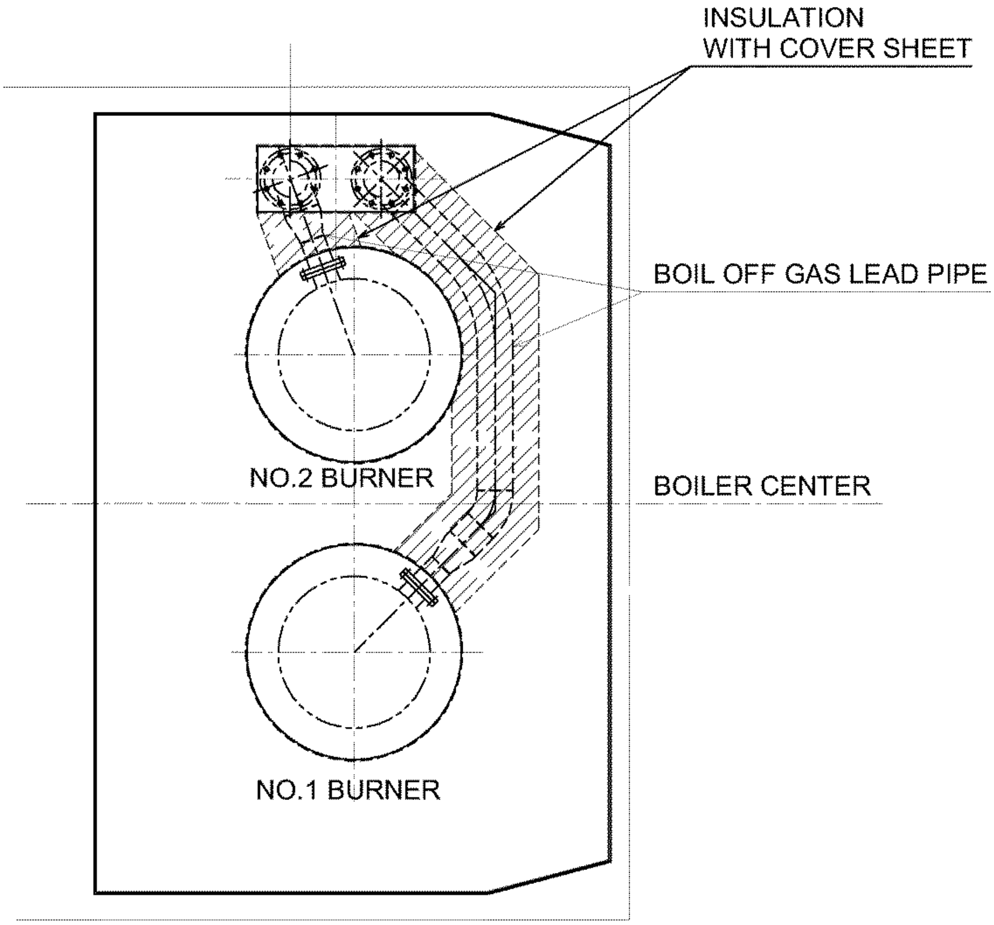


Fig. 9-1 cover to the boil off gas lead pipe

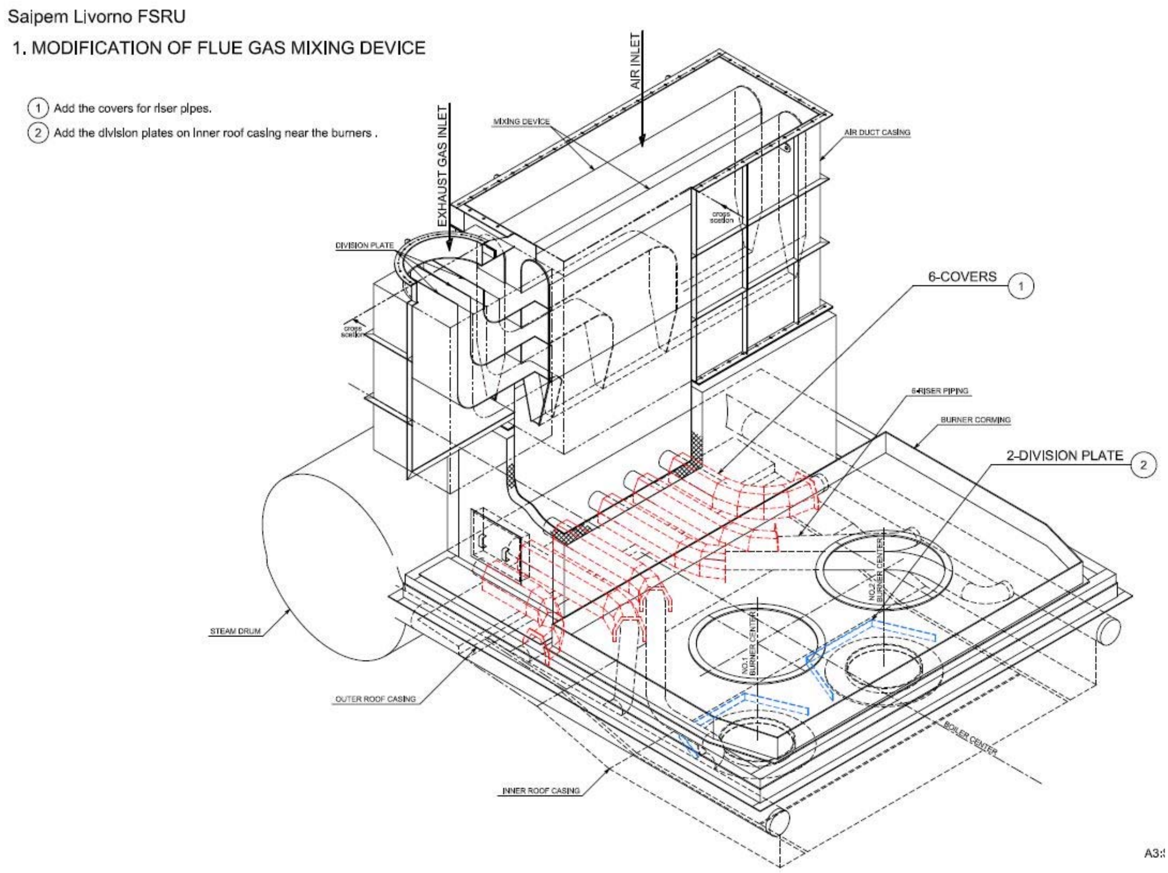


Fig. 9-2 cover to the riser pipe