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MATHEMATICS MODELING FOR
HIGH TEMPERATURE AIR COMBUSTION (HiTAC)

Summary final report by Yuang Weihong, Dong Wei, Wlodzimierz Blasiak,
Royal Institute of Technology (KTH)

Key words: reheating furnaces, burners, regenerative burners, mathematical modeling

SUMMARY

Mathematical simulations have been performed for a small-scale single fuel jet HiTAC and a semi-scale HiTAC test furnace with two different regenerative burners system (one and two-flame).

The objectives of the present study are to
1. Develop and experimentally verify mathematical model
2. Study of characteristics of the HiTAC combustion phenomena.
3. Parametric study on the combustion process, including oxygen concentration, temperature of preheated air, fuel temperature, fuel flowrate, excess air ratio and flame locations.
4. Heat transfer evaluation in HiTAC test furnace.
5. NOx formation and emission in HiTAC technology
6. Evaluation of optimal design for a HiTAC furnace.

The main results of the study are:
1. Combustion model, Eddy-Dissipation-Concept with multi-step chemical reactions, is suitable numerical model for HiTAC especially when modelling is applied to large scale industrial furnace.
2. NO emission formed by N_2O-intermediate mechanism is of outstanding importance during HiTAC.

3. The concepts, including oxidation mixture ratio, furnace-gas-temperature-uniformity-ratio, Furnace Flame Occupation Coefficient and Flame entrainment ratio, were defined to describe the characteristics of HiTAC, which are help for optimal design of HiTAC furnace and burner.
4. The benefits of HRS is quantitative demonstrate by mathematical models. They are: lower peak temperature, larger flame volume, more uniform thermal field, lower local firing rate, higher heat transfer, higher energy utilizing efficiency and lower combustion noise.
5. Operation parameters, including oxygen concentration and temperature of preheated combustion air, fuel temperature, fuel flowrate, excess air ratio and flame locations have stronger influences on combustion and NO emission in HiTAC furnace. The optimal combination of these parameters should be considered
6. The criteria diameter and length of the furnace fitted with HRS are proposal in order to achieve an optimal design of HiTAC.

Finally, the whole work shows numerical simulation is very encouraging and can be used as an analytical and designable tool of industrial furnace.

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1 INTRODUCTION

The principles of technical improvement of the performance of fuel fired furnaces in steel industry are a more uniform and well-controlled temperature distribution in every furnace zone and high energy utilization efficient as well as lower pollution emissions. Combustion combining high-temperature preheated air with suitable hot-combustion-product recirculation is one of the most promising technologies to meet these targets over recent years. This technology is referred to as high-temperature air combustion or HiTAC or Flameless oxidation (FLOX).

The main benefits of this technology have been verified by the studies and applications as following:

1. Larger energy saving,
2. Low NOx emission,
3. Low CO emission,
4. Decreased CO2 emission,
5. Lower combustion noise,
6. No need for extra energy saving devices,
7. Smaller flue gas tubes.

For its industrial application, high-temperature air can be obtained using a modern regenerative heat exchanger, and lower oxygen partial pressure is maintained with an internal exhaust gas recirculation, which is achieved aerodynamically in the combustion chamber by special burner design. Because of the switch interval of modern regenerative heat exchanger is very short, correspond to known applications of HiTAC referred to as a high-cycle regenerative system or HRS. The two main HRS solutions currently used feature either a one or a two-flame burner system according flame appears location at a switch cycle.

In order to understand the characteristic of this novel combustion technology, the single jet gas combustion in the condition of low-oxygen partial pressure and high-temperature air is studied numerically. Furthermore, progress in applications of the HiTAC increased also needs of more information and data required by furnace and process designers. In particular, it is very important to specify optimal conditions for installation of HiTAC in industrial furnaces. For these reasons studies in larger scale where at least one set of regenerative burners systems is installed are calculated numerically.

The computational fluid dynamics (CFD) is used in this project because CFD has been proven to be a valuable tool to simulation the flow, heat transfer and combustion process in industrial furnaces and boiler in the last decade.

2 OBJECTIVES

General objective of this project is to develop and experimentally verify mathematical model. Modelling is to be verified against results of experiments. We also expect to develop some parameters to classify the characteristics of HiTAC, which are difference from the normally combustion, for example, volumetric combustion and invisible or less visible flame, and from these parameters, optimal design of HiTAC furnace is expected to address.

3 METHOD OF ATTACK

In order to meet the above objectives, mathematical modelling is based on two main steps:

1. Modelling of a single fuel jet in conditions of HiTAC including cross-flow and co-flow of fuel and air.
2. Modelling of the HiTAC test furnace for two different High Cycle Regenerative Systems (one flame and two flames systems).

The contents studied of mathematical modelling lie on the sides as following:

1 Mathematical models study, which include combustion model and the formation and destruction of NO. Modelling is to be verified and verified against results of experiments.

2 Characteristics study. The characteristics of combustion and flame of HiTAC are expected to classify. The main characteristics of HiTAC are elevated basing on comparison with a conventional turbulent jet flame

3 Parametric studies. The influences of the parameters on combustion, NO emission and heat transfer are researched. These parameters include oxygen concentration, temperature of preheated combustion air, fuel temperature, fuel flowrate, excess air ratio and flame locations.

4 Heat transfer evaluation in HiTAC test furnace with HRS. The heat sink includes stationary heat sink and moving slab.
5 Evaluation of optimal design for HiTAC furnace equipped with HRS.

In this study, the first step of mathematical model was used to prove the HiTAC flame features by means of simulating the gas single jet flame, and the HiTAC model was further investigated [1-5]. In these works, the suitable HiTAC flow models and combustions model were found. Meantime, some concepts were defined to describe the characteristics of HiTAC, which quite differ from conventional combustion. The second step, these results were used to calculate the semi-industry furnace equipped by High-cycle Regenerative System (HRS) burner, which built /KTH. The simulation results further proved the benefits of HiTAC shown above [6-15]. To improve the accuracy of mode, the validation and verification of HTAC test furnace numerical modelling were performed [8-15]. In this work, the parameters of demonstrating HiTAC features were further replenished. The results of comparing predicted and measured were quite encouragement.

We also took charge of the simulation of Super Advanced Regenerative Industrial Furnace (SARF), which was built in Malaysia granted by New Energy and Industrial Technology Development Organization (NEDO), Japan (Report 3, [6]).

NO models were developed and the effects of parameters on the formation and emission were studied. The details of new NO model can be found in [Ref.15].

4 DESCRIPTION OF MATHEMATICAL MODELING PERFORMED

4.1 Turbulent combustion model

In this study, three different combustion models were applied to simulation the LPG (Gasol) combustion.

- Eddy-Break-Up (EBU) model,
- Eddy-Dissipation Conception with multi-step chemical reaction,
- PPDF-mixture fraction model with equilibrium.

4.2 Other models used

Flow model:

- k-ε model
- RNG k-ε model
- RSM model
- Large Eddy Simulation (LES) model.

Radiation model:

- Radiation: Discrete Transfer Method.

NO model:

- Thermal NO_x
- Prompt NO_x model
- N_2O intermediate model
- NO reburning mechanism
- Turbulence fluctuations are taken into account via the use of a beta-function PPDF.

The above mathematical models except N_2O-intermediate NO model were obtained from STAR-CD [16] and Fluent [17] commercial CFD codes. N_2O-intermediate NO model is developed in this work. Two general-purpose codes, STAR-CD and Fluent were used.

5 DEVELOPED CONCEPTS FOR DESCRIBING OF HITAC CHARACTERISTICS

HiTAC has many characteristics that are completely difference from conventional combustion. For example, the HiTAC flame is less visible than the combustion with a higher concentration of oxygen by volume (more or equal 21%), and therefore it is generally accepted that flame length is not suitable parameter for characterizing flame size. Instead, it is necessary to demonstrate flame shape and size using a comprehensive numerical simulation.

To describe the flame under HiTAC, the oxidation mixture ratio is used in this work [1]. The oxidation mixture ratio allows the combustion progress to be estimated and can be calculated as mass fraction of oxygen to mass fraction of oxygen and the sum of oxygen needed to complete combustion at any point in the combustion chamber, as follows:

$$R_o = \frac{m_O}{m_O + \sum_c s_c m_{F,c}} \quad (1)$$

where $s = n_O M_O / n_F M_F$. *m* is the mass fraction of oxygen, *n* is the stoichometric coefficient (number of moles) and *M* is the molecular weight. The subscripts *o* and *F* correspond to the oxygen and fuel respectively, and the subscripts *c* indicates the combustible species in the flue gas. This ratio has a value of R_O=1 when it is at the air inlet or when combustion is completed, and a value of R_O= 0 at the fuel inlet.

The lean flammability limits for different fuel species has been used to indicate the outside border of the flame, and the rich flammability limits of them are used to given the insider border of the flame. R_O= 0.99 is assumed to indicate a flame border [1]. Thus the flame volume can be approximately defined when

$$0 \le R_O \le 0.99 \quad (2)$$

To evaluate gas temperature field uniformity inside the furnace, a furnace-gas-temperature uniformity-ratio, $\boldsymbol{R_{tu}}$, was defined as follow [1]:

$$R_{tu} = \sqrt{\sum \left(\frac{(T_i - \overline{T})}{\overline{T}} \right)^2} \quad (3)$$

where T_i [K] is the temperature of calculated cell number and $\overline{T}$ [K] is the average temperature in the furnace. When R_{tu}=0, there is no gas temperature gradient inside the furnace.

In the case of application of HiTAC, in order to characterize the flame volume in relation to the volume of the combustion chamber a dimensionless coefficient called Furnace Flame Occupation Coefficient (FOC), R_{FOC} was defined as a ratio between the flame and furnace volume:

$$R_{FOC} = \frac{V_f}{V_F} \quad (4)$$

where, V_f [m^3] is flame volume calculated according to relationship (9), and V_F [m^3] is the furnace volume calculated from the geometrical dimensions of the furnace.

Combustion intensity is also very important parameter for designing furnace and burner. To evaluate quantitatively chemical reaction intensity in the furnace, especially in the chemical reaction zone (flame), two parameters are used. One is Flame Heat Release (FHR), which is defined as the ratio of heat released inside the flame zone (Q_f) to the flame volume (V_f):

$$q_{FHR} = \frac{Q_f}{V_f} \qquad \text{kW/m}^3 \quad (5)$$

where Q_f is obtained as follow:

$$Q_f = \int_{V_f} \sum q_c dV \quad (6)$$

where q_c (kW/m^3) is local heat release of different fuel species.

Another parameter used in this work is the ratio between the heat released by the flame zone (Q_f) and total heat released inside the combustion chamber, (Q_F). It is termed Flame Heat Occupation Coefficient (FHOC), and defined as follows:

$$R_{FHOC} = \frac{Q_f}{Q_F} \quad (7)$$

where, Q_F is calculated by:

$$Q_F = \int_{V_F} \sum q_c dV \quad (8)$$

Furthermore, although the entrainment ratio of nozzle is good parameter for describing internal recirculation of the flue gas that plays such an important role in HRS, due to the interaction between fuel and air nozzles for one-flame HRS, the entrainment of a single nozzle is not suitable parameter for characterizing the internal flue gas recirculation. Therefore, the entrainment ratio including the interactions between nozzles must be considered.

In order to describe the interactions between fuel and air nozzles, flame entrainment ration is more efficient. The flame entrainment ratio (R_{fe}) is defined as following:

$$R_{fe} = \frac{m_f}{m_0} \quad (9)$$

Here, m_0 (kg/s) and m_f (kg/s) represent the initial total mass flow rates and mass flow rates through the cross section of the flame respectively.

In order to describe the overall radiation field of a flame, the radiant fraction (f_{rad}) is used. It is defined as the ratio of net radiative heat loss from the flame (Q_{rad}) to the total heat released during combustion (Q_F) as following:

$$f_{rad} = \frac{Q_{rad}}{Q_F} \quad (10)$$

6 STUDIED FURNACES

In order to study the HiTAC phenomena, three test stands were built and simulated. The first two were used to study the interaction between a single jet and a pr-heated oxidizer, here after called cross-flow and co-flow single jet flame furnace. The third test stand was a semi-industrial facility equipped with two different HRS (single-flame and two-flame) burner systems.

6.1 Single fuel jet test furnace

The single flame experimental facility was constructed to isolate the interaction between the fuel jet and the diluted air in a steady state condition. The schematic of the combustion chamber are showed in Figure 1. The combustion air for the first test stand is preheated by an electrical preheated, and diluted by nitrogen. The fuel and air are injected with a cross-flow. The combustion air for the second test stand is preheated and diluted by a flue gas generator. In this case, the composition of the oxidizer is close to what can be found in a real industrial furnace. The fuel was injected in a co-flow to the main flow of hot flue gases. The details test stand can be seen in [18-19]. Fuel studied in this work is gasol (98.5% of propane).

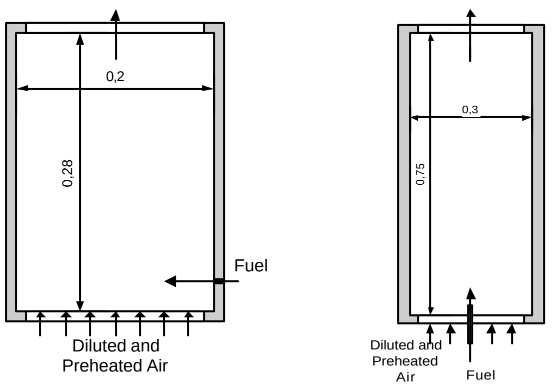


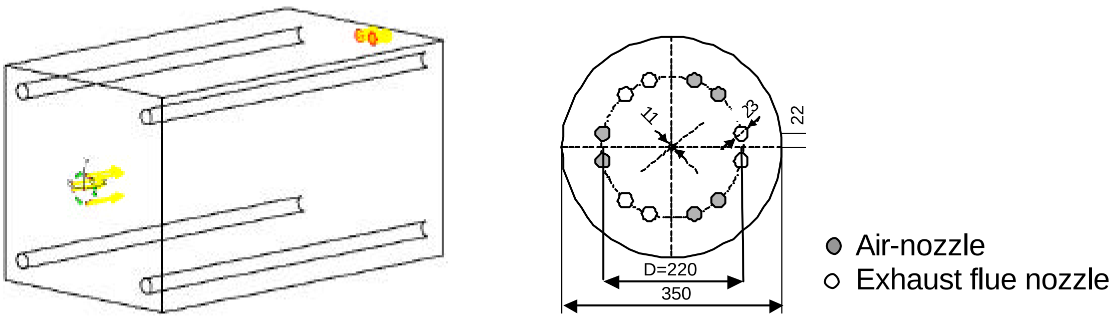
Figure1 Schematic of combustion chamber for single fuel jet test furnace
(a) Cross flow (b) Co flow

6.2 HiTAC test furnace and burner

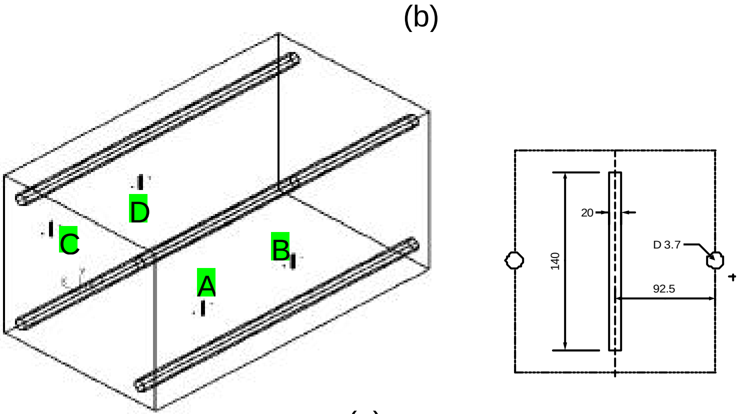
The two main HRS solutions currently used feature either a one or a two-flame burner system. One-flame HRS is characterized by a single flame created by the same one fuel nozzle surrounded by air inlets and flue gas outlets. In two-flame HRS, there are two separated high-cycle regenerative burners. The two burners are located in the walls of the furnace and work in pair by means of a set of valves, which change the direction of the air and flue-gases according to the required switching time. Both of them were investigated numerically.

The HiTAC test furnace built in KTH has an internal furnace body dimensions 2.85×1.60×1.60 m. The furnace system was described in [20]. The scheme is shown in Figure 2. Four tubes with an external diameter of 110 mm each and cooled with air have been installed horizontally in each corner of the furnace to remove heat from the combustion chamber. The cooling air flows from one side of burner to the other. On the opposite side of the furnace to the burner face, there are two flue gas ducts of 110 mm external diameter for exhausting hot flue gases from the furnace. The walls of the test furnace consist of two layers: an outer steel cover 5.0 mm thick and an inner layer of fibrous ceramic insulation 300 mm thick.

(a)



(b)



(c)

Figure 2 HiTAC test furnace and burner
(a) HiTAC test furnace at KTH
(b) Configuration of HiTAC test furnace with one-flame HRS
(c) Configuration of HiTAC test furnace with two-flame HRS

The furnace is designed so that two different HRS can be sued. The first system is attached in the front of the furnace. It is a so-call one-flame system and has a thermal capacity of 200 kW. Figure 2 (b) represents the computational domain of the HiTAC test furnace. The other system which is composed of two pairs of HRS is installed in the left and right sides of the furnace as shown in Figure 2 (c).

For the 200 kW one-flame HRS with honeycomb regenerative burners was first used in this project. The ceramic honeycomb regenerators, through which the exaust gas and combustion air, are an intergral part of the burner body. Figure 2 sketches the dimensions of the burner and locations of fuel and air injection ports. There are 12 regenerators in all, working in pairs and organised into two groups separated by intervals. 80% of flue gases through the burner outlets is sufficient to preheat the combsution air for desired fuel. The remainder of the exhaust gases flow out from the furance through the chimney located on the rear wall of the furnace.

The second calculated case is that the furnace is equipped with four high-cycle regenerative burners with capacity of 100 kW each. The burners (four burners marked A, B, C, D) are placed on the sidewalls of the furnace as it is shown in Figure 2(c). Each burner consists of one injection port for combustion air and two nozzles for fuel injection. Combustion air and fuel are injected separately. The combustion air injection port is located in the centre of the burner. Fuel nozzles are placed in the same plane on both sides of the combustion air port as shown in Figure (b). This type of regenerators allows preheating of combustion air up to 1537 K. Both fuel nozzles are placed in one plane parallel to the furnace floor.

For the reason of study in larger scale, two sets of HRS are installed are needed because the interactions between burners are also important. The three basic flame configurations named as Parallel Mode (firing by combining of burner A and B or Burner C and D), Counter Mode (firing by combining of burner B and D or Burner A and C) and Stagger Mode (firing by combining of burner A and D or Burner B and C) are investigated.

The fuel used in the study was gasol, which has more than 98% of propane. The composition of fuel and the operating conditions tested can be found in report [7].

7 RESULTS FROM THE SIMULATIONS OF SINGLE JET TEST FURNACE

7.1 Study of numerical models

The suitable HiTAC flow models and combustion models were studied. A summary of these study from our work [1-4] are listed as following:

- Flow models, k-ε , *RNG*-k-ε , *RSM* and *LES* coupling eddy dissipation reaction model are suitable for predicting of temperature and NO_x emission under the conditions of HiTAC.
- Advanced turbulent models, like large eddy simulation (*LES*) and *RSM*, give small differences in the near field predicting of the flow.
- The empirical constants as for example C_s in *LES* model, A_{ebu} and B_{ebu} in *EBU* combustion model have significant influence on the predictions, which implied the empirical constants in tradition models are necessary to adjust to obtain the best performance for HiTAC.
- EDC combustion model with multi-step chemical reactions is more suitable than other models since it predicts more realistic peak temperature and the flame shape and size.

7.2 Characteristics and Parameter study

The main combustion parameters including oxygen concentration in air, temperature of air and fuel varied markedly in our report [1,4]. The main results are depicted in Figures 3. For brevity, only a summary of the results is presented as following:

1) It was showed that High Temperature Air Combustion is spread over much larger volume then conventional combustion. Decrease in oxygen concentration in air increase the flame volume as well as flame length.
2) Flame volume has a slight increase with the increasing of air preheated temperature. From the study of cross-flow of single jet, the results show that the flame volume was found almost constant for the investigated temperature range (1041 K–1273 K) of the preheated air at fixed oxygen concentration and fuel inlet temperature.
3) Peak temperature increases with the increasing the preheated temperature of combustion air as well as increasing of oxygen concentration.
4) More uniform temperature field is found at the case of lower oxygen content, and the influence of the fuel inlet temperature on the temperature uniformity ratio R_{tu} is difficult to detect.
5) Mean residence time of fuel gas parcels inside the flame volume increases with reduction of oxygen concentration as well as with decrease of fuel inlet temperature and slightly increases with decrease of the preheated air temperature.
6) Increase of the fuel inlet temperature results in smaller flame, shorter mean residence time.
7) Radiant fraction is almost constant when oxygen concentration varies. The increasing of flame volume compensates the influence of decrease of flame temperature on radiation.
8) The results from co-flow cases show that the flame length is found to be nearly constant for each oxygen concentration and is essentially independent of the fuel flow rate. Only a slightly increase can be found at lower oxygen concentration. The flame volume increases with increase in fuel flow rate. This increase is higher at lower oxygen concentration than higher oxygen concentration.

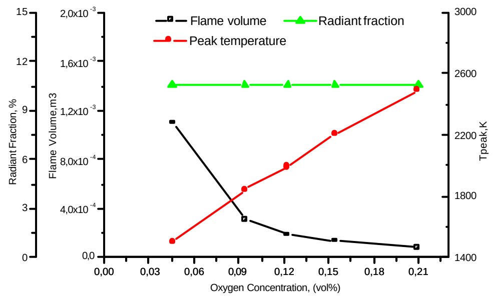


Fig.3 Flame volume, peak temperature and radiant fraction versus oxygen concentration during 1173K of air temperature and 299 K of fuel temperatures for single gas jet with co-flow test

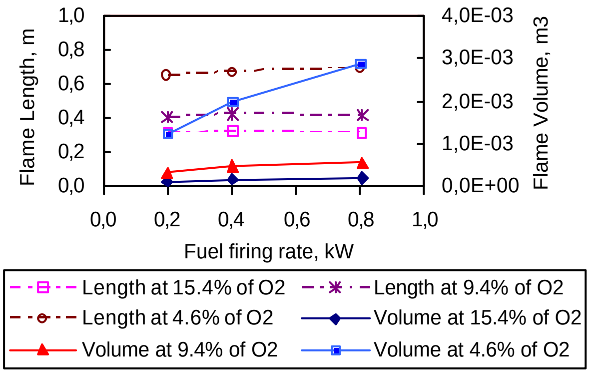


Figure 4 Flame length and volume of LPG flame at difference fuel firing rate for single gas jet with co-flow test

8 RESULTS FROM THE SIMULATIONS OF HITAC TEST FURNACE

8.1 Validation of the numerical models

As we known, mathematical models must be tested against experimental measurements when they are applied to new problems. The modelling validation is performed by comparison of the following computed and measured data basing on the HiTAC test furnace equipped with one-flame High-cycle regenerative System (HRS).

- Energy balance,
- Wall temperature profiles,
- Heat Flux on the furnace wall,
- In-furnace gas species.

Details of validation for HiTAC test equipped with one-flame HRS can be found in the report 5 [8] and the published paper [9-11]. Generally, the agreement of predicted and measured species is good with the experimental error except the small zone near the burner. In particular, the flame diffusion was good predicted. Below the only main verified results from HiTAC test furnace with one-flame HRS are presented.

8.1.1 Energy Balance

Figure 5 shows the energy balance Sankey diagram for measured and prediction.

The overall thermal energy input to the test furnace in this study was 182 kW. The sensible heat flow rate at the fuel inlets was zero since the reference temperature was set at T=298 K. The heat of exhaust after the burner for simulation was approximately calculated as the value of heat of flue gas through the burner minus combustion sensible heat of the combustion air.

A figure of 54.65% of the predicted fuel thermal input passed through the burner outlets, and 83.6 percent of the sensible heat carried by the flue gases through the burner outlets was used to preheat the combustion air from 300 K to 1211 K, which is about 45.71 % of the total thermal input. This implies that a very high level of energy utilization efficiency can be achieved. Reiterating here, 8.94% of the predicted total fuel thermal input is removed by flue gas through the burner. This value is higher than measured value of 5.21%. Possible reasons for this could be one or a combination of the following: heat loss in the burner, or the measurement point being on the outside of the burner.

The predicted amount of heat led off by air-cooling tubes occupies 51.67 % of total fuel thermal input. Results also indicated that 97.4% of heat transferred to the air-cooling tube was due to radiation, and 2.6% was due to convection. The heat absorbed by air-cooling tube was measured to be around 54.27% of total fuel thermal input. Therefore, the predicted and measured heat amounts of heat removed by air-cooling tubes were in reasonable agreement within the margin of measurement error of 6.44%. Furthermore, the predicted value for flue gas carrying through the main chimney was 9.78% of the fuel thermal input, while the actual value measured was 11.25%. Again, the agreement was acceptable, falling within error limits of 6.44%. The predicted heat loss through the furnace walls was accounted for 29.61% of the thermal input, compared with an actual measurement of 29.49%. Thus, they were also in good agreement.

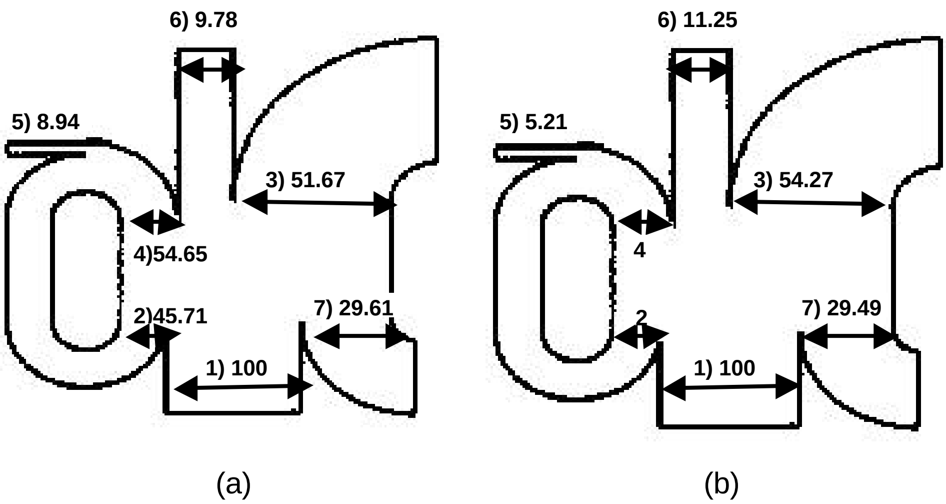


Figure 5 Energy balance (Sankey diagrams)
(a) CFD predicted, (b) Measured

1 Heat of combustion 2 Heat of preheat air
3 Heat of absorbed tubes 4 Heat of flue gas through burner
5 Heat of exhaust after burner 6 Heat of flue gas through main chimney
7 Heat losses from walls and inlets/outlets

It is possible to improve further recovering efficient from waste flue gas from now 80% to 100%. The extra heat recovering from flue gas can be used to preheated fuel, which can bring benefits for example more decreasing NO emissions. This way is very important for the maintaining of combustion stability when using low and medium caloric fuels in this technology as at these cases, the fuel volume is larger. This method features preheating of both fuel and air, and may be referred to in the field as twin-preheating. The method involving preheating of the combustion air only is preheated can be referred to as single-preheating.

8.1.2 Temperature field and heat flux

Furnace temperatures in HiTAC test furnace were measured at various positions along the left-hand-side wall of the test furnace (viewed from the burner side). Conclusions from furnace and in-furnace temperature and flux validation are:

1. The predicted and measured temperature on the furnace wall is reasonable agreement, the maximum difference being about 10 K with the range of error in 2%.
2. The predicted temperature in up part furnace is slight lower that that in the down part furnace.
3. The temperature increases slight with the increasing of distance from burner face.
4. The temperature gradually increases with the greater distances from the centerline in the main chemical reaction zone.
5. The in-furnace temperature difference between predictions and measurements are big near the burner zone, but the agreement of predicted and measured out of the burner zone is good with the range of error 3%.
6. The agreement between heat fluxes predictions and measurements on the roof are quite good.

8.1.3 In-furnace species

Conclusion from concentrations validation:

1. The calculating O2 and CO2 contents are in good agreement with the measured. Both of them show the same locations and magnitudes of their maximum and minimum O2 and CO2 concentrations.
2. The measured CO agrees with the predicted level. The predicted CO concentrations on, or close to, the burner centerline are lower than the measured values, however, the relative difference decreases with

increasing distance from the burner. Meanwhile, the modelling underestimates the fuel consumption in the front part of furnace.

3. The agreement of predicted and measured concentration of N2 is good with the range of error in 3.16% except the point on the burner centerline at 0.3 m from the burner face.
4. The flame diffusion in furnace is good predicted since there are good agreement of the locations and magnitudes of the combustible including hydrocarbon, CO and O2.

8.2 The benefits of HiTAC in comparison with conventional turbulent jet flame

Studies are performed numerically and the differences with respect to heat transfer and combustion features between conventional high velocity turbulent jet flame and HiTAC flame are shown. The influence of stationary and permanent heat sink on furnace heat transfer with these two types' difference burner systems was investigated as well. Figure 5 shows a typical difference of flame shape and size. References [7] and [9-11] give all the study details and main conclusions for this comparison are listed as follows:

1. The in-furnace peak temperature for HiTAC flame is much smaller than for the conventional flame mode independently on the type of the charge used,
2. The in-furnace gas temperature for HiTAC mode is more uniform than for the conventional flame mode. Larger charge leads to less uniform temperature distribution.
3. HiTAC flame is spread over much larger volume than conventional flame. The furnace flame occupation coefficient in case of HiTAC with the stationary heat sink is 15.8 times bigger than for the conventional flame mode.
4. The predicted maximum normalized flame length for one-flame HRS is 12.95 for one-flame HRS at the design conditionand the predicted maximum normalized flame diameter was 2.4.
5. Local firing rate in the combustion reaction zone for HiTAC firing mode is lower than that for the conventional flame mode. The maximum local firing rate for HiTAC flame firing mode is 32.3 times higher than that in conventional firing mode. Furthermore, around 94% and 96% heat release comes from flame zone for HiTAC and flame modes, respectively.
6. The in-furnace turbulent kinetic energy for HiTAC mode is more uniform than that for flame mode.
7. The combustion noise of HiTAC mode may be lower than that in flame mode since both turbulence levels and combustion intensity within a combustion reaction are reduced.
8. The influence of heat sink on HiTAC technology is more sensitive than on the conventional combustion (high velocity turbulent jet flame combustion).

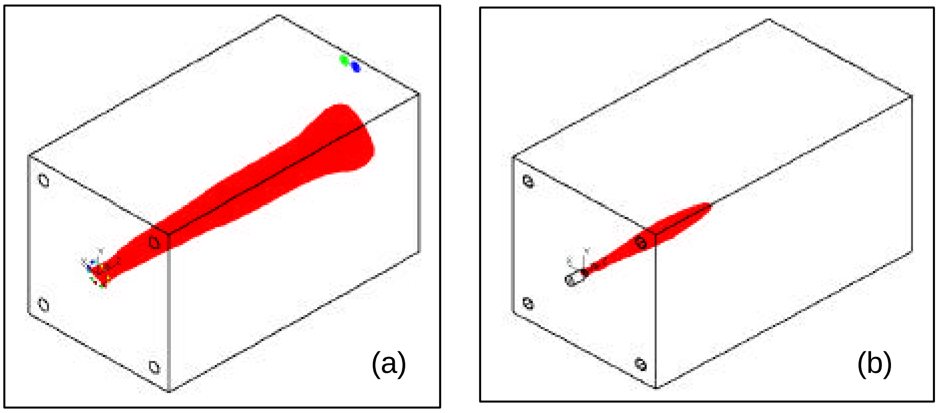


Figure 6 Predicted flame shape for HiTAC and Conventional burner
(a) HiTAC burner (b) Conventional burner

8.3 Effect of parameters on the properties of flame from HRS

For the purpose of heating the material uniformly, two-flame HRS can be operated in pair under various firing configuration with various switch time. In this project, the effects of the flame locations were checked numerically. Three basic flame configurations named as Parallel Model, Counter Mode and Stagger Mode are investigated [13]. The maximum flame temperature occurs at the case of stagger mode. This is the fact that the recirculation formed by burner's locations for stagger mode decreases the heat transfer from flame. The flame shape and size of three modes are depicted in figure 7.

The Counter flame occupies the smallest fraction of the furnace volume and the Parallel flame occupies the biggest fraction of the furnace volume. Consistent with this conclusion, the Counter mode has maximum local peak firing rate and maximum flame combustion intensity. This implies that the combustion noise in Counter mode is larger than in the other two modes.

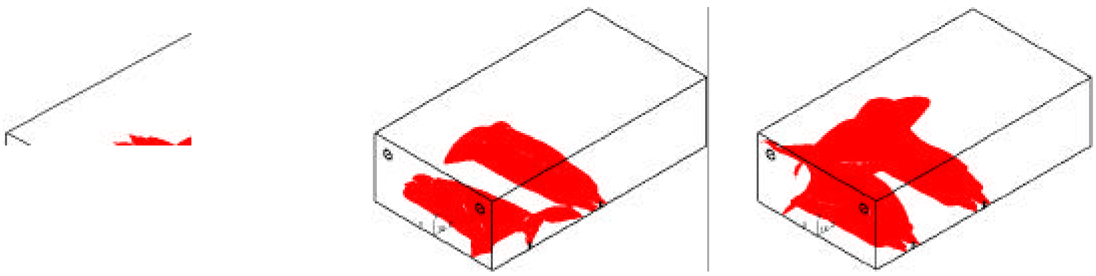


Figure 7 Flame shape for difference firing modes
(a) Counter mode (b) Parallel mode (c) Stagger mode

The effects of elevated fuel temperature on the combustion and flame properties in the furnace equipped with two-flame HRS are also investigated numerically. Simulations are performed for fuel temperature from room temperature to 1273K. It can be drawn that the flame temperature decreases as the preheated fuel temperature increasing, and the temperature distribution tends to more uniform. The explanation for this phenomenon is the effect of fuel injection at a higher temperature, thus a higher velocity limits the mixing of the fuel with the combustion air in the primary combustion region. It creates more uniform distribution of reactants inside the flame and larger flame volume.

8.4 Heat transfer

Heat transfer was evaluated in a test furnace equipped with the one-flame HRS as shown in Technical Report 2 and 5 [5,7] including stationary sink and moving sink. Figure 8 summaries some results.

Various heat flux densities were obtained depending on the type of the used charge. Highest values are obtained for the stationary heat sink. For the HiTAC mode with stationary sink the value of the heat flux density is average of 162.9 kW/m^2. For the flame mode it is in the range 91.4 kW/m^2. It indicts that the heat flux density for HiTAC mode is 1.78 times than that for the flame mode basic on the same type of sink.

Air cooling tubes are characterized by another distribution of the heat flux density. For the HiTAC mode the value of the heat flux density is in the range 36.8 to 40.8 kW/m^2. For the flame mode it is in the range 21.0 to 27.2 kW/m^2. 59 % more average heat flux density for Case 0 is demonstrated.

Total radiation heat flux density for stationary heat sink is also dependent very much on the combustion mode [7]. For the HiTAC mode with the stationary heat sink the value of the heat flux density is in the range 191.0 to 205.4 kW/m^2. For the conventional mode it is in the range 108.7 to 117.6 kW/m^2. The average difference of total radiation for these two firing modes is the same proportion to the net heat flux as show above.

Total radiation heat flux density along the furnace wall depends also very much on the combustion mode. For the HiTAC mode the value of the heat flux density is around 200 kW/m^2. This value is at the same level with total radiation heat flux on the stationary top. For the conventional mode it is in the range 138 to 151 kW/m^2.

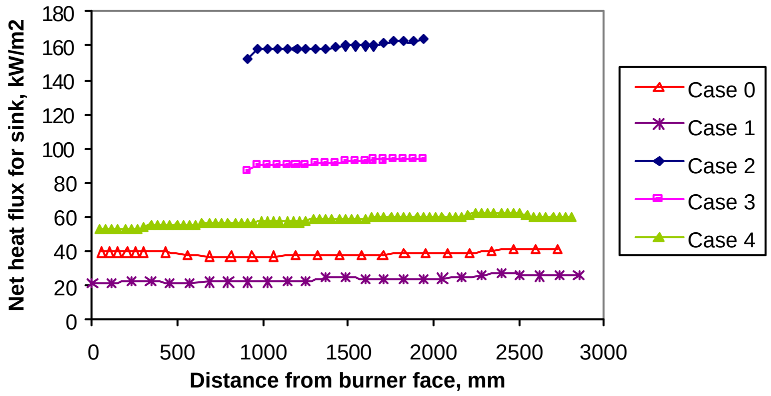


Figure 8 Predications of heat flux absorbed by the charge in test furnace

Case0: Heat fluxes through the air cooled tube in the test furnace with a one-burner HRS without any charge or heat sink.

Case1: Heat fluxes through the air cooled tube in the test furnace with conventional turbulent jet flame without any charge or heat sink.

Case2: Heat fluxes distribution along central line on the top of sink in the test furnace with a one-burner HRS and with a stationary heat sink whose surface temperature is equal to 20^{O}C and constant,

Case3: Heat fluxes distribution along central line on the top of sink in the test furnace with conventional turbulent jet flame with a stationary heat sink whose surface temperature is equal to 20^{O}C and constant.

Case4: Heat fluxes distribution along central line on the top of sink in test furnace with a one-burner HRS with a moving steel slab which initial surface temperature is equal to 20^{O}C.

8.5 Simulation of the moving slab

To prepare to calculate the real industrial furnace with moving heat sink, a moving slab is assumed in HiTAC test furnace equipped with an one-burner HRS and its' initial surface temperature is equal to 20^{O}C. This simulation results can be found in report 4 [7].

The moving slab is assumed to be made of low carbon steel in a form of moving plate. The moving slab was treated as a charge and its heating was calculated parallel to the in-furnace processes. Total heat transfer surface of the moving slab is equal to 2.945 m^2 and the heated capacity is 1.25t/h. The steel slab moves with velocity equal to 0.000833 m/s along the furnace length beginning from the furnace "inlet" located below the burner.

Changes of the moving slab surface temperature heated under the one-flame HRS are shown in Figure 9. The slab's surface temperature increases gradually and it is fairly uniform across the furnace width. It should be noticed that the slab end temperature is 608.5 K. This is of course because of the limited length of the test furnace and because of the surface initial temperature is equal to 20 ^{o}C. The test furnace can be treated as a short section of the real heating furnace.

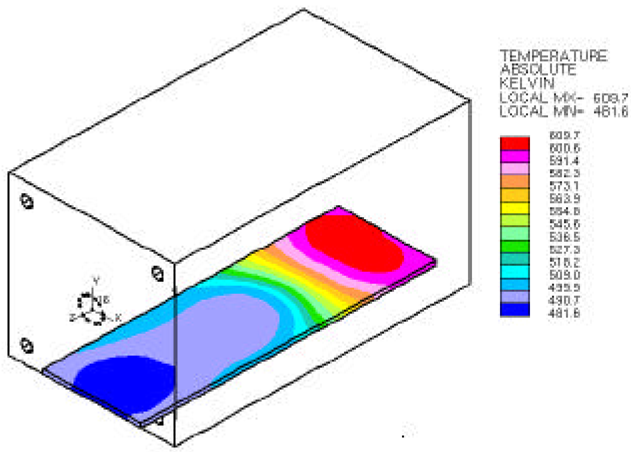


Figure 9 Predicted of temperature distribution on moving slab at one-flame HRS

9 NOX EMISSIONS

Because of the large quantities of recirculated combustion products entrained into the fresh reactants before combustion, the maximum temperature after reaction is consistently limited with respect to the adiabatic flame temperature of the pure reactants. Consequently, mean temperatures in the reaction zone are everywhere close to the temperature of reaction products, i.e. of the furnace or process temperature. Turbulent fluctuations of temperature and oxygen concentration are inherently limited and free radical formation is also hampered. Because of lack higher peak temperature (T<1800 K), thermal NOx is suppressed and much of NO maybe form mainly by mechanisms that are insignificant in most conventional combustors. One of most possibility routine is nitrous oxide mechanism. The emphasis of this study is predicted NO formation by the nitrous oxide mechanism. The details of developed NO model can be seen in [15].

The studies are performed as a so called parametric study in order to distinguish influence of the main combustion parameters on NO formation during HiTAC firing mode. From these simulations of single jet combustion test furnace (Figure 10, 11) the following can be concluded:

1. N_2O-intermediate mechanism is of outstanding importance during HiTAC at low preheated level. The numerical simulations of co-flow single jet test stand show that when oxygen concentration is larger than 10%, thermal and prompt NO emissions play a domain role. However, when oxygen concentration is less than 10%, the NO emissions formed from nitrous oxide mechanism (N_2O) have substantial influences. For LPG combusting with 1173K of air temperature, the approximate percentage of NO production by the nitrous oxide to Zeldovich and prompt mechanism vary from 5:95 at 10% of oxygen concentration to 95:5 at 5% of oxygen concentration.
2. NO emissions decrease with reduction in oxygen concentration.
3. Increasing preheated temperature of air leads to increasing of NO emission.
4. NO emissions increase with the increasing of the fuel inlet temperature for co-flower single jet gas combustion. .
5. Increasing fuel flow rate, NO emissions increase. This increase is lower at lower oxygen concentration than higher oxygen concentration.

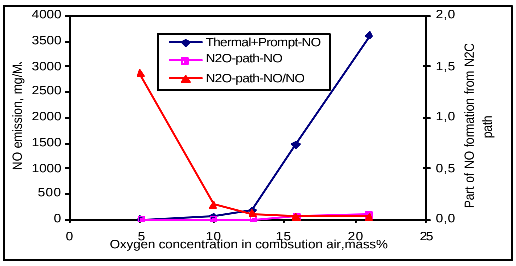


Figure 10 Effect of oxygen concentration on NO emission at air temperature of 1173K and fuel temperature of 299K for single gas jet at co-flow test

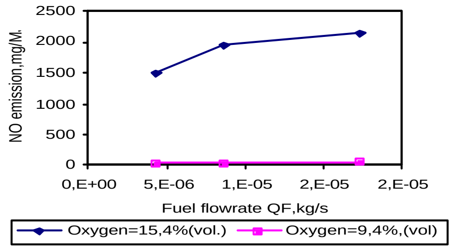


Figure 11 Effect of fuel flowrate on NO emission at single gas jet at co-flow test

NO emissions also have been predicted for the HiTAC test furnace with one-flame HRS only with thermal and prompt NO models. Figure 11 depicts total NO emissions including emission through the main chimney and chimney after burner for both measured and predicted values. NO emission was found to increases with increasing excess air ratio. Both the measured and predicted values exhibited this trend.

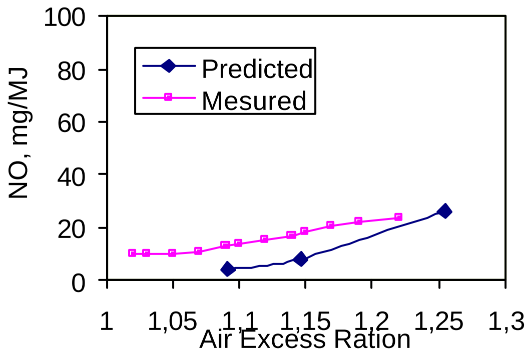


Figure 12 NO emission vs. excess air ratio at HiTAC furnace with one-flame HRS

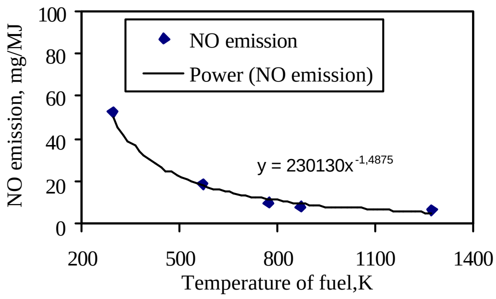


Figure 13 Effect of fuel temperature on NO emission at Stagger Mode

The measured NO emission generally agreed with the predicted values, and exhibited similar changes in ratios ratio. However, the computed total NO emission values were lower than their corresponding measured values. These differences decreased with the increasing excess air ratio. The possible reason is that both thermal-NO and prompt-NO used in this simulation are hardly formed when the flame temperature is lower than 1800 K according used NO model.

The influence of elevated fuel temperature on NO emission in HiTAC equipped with two-flame HRS is studied. The fuel temperature has a strong influence on the NO production in the furnace, especially when the fuel temperature is at a low level. NO emission decreases with increase of the fuel inlet temperature as shown in figure13.

The influence of flame locations were studied for HiTAC test furnace with two sets of two-flame HRS [14]. The stagger mode has higher emission of NO and parallel leads to less emission of NO. The effect of fuel/air injection momentum ratio on NO emission is further argued [10]. It was found that the fuel/air momentum ratio has a strong influence on the NO emission in the furnace.

10 OPTIMAL DESIGN OF HITAC FURNACE

10.1 Flame entrainment ratio

Figure 14 shows the flame entrainment ratio is function of the normalized distance, which is defined by the ratio of flame length to burner diameter for HiTAC test furnace equipped with two sets of two-flame HRS fired at stagger and counter modes [13].

The effect of fuel temperature is apparent. When fuel temperature is 293K, the location of maximum flame entrainment is bit far away from the flue gas outlet. In this case, CO emission is zero. When fuel temperature is elevated, fuel velocity increases, the location of the highest flame entrainment is moved to more close to the outlet. Then combustion efficiency is decreased. According to the simulation, the emissions of CO are 118,183 and 250 ppm (mass) for fuel temperature 573, 873 and 1273 K, respectively. Therefore, an optimum furnace width should be designed.

The counter mode offers a difference profile of flame entrainment ratio since the flows of two firing burners are impeded. The profile of flame entrainment ration is symmetrical. The value of entrainment increases with flame length from both burner faces. There are two the peaks ratio and they occurred at around 4 times of burner diameter from both burner faces. The entrainment of flame became very small at the middle of two firing burners. This is the fact that the flow direction of flue gas in flame is changed from vertical burner face to parallel burner face as shown in Figure 2(c).

Generally, the highest flame entrainment ratio is at the same level (around 3) although they occurred at difference locations since the total momentum of burners for two studied modes are the same. This could be used to estimate optimum furnace design.

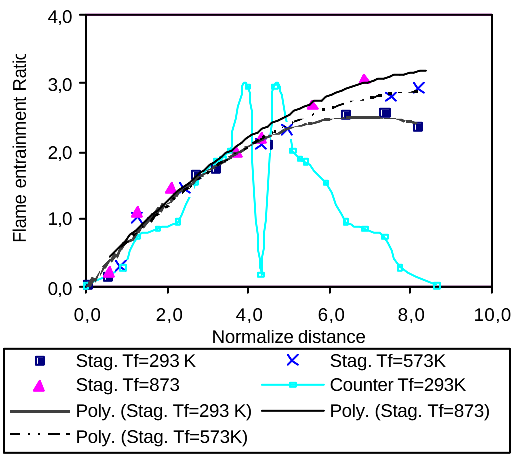


Figure 14 Effect of fuel temperature on flame entrainment ratio

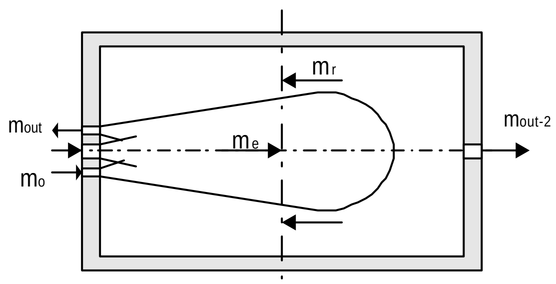


Figure 15 Scheme of structure of the flame zone and recirculation in an enclosed combustion chamber

10.2 Optimal design of HiTAC furnace

The purpose of the design of high performace industrial furnace is to provide a high level and uniform temperature in the furnace and a low NO_x emission without sarcrify combustion efficiency. Because of HiTAC has the characteristics of slow combustion diluted by internal flue gas recirculation, in order to maintain the enough internal flue gas recirculation for a special burner structure, the minimum flow area of the furnace cross section is requried. Furthermore, the width of furnace (distance from burner face to exhaust exit) also should be maintaimed otherwise the problem of ejection of unburned matter through discharge burner arises. In this part of the work, we wish to identify these two parameters.

It is clearly seen from above results and discussion that a high entrainment ratio should be maintained from flue gas. Therefore, according the flame shape and the flame entrainment ratio, the miminun flowing area of recirculation zone and furnace length can be determined. The minimum cross section of the flue gas recirculation flowing could be founded at the section which the maximum flame diameter exists.

Figure 14 shows the scheme of the flame zone and the flue gas recirculation zone. In this study, it is assumed that all the positive velocities across the cross section of the furnace are included in the flame section. This assumption has enough precision at least in the partly furnace from the burner face to the maximum flame cross.

The criteria area of the fuel gas recirculation, $A_{r,cr}$ can be determined by the maximum flame entrainment ratio R_{fe}.

$$A_{r,cr} = \frac{m_o (R_{fe,\max} - \frac{m_o - m_{out}}{m_o})}{r_r v_r} \quad \text{m}^2 \quad (11)$$

Here, $A_{r,cr}$ is the minimum cross area needed of flue gas recirculation, m_o is initial total mass flow rates of the burner. r and v are density and velocity respectively, r denotes the recirculation flue gas in the combustion chamber. Normally, for one-flame HRS, $m_{out} = 0.8 m_o$, and for two-flame HRS, $m_{out} = 0$.

It can be seen clear that the criteria minimum area of combustion chamber is function of:

1. the initial momentum of the burner, $R_{fe,max}$,
2. the initial total mass flow rates of the burner, m_o,
3. density of in-furnace flue gas, thus furnace temperature,
4. velocity of in-furnace flue gas which is effected by furnace temperature and the length of furnace along the vertical direction of burer's face.
5. the type of HRS. i.e., one-flame or two-flame HRS.

Accordingly, it is easy to give the optimal design of HiTAC furnace. For example, For the stagger firing mode of the studied burner at the design condition, the $R_{fe,max}$ is 2.6 according calculation. The temperature of furnace is around 1373 K, and the average density is around 0.28. Additionally the average velocity of recirculation flue gas is approach 1 m/s on the cross section of $R_{fe,max}$ at this furnace temperature. The area of flame cross section at the $R_{fe,max}$ is 0.155168 m^2, which occurs at 1.2m from burner's face.

If the studied burner is equipped to a furnace with cylinder combustion chamber, the criteria area of flue gas recalculation of the chamber is 0.04m^2, therefore, the criteria diameter for the burner with 100 kW is 0.5m. This is approximately 2.7 times of the burner diameter.

Another parameter for optimal design is the length of furnace. The following three aspects could be considered. The first, according to the characteristics of HiTAC, larger entrainment ratio leads to lower NO_x emission, it is easy understood that if the peak temperature occurs at the location of peak flame entrainment ratio appearing, the lowest NO_x emission will be realized for a special burner. Therefore, the location of peak flame entrainment ratio should be designed to near the firing burner as possible. The second, the maximum uniform temperature profile in the furnace can be achieved when the peak flame entrainment ratio locates on the middle of furnace width. Finally, the combustion efficiency in flame increases with the increasing of width. In order to achieve complete combustion, enough furnace width is necessary. In summary, the maximum flame cross section at least could be at a half of the furnace length.

Consequence, for HiTAC furnace fitted with two-flame HRS, the optimum furnace length is at the range of 1.2–2.4m for the studied burner at stagger firing mode. This is at the range of approximately 6.5–13 times of the burner diameter.

Similarly, the optimal design of HiTAC furnace equipped with one-flame can also be decided [11,15].

11 CONCLUSIONS

Single gas jet test furnace and the HiTAC test furnace equipped with HRS (both one-flame and two-flame) were studied numerically and main conclusions formulated:

1. Combustion model, Eddy-Dissipation-Concept with multi-step chemical reactions, is more suitable numerical model for HiTAC especially when modelling is applied to large scale industrial furnace.
2. NO emission formed by N2O-intermediate mechanism is of outstanding importance during HiTAC.
3. The concepts, including oxidation mixture ratio, furnace-gas-temperature-uniformity-ratio, Furnace Flame Occupation Coefficient and Flame entrainment ratio, were defined to describe the characteristics of HiTAC, which are help for optimal design of HiTAC furnace and burner.
4. The benefits of HRS is quantitative demonstrate by mathematical models. They are: lower peak temperature, larger flame volume, more uniform thermal field, lower local firing rate, higher heat transfer, higher energy utilizing efficiency and lower combustion noise.
5. Operation parameters, including oxygen concentration and temperature of preheated combustion air, fuel temperature, fuel flowrate, the excess air ratio and flame locations have stronger influences on

combustion and NO emission in HiTAC furnace. The optimal combination of these parameters should be considered

6. The criteria diameter and length of the furnace fitted with HRS are proposal in order to achieve an optimal design of HiTAC.

Finally, the whole work shows numerical simulation is very encouraging and can be used as an analytical and designable tool of industrial furnace.

12 FUTURE WORK

The mathematical models for high-temperature air combustion have been verified against results of experiments. The next step is using CFD as a tool to redesign, retrofit and design industrial furnace equipped with HRS.

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