Emission Characteristic Map and Optimization of NOx in 100 MW Staged Combustion Once-Through-Steam-Generator (OTSG)

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Abstract

In the present paper a generalized methodology to reduce emission from a staged combustion burner in a typical Once-Through-Steam Generator is outlined. Initially Computational Fluid Dynamics (CFD) tools were used to generate an emission characteristics map (ECM) of the combustion system and it was used then as a guideline towards efficient characterization and optimization of the OTSG in during a field testing. It was demonstrated that for a staged combustion system, there exists a unique ECM subject to the fuel deliver pressures at core, inner and outer header, respectively; and with the help of the ECM the global minima for NOx emission can be successfully identified and achieved. This method of emission reduction based on engineering calculation was found to be cost-effective compared to costlier conventional methods like Flue-Gas Recirculation (FGR).

Introduction

Once-Through Steam Generators (OTSG) are regularly used in the Oil-Sand industry in Western Canada as for the Steam-Assisted Gravity Drainage (SAGD) applications. With the rapid development of oil-sand facilities, there has been a steady increase of the number of OTSG's in operation and as a result, the associated environmental pollution, especially Nitrous Oxides (NO_x). In the province of Alberta in Canada, following the implementation of certain legislation under Environmental Protection and Enhancement Act (EPEA) and the requirement of Alberta Continuous Emission Monitoring System [1], there is an urgent push to reduce the emissions from these OTSGs to legislated levels set forth by the Environmental Protection and Enhancement Act (EPPA), a dependency of the Government of Alberta [2].

Formation of NO_x on an open flame combustor like OTSG is a complex process and usually involves a large number of intermediate species. However, it is demonstrated [3] that all of these processes can be described sufficiently by three pathways of NO_x formation/destruction: 1) Thermal NO_x, which is generated by the oxidation of the nitrogen present in the combustion air. 2) Prompt NO_x; which is generated due to the reaction of air with C, CH and CH_2 radicals present in the fuel ; and 3) Re-burning which reduced overall NO_x concentration through reaction with CH_4 radicals [4]. Out of these three mechanisms, it was observed that Thermal NO_x is the main pathway for generation in heavy duty boiler while the contribution from Prompt NO_x and re-burning is negligible [4, 5, 6]. Currently several NO_x reduction technologies are in place [7]; for example, burner design modifications, staged combustion, temperature reduction and flue gas recirculation. The main objectives sought by all these modifications are; to reduce the reaction temperature (for thermal NO_x); to minimize the contact between the nitrogen in the fuel with the oxygen in combustion air (for prompt NO_x) and; to create a fuel rich zone for possible re-burning [4, 8, 9]. Out of these technologies, the one involving staged combustion to reduce Thermal NO_x is fairly matured for natural gas boilers. Staged combustion can be one of three different types: fuel staging – where the fuel is introduced in a manner to generate fuel rich and lean zones of combustion, air staging – where the air is introduced in stages to keep the flame temperature down; or a combination of fuel and air staging. Usually all commercial boilers were fitted with complicated multiple air and fuel inlets to accomplish a combination of fuel and air staging. This technology for low NO_x burner using staged combustion is relatively mature now and is generally accepted as an effective method for NO_x reduction [10]. Usually for industrial furnaces, the furnace manufacturer integrates the burner (manufactured by a separate vendor) based on the design requirement of the furnace, and therefore there is a need to characterize the combined system following commissioning to optimize the burner operation with respect to furnace requirement (e.g., louver opening, steam requirement, emission limit etc.). This is usually accomplished by field characterization of furnace after commissioning where the feedback control system of the furnace system is calibrated. Usually field NO_x optimization is performed at this stage. The present paper outlines a proper framework to quickly identify the operating point corresponding to the lowest possible NO_x, which reduces the characterization effort drastically.

Since NOx emission is strongly controlled by a range of fluid flow and heat transfer variables, such as turbulence, combustion, temperature field, mixing, NOx forming mechanism, radiation and more, it is generally a complex task to find the effect of each variables in the NOx emission. This is a more prevalent problem in industrial settings, where there are a large number of parameters to be optimized and it is usually unclear how to figure out *a-priori* what combinations of parameters would lead to the lowest possible NOx for a given operating condition. Nevertheless, a functional relationship between the NOx level and the operating conditions is always helpful to guide the decision making-process by operators. To address this need, detail characterization of the burner is usually undertaken. However, obtaining characterization correlations over the full range of operation is a very time consuming task and sometimes even impossible for a large industrial plant as the operation schedules of such plants are very constrained. Given the size and complexity of state of the art equipment, only a limited set of tests can be planned and executed. Frequently, the gathered datasets are incomplete and may contain a large number of uncertainties [11].

Because of the above reasons, the usage of mathematical models and computational fluid dynamics seems more appropriate to gain a complete understanding of the various physical processes involved inside the OTSG. However, one should also bear in mind that matching the computational result with the actual condition in an industrial setting may be extremely difficult due to uncertainties on the input data and lack of proper experimental planning due to operational constraints. Nevertheless, if properly used, numerical calculations can be used to provide accurate enough guidelines for variation of various parameters with respect to operating condition. Results of numerical simulations, also can serve as useful guideline for the operations department. The simulation can start with a validation case, where the field data from a particular operating point would be matched to obtain a reliable computational model. Once a validated model is obtained, a number of variables can be changed in the computational model to evaluate the effect on the OTSG performance to generate a quantitative, approximated Emission Characteristics Map (ECM). Using the trend map, need for long and expensive burner characterization can be greatly diminished or even altogether eliminated.

The present work outlines the computational and field effort undertaken towards NOx optimization for a typical furnace with staged combustion burner. Initially a moderately detailed computational simulation was performed to generate an approximate ECM, and following that a field characterization study was organized in an attempt to follow the generated emission map towards minimizing NOx emission. It was shown that the present effort successfully reduced the emission by 40% simply by adjusting the fuel header pressures to alter the combustion characteristics. This reduction was achieved simply by adjusting the valves to control the fuel header pressure, and therefore most cost effective to implement.

The present work intends to serve as a typical case and a guideline which can be extended to any type of furnace following our general framework and procedure.

Problem Description

A typical schematic of an OTSG is shown in Figure 1. In this figure, the burner is at the right, where the combustion takes place. The horizontal section of the OTSG is called radiant section, since the primary mechanism of heat transfer is radiation at this location. After the radiant section, the hot combustion products enters the vertical part of OTSG (convection section), where heat is transferred primarily through convection. For a typical OTSG used for SAGD operation in Northern Alberta, the exit steam quality at the outlet of radiant steam tube is usually maintained at 0.8. Because of the nature of operation of OTSG, it is usually easier to control the steam quality compared to the convection boiler.

For the OTSG in question, Figure 2 shows the windbox, fuel header and combined view of the whole air and fuel delivery system. The windbox has a side inlet where combustion air from a blower is supplied. This fresh combustion air is passed through a series of radial slots to homogenize the flow and then directed axially to the combustion chamber through eight rectangular slots arranged radially at the exit of the windbox. The slots were designed in such a way to achieve proper mixing with the fuel discharged through the inner header of fuel tip and ignited after the burner slot exit and to generate enough flow velocity to reduce the possibility of flame flashback into the windbox. As seen in Figure 2, the main fuel delivery line is split into three different headers – the core, inner and outer header. These three headers are used to supply appropriate amount of fuel into each combustion zone and thereby control the flame by changing the air-fuel mixture fraction. The core header supply 5-10% of the fuel and is mainly used to ignite and stabilize the flame. The rest of the fuel is delivered to remaining inner and outer headers. The fuel discharged from the inner header is mixed with the fresh combustion air and is ignited immediately exiting the burner slots by the core flame and comprise the primary combustion zone. The fuel discharged from the outer header is used to support the secondary combustion zone, which feeds from partially exhausted flue gas from the primary zone. The resulting delay in ignition of this secondary zone helps to reduce the overall flame temperature and leads to reduction of NOx generation. In the burner tested, three independent butterfly valves were installed at the individual fuel lines to manually adjust the supply pressure at each fuel header.

It is postulated that the pressures at these individual zones can be varied to control the overall combustion characteristic of the burner and therefore can be used to change the operating condition in such a way to generate minimum NOx emission, without compromising the heat flux. Thus, initially a series of computational fluid dynamics simulations were carried out with various combinations of header pressures and from the result, an approximate ECM was generated. Afterwards during the field testing the header pressures were adjusted in accordance with the produced ECM to achieve the minimum possible NO_x from the burner. It should be mentioned here that the absolute magnitude of the NO_x is not important in this scenario, but the relative trend with changes in the header pressures needs to be accurate. This, lowers the required level of accuracy, the complexity of the computational model, and therefore reduces the computational cost drastically.

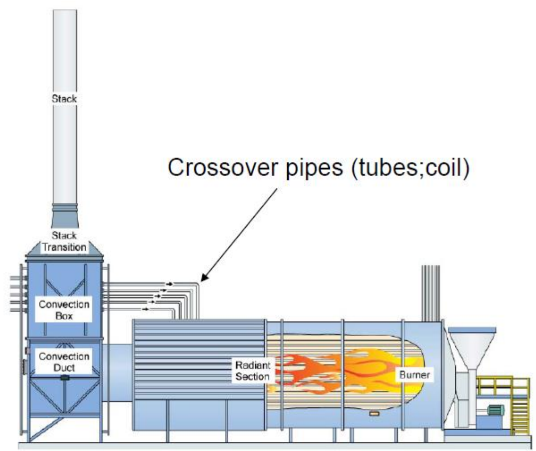

Figure 1: Schematic of typical OTSG (Courtesy: Angelo Scotton)

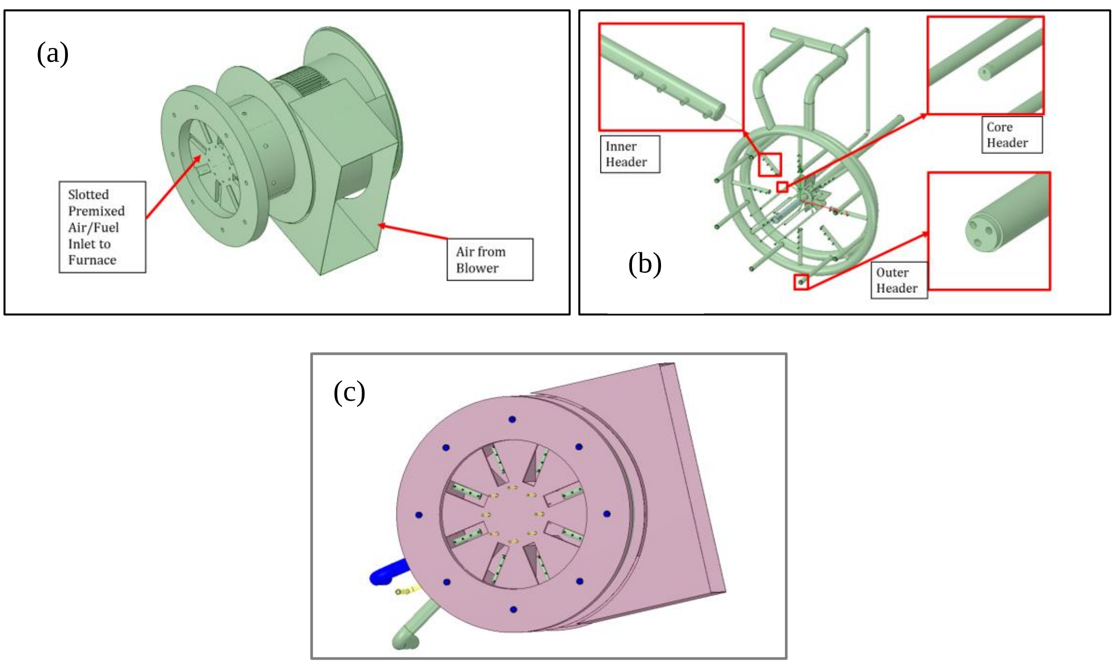

Figure 2: Model of the Windbox (Inset (a)), Fuel Delivery System (Inset (b)) of the OTSG. Inset (c) shows the combined view of air and fuel delivery to the OTSG

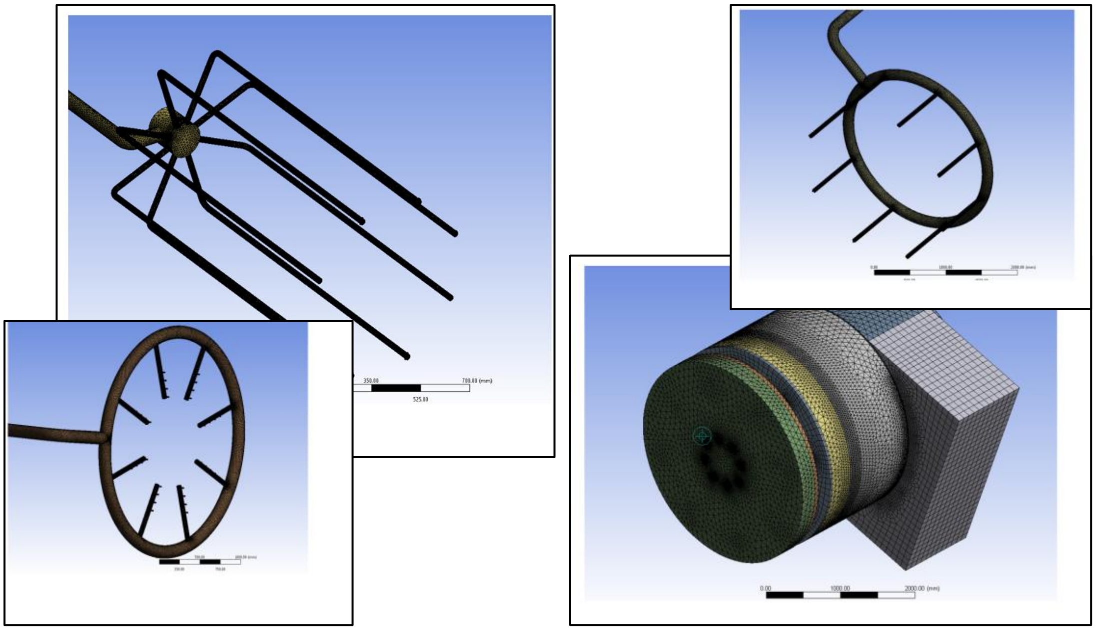

Figure 3: Typical Mesh of some regions of the computational domain

Result and Discussion

In the present work, commercial software ANSYS Fluent has been used for solution. The full furnace geometry was modelled and the resulting meshes at some important locations were shown in Figure 3. A grid independence study with cold flow simulation without combustion was performed and the resulting mesh was adjusted to have the final mesh size of 10073489 nodes and 22959649 elements.

Combustion was simulated using Eddy Dissipation Concept Model (EDC) [12] which accounts for the interaction between the turbulence and the chemical reactions and is generally accepted to be an accurate model to predict the combustion behaviour where the fast chemistry assumption may not be applicable. The reduced GRI-Mech 1.2 Chemistry mechanism [13] has been used in the model, instead of the full GRI-Mech 3.0 set which contains 325 chemical reactions and 53 species. The simulation was completed in several steps: initially a cold flow was established and the air fuel mixture is ignited using a presumed PDF model [14]. The presumed PDF model uses a calculated probability distribution function of temperature with respect to the mean and variance of mixture fraction. However, this model does not account for the mixing and assumed instantaneous combustion. Following a stable solution, the combustion model was switched to Eddy Dissipation Concept Model (EDC) to account for the finer scales of the turbulent flow.

For fuel and air, mass flow inlet boundary conditions were applied at the inlet boundaries, respectively, as tabulated in Table 1. The simulations were performed for only one operating condition, namely 100% firing with the aforementioned fuel and air mass flow rate. A pressure outlet with zero relative pressure outlet condition was imposed at the stack outlet. The wall heat flux at the convective and radiant tubes were imposed on the model as shown in Table 1. Each case required 30 hours of computation time in a 16-core ANSYS HPC cluster.

Initially the simulation was run with mass flow inlet boundary condition for fuel and air inlet with no pressure drops at fuel control valves. The result of the simulation indicate that to maintain the mass flow rate as per the equipment datasheet, the fuel mainline pressure needs to be maintained at 160 kPa. This value matches closely with the actual fuel main delivery pressure of 165 kPa. This condition corresponds to the Case 1 in Table 2. With this initial case, the closure of fuel valves were modelled as lump-sum pressure jump applied across a domain just before fuel header. For nine different cases, varying amount of pressure jump was introduced in the model and the resulting pressure at the fuel header downstream of the pressure drop application was reported in Table 2.

Table 1: OTSG Dimensions and Boundary Conditions

Firing Condition	
Power	106 MW
Fuel Flow	2 kg/s
Air Flow	42.4 kg/s
Hear Transfer to Radiant Tubes	50,915 W/m^2
Heat Transfer to Convective Tubes	71,600 W/m^2
Fuel Composition [Volumetric]	
CH_4	0.950
C_2H_6	0.017
C_3H_8	0.050
CO_2	0.028

Table 2: Simulation Cases, corresponding flame individual flame temperatures and calculated NOx

Case	Flow Split Ratio			Individual Flame Temperature [K]			NOx at Stack [ppm]
	Inner	Outer	Core	Primary	Secondary	Core	
1	56.1	37.6	6.3	1287	1004	1735	37
2	56.9	36.8	6.3	1231	1249	1890	21
3	57.5	38.3	4.2	1315	1239	1514	22
4	57.1	37.9	5.0	1241	1189	1835	56
5	53.2	39.5	7.3	1325	1261	1887	61
6	52.0	41.1	6.9	1324	1210	1888	59
7	56.1	37.5	6.4	1465	1201	1994	30
8	56.1	37.5	6.4	1409	1226	1876	30
9	56.7	38.5	4.8	1331	1165	1834	14

Figure 4 shows the temperature distribution downstream of the burner to illustrate the flame in separate zones. It can be seen that the flame is mainly comprised of three zones: (a) Core Zone: The flame generated at the core header tip usually burn in a fuel-rich condition and acts as a pilot flame and provides stability to the whole combustion system; (b) Primary Zone: This zone comprises of the premixed flame generating out of the inner header. The fuel discharged from this header gets mixed with the combustion air and then discharged out of these rectangular slots at high velocity, where they get ignited right at the exit of from the burner back plate. The size of the recirculation zone is important in this case since this dictates the mixing of the fuel with air and ensures that the flame does not blowout at lower turn-down condition. Moreover, this also ensures proper mixing of the air and fuel so to avoid any high temperature zones to ensure less NO_x generation; (c) Secondary Zone: This zone contains the flame generated at the tip of the outer header and burn in slightly exhausted hot flue gas coming out from primary zone. The resulting delay in combustion, in addition to the partially burnt mixture, reduces the overall flame temperature, leading to lower emission from the burner.

Out of all the cases mentioned in Table 2, the iso-contour of stoichiometric mass fraction of methane (f = 0.054) superimposed with the temperature contour for Case 1 only is shown in Figure 5. It should be mentioned here that the ppm reported in the present work are the wet NO_x corrected to 3% excess air. In this figure, the flames corresponding to core, inner and outer can be seen clearly. For each cases, the surface averaged temperature from each flame is estimated and reported in Table 2. The measured NO_x emission at the stack was also reported in the same table.

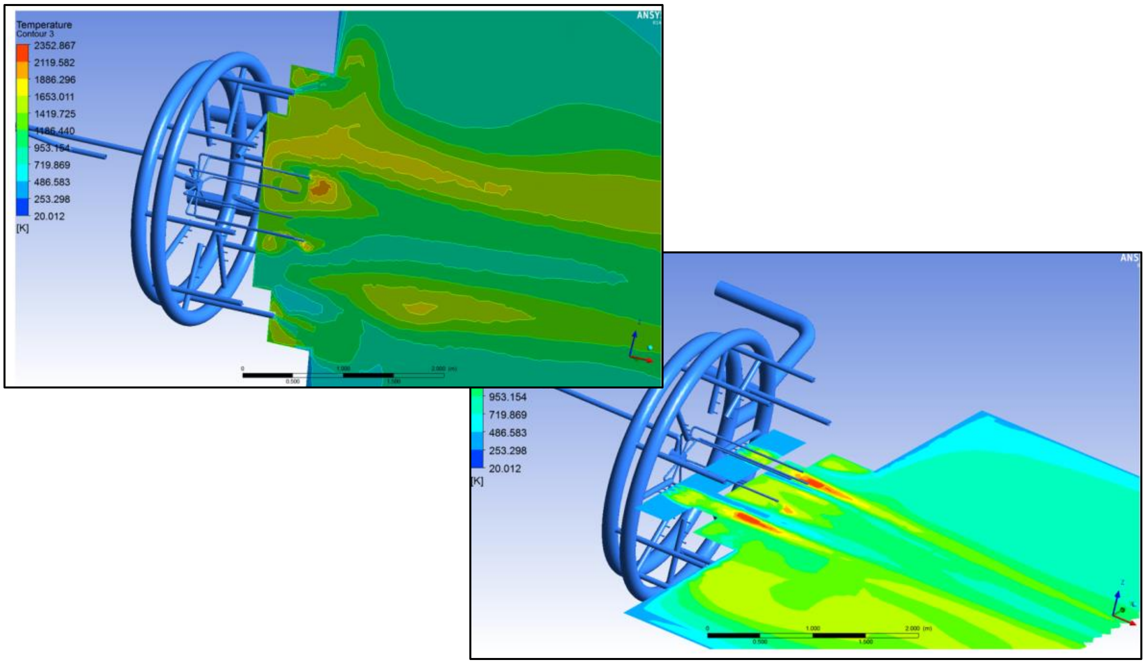

Figure 4: Temperature Distribution for different flames in vertical, and horizontal planes, respectively.

It can be seen that there is a complex interrelationship between the fuel header pressures and the resulting NO_x emission, depending heavily on a variety of factors, namely burner design, fuel type, firing load, to name a few. While the optimization approach presented here can be generalized for any burner in question, the specifics of the optimization point is applicable only for the present burner in question. A number of conclusions can be drawn based on the present burner in question. It was found that the inner header was always running in chocked condition for fuel header pressures more than 45 kPa. Therefore the inner header pressure has a weak effect on the individual flame temperature. The variation for the present case was found to be approximately 50 K, on top of 1200 K mean flame temperature. However, with inner header running chocked, changing the header pressure in the outer header can influence the secondary flame temperature. It can be seen that the secondary flame temperature increases until outer header pressure of 56 kPa and then starts to decrease with increasing outer header pressure. An exactly reversed trend can be observed for the core flame temperature with the core header pressure for chocked inner header – the temperature drops until core pressure of 30 kPa and then starts to increase again. However, the relationship between total NO_x emission and the fuel header pressure is not very straightforward and no clear trend can be extracted from there. Moreover, the complex interrelationship can be difficult to explain analytically and no mechanistic model can be determined, except using computational fluid dynamics.

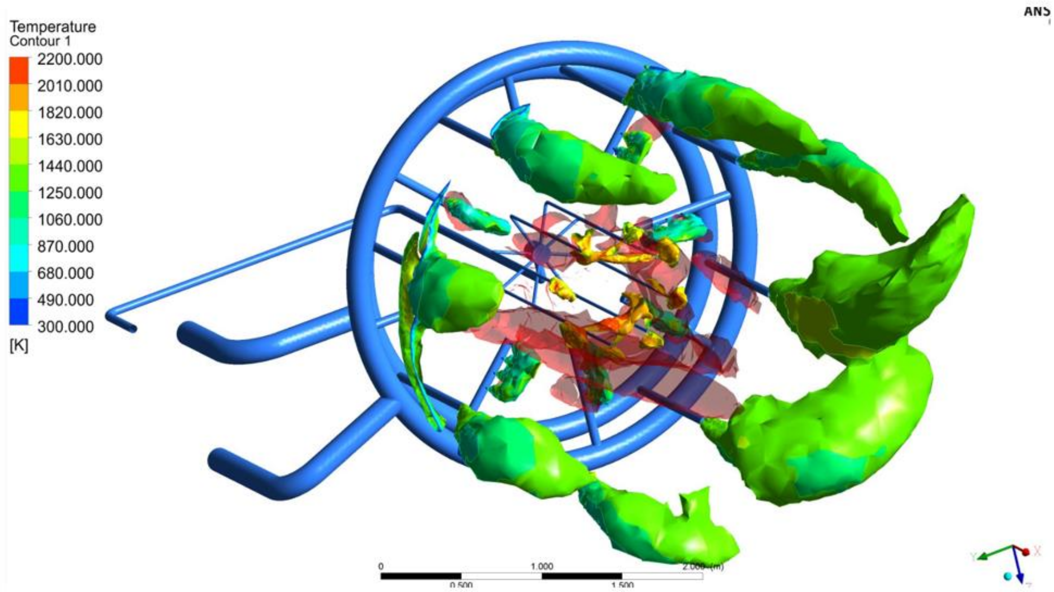

Figure 5: Iso-Contour of Stoichiometric Methane Mass Fraction superimposed with the temperature contour for Case 1. The iso-surface of 150 PPM NO_x concentration is shown in red.

For the present case, a number of ways were explored to map the NO_x emission with core, inner and outer header pressure. It was found that there is a functional correlation for the concentration of NO_x when it is plotted against the core header pressure and the difference between the inner and outer header pressure. It might be possible to scale these variables and extract some other useful correlations, but for the present case, it was found that this mapping would provide an adequate guide for field testing and characterization. The resulting ECM is shown in Figure 6. It can be seen that NO_x would increase of the core pressure is more than 50 kPa and the difference between inner and outer is more than 30 kPa. However, the valley of the NO_x emission can be found if the core pressure is dropped below 30 kPa and the difference between the inner and outer header pressures can be maintained either more than 30 kPa or less than 10 kPa. It was also concluded, based on the simulation, that there is a critical pressure for core fuel header below which the core flame might become unstable and extinguish, leading to global combustion instability.

Following the generation of this ECM a field test was conducted aiming to reduce the NO_x emission following the guideline. The result of the field measurement is tabulated in Table 3. Due to production schedule the test furnace was available for testing purposes only for 8 hours. Given this constraint, it was decided that the shortest possible path towards the region of minimum NO_x emission will be followed during test. It was also decided to reduce the core pressure gradually at 5 kPa interval and change the inner and outer header pressure to maintain a difference of 30 kPa. During the course of testing, it was found that if core pressure is reduced below 25 kPa the flame starts to de-stabilize, leading to high structural vibration generating pulsations in the furnace. Upon further reduction, the core flame gets extinguished and the inner and outer flame gets de-anchored, and impinge on the refractory surface of the furnace, leading to severe vibration and tripping of the furnace. Each modifications in fuel header pressure was allowed an hour to get the stable combustion and the corresponding emission reading was acquired. At 25 kPa core header pressure, the outer spud was fully opened and a pressure of 89 kPa was achieved. But at this point the inner header was almost closed and it was not possible to close it further to achieve the desired 58 kPa pressure at the inner header. Thus, it was not possible to match the actual operating condition with the optimal condition based on the simulation. Nevertheless, it was proven that by following the guideline prescribed by the simulation, it was possible to reduce the emission by 37% by changing the combustion pattern and the associated physics. Following the tuning, the furnace was observed for next one month and the NO_x reading was found to be consistently stable and fixed. As a further step, measures were being taken to replace the manual butterfly valves with fully automated control valves to achieve further optimization of NO_x.

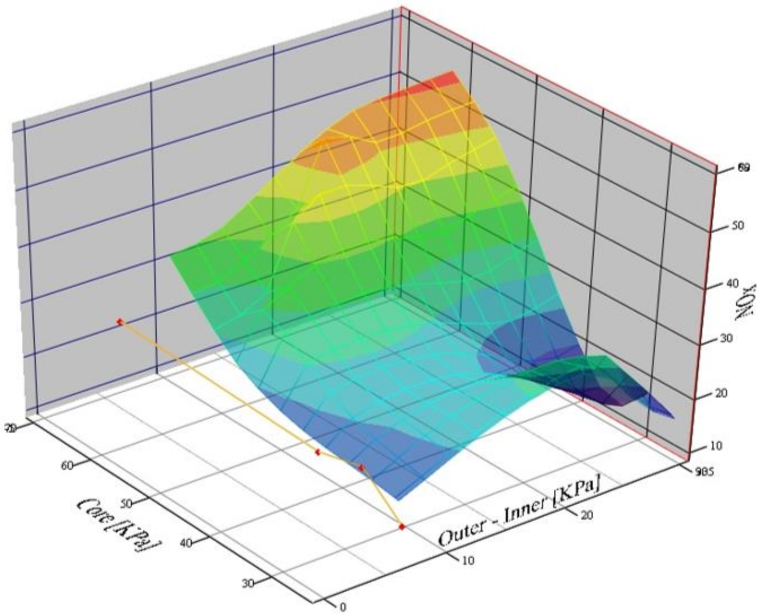

Figure 6: Emission Characteristic Map of the burner

Table 2: Data from field performance testing

Header Pressures [kPag]			NOx [PPM]
Core	Inner	Outer	
69	79	84	23
40	91	83	17
35	92	83	17
25	91	84	15

Conclusion

Industrial furnace tune-ups to minimize NO_x emission can be costly and time consuming because of lack of a proper methodology and procedures that help operators to restrict the search space over many continuum variables. In the current paper, a methodology was developed which used computational fluid dynamics to provide a preliminary map of emission which can be used as a guideline to furnace tune-up. It was demonstrated that this methodology can effectively to cut down the costly tune-up time and also able to reduce the NO_x emission by 37% without any costly accessories. Initially the furnace and the burner geometry was modelled and parametric computationally fluid dynamics simulations were performed to generate a global emission map. That global emission map was used to provide guidance during the actual field tune-up. Whereas only one industrial burner was used in this present study, the outlined methodology is universal and can be adopted for any burner and fuel compositions.

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