Fired Heater Study Report

Vacuum Heater

HeaterSIM ref: H-13114

1. Executive Summary

This report is based around the Vacuum Fired Heater tag no. 1105-01 currently installed and in operation at the CLIENT Refinery facility. The heater was built in 1980 and is a Twin Cell Cabin Heater designed to achieve a maximum duty of 42.73 MW. The heater shares an extensive common duct and stack system with several other heaters.

The refinery have raised concerns about the high CO emission levels measured in the common stack and strongly suspects that the vacuum heater is responsible as the excessive CO is measured when the vacuum furnace is operating at its maximum rate. Thus, in accordance with CLIENT's request, the scope of this study is limited to the Vacuum furnace only and it is assumed that the other furnaces are operating normally and within their required emission limits.

CO is produced when there is insufficient oxygen for combustion which can arise by either:

- A restriction on the air supply
- An excessive supply of fuel to the burners creating 'fuel rich' conditions
- Damaged burner parts impacting upon the ratio between oxygen and fuel within the combustion zone.

This report details the investigation into the three main areas mentioned above, discussing potential causes and solutions where necessary.

The burners are Natural Draft type and from our visual inspection there were no blockages identified on the air wind boxes. However, the fuel pressure observed at site showed that one cell was being provided with higher pressure fuel than the other. This report investigates some of the potential reasons and consequences for this discrepancy and makes some recommendations in regards to resolving it.

A site survey was carried out as part of the study, where some general information and data points were collected. This data was then subsequently used to produce a heater simulation which would identify some key points of interest including Radiant section temperatures and maximum tube skin temperatures.

1.1. **Referenced Documents:**

This report should be read in conjunction with the following documents

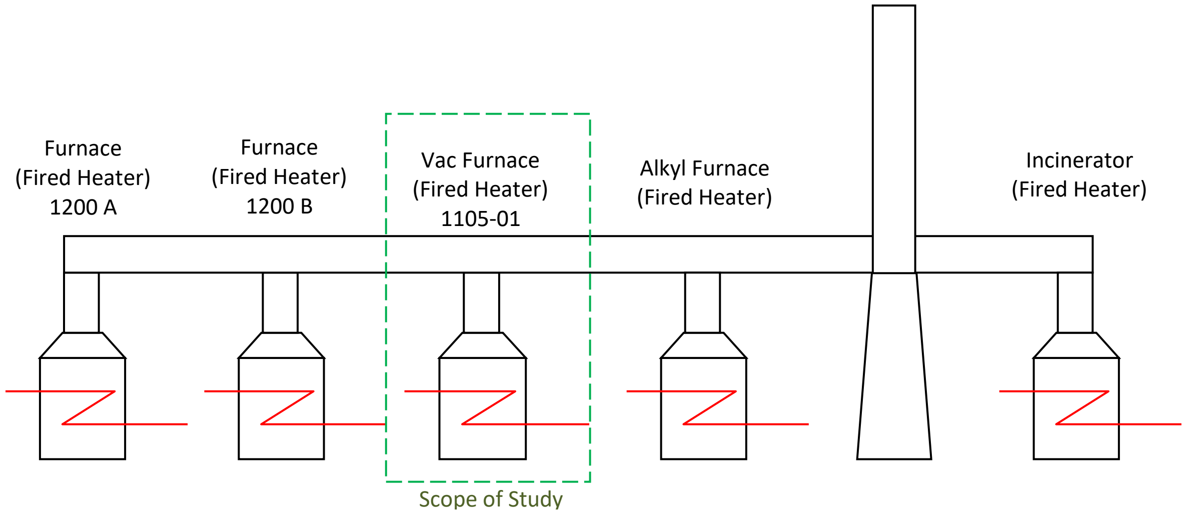
- Fired Heater Datasheet (CLIENT document)
- Vacuum Unit P&ID (CLIENT document) – Drawing no.:53.1100-06A
- Vacuum Unit P&ID (CLIENT document) – Drawing no.:53.1100-06B

1.2. **Abbreviations and Acronyms**

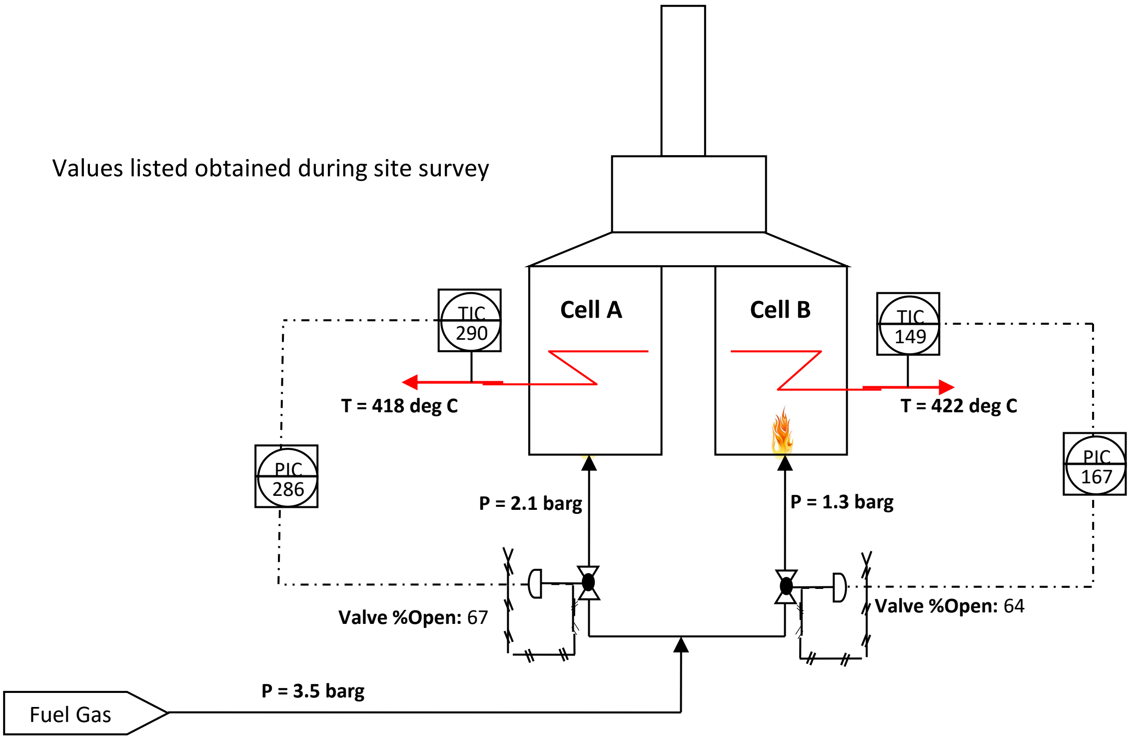
- AFR – Air:Fuel Ratio
- LHV – Lower Heating Value
- Mw – Molecular Weight
- P – Pressure (Pa (a))
- V – Volume (m^3)
- n = no. of moles
- R – Gas Constant 8.314 J / mol K
- T = Temperature (K)
- P&ID – Process and Instrumentation Diagram
- PLC – Programmable Logic Controller
- TSOV –Tight Shut Off Valve

2. Introduction

2.1. This report examines the Vacuum Heater 1105-01 at the CLIENT Refinery, which has a Twin Cell Cabin configuration with a common convection section and a shared ducting and stack system. There are a total of 20 natural draft burners (10 per cell) located in the floor.



2.2. The fuel gas supplied to each radiant cell is modulated by a separate Pressure Control Valve (PCV) that is linked on a control loop with the process outlet temperature of the respective cell. Site measurements showed a discrepancy between the fuel gas pressures downstream of the valves, despite being at very similar open positions.



3. Methodology

3.1. Based on the site data received and heater design documents from CLIENT, a series of simulations and calculations were carried out with the key points of interest being:

3.1.1. **Coking/Fouled Layer Thickness (section 5):** The thickness layer may have some impact upon the CO2 produced, as an increased coke/fouled layer would mean that a greater amount of heat is required in order to maintain the required process outlet temperature. This greater heat requirement would mean that the fuel gas PCV valves would open more and possibly supply an excessive amount of fuel gas for the air available would'nt air flow rate increase accordingly though with control system

3.1.2. **Fuel Gas Pressure Supply (section 6):** Faults within the fuel gas pressure supply control system (either within mechanical aspects or instrumentation) may lead to an excessive fuel supply in relation to the available combustion air and potential CO production as a result.

3.1.3. **Burner Malfunction (section 7):** Malfunctions within the burner itself can have an impact upon the fuel-air ratio of mixing within the burner and sub-stoichiometric combustion zones (mixing efficiency can be compromised), producing CO.

3.1.4. **Draft Analysis:** From our experience with such common heater duct systems, in max firing cases whereby all heaters are operating at their maximum duty the load on the ducting and stack system could be such that the available draft for the vacuum heater is reduced. However, our visual inspection and the measured draft data did not show any indication that the vacuum heater was struggling for draft, thus such analysis is not discussed within this report.

4. Simulation

The summary of simulation model and calculation is as follows (please see our attached heater datasheet for further details):

4.1. **Mechanical Data**

Parameter	Dimension
Heater Design Configuration:	Twin Cell Cabin Heater
Radiant Height:	9
Radiant Tube Effective Length:	20m
Convection Effective Length:	18m
Coil Tube Material	A335 P9

4.2. **Process Data**

Parameter	Design Case (per CLIENT datasheet)
Total Process flow (kg/s)	85.83
Inlet Temperature deg C	272
Outlet temperature deg C	418
Fuel Type	Fuel Gas
Excess Air %	15%
Ambient Air Temperature	15.5

4.3. **Fuel Gas Composition**

Component	Mol %
H_2	20
N_2	9
CO	0.8
CO_2	1.3
CH_4	30
CH_2H_6	17
C_3H_8	4.5
C_4H_{10}	0.2
C_4H_{10}	0.6
C_2H_4	14.5
C_3H_6	2.5

4.4. **Simulation Results**

Item	Design Case (per CLIENT datasheet)
Total Heat Absorbed, MW	42.73
Heat Release, MW	53.231
Excess Air, %	15
Flue gas flow rate, kg/s	21.6
Flue gas temp. at arch, °C	766
Flue gas temp. leaving convection, °C	349
Max Tube Temp. °C	518
Combustion Air flow, kg/s	20.34 (10.17 per cell)
Avg. Radiant Flux W/m^2	24,483

4.5. **Flue gas composition (design case – i.e. complete combustion)**

Component	Mol % (wet basis)
CO_2	9.3
H_2O	16.0
N_2	72.2
O_2	2.5

General Analysis of Results

4.6. The simulation model results above described the intended operational conditions of the heater. The calculated temperatures and flux are consistent with modern heaters built in accordance with API 560.

4.7. The flue gas composition described above is based on a particular fuel composition with 15% excess air level as per the original fired heater datasheet. Variations in the fuel composition will have a direct result on the composition of the fuel gas. It is also important to consider the amount of CO within the fuel gas itself, as this may have a direct impact upon the CO emission readings.

4.8. However, for the purpose of this study, it has been assumed that the fuel gas composition will not significantly deviate from the composition described above.

5. Coking/Fouled Layer Thickness within the process coils

5.1. The simulation software does not produce any meaningful predictions in regards to actual coking thickness rates (amount of coking formed within a given period). Nonetheless, we have conducted simulations with various fouling factors in an attempt to examine the effects of various thickness upon required firing rates to achieve the specified process outlet temperature.

Table showing coking thickness and required firing rates and true excess air amounts:

Fouling Factor (K m^2 /W)	0.0002	0.0004	0.0006	0.0008	0.001	0.002
Firing Rate (MW)	52.928	53.084	53.229	53.379	53.566	54.345
Excess Air %	15.67	15.33	15.01	14.69	14.29	12.65
Max Tube Temperature ^{o}C	490	499	508	518	529	574

Note: Fouling factor of 0.002 K m^2 /W is considered an extreme scenario and considerably greater than the highest values recommended by TEMA Standards. Even at these extreme cases the excess air available is still above 10%

5.2. The results above demonstrate that an increased coking thickness within the process coils will increase the amount of firing required (as expected), the extent of additional firing is not such whereby sub- stoichiometric conditions can be realistically expected. Firing rate increase is negligible

6. Burner Damage

6.1. It was observed that the burner at the end of each radiant cell showed an unusual flame, with what appeared to be a large amount of dust particles. This ‘dusty’ flame extended upwards significantly and would occasionally lick the roof tubes and supports. This abnormality was visible on the terminal end burner in each cell and can be indicative of CO production.

6.2. The fact that the affect was only apparent on particular burners highlights the distinct possibility of a fault within the actual burner itself. From discussions with CLIENT site engineers, it was understood that extensive sections of fuel lines had solid contaminant deposits. The fuel lines had been recently cleaned and the solid deposits removed. However, the burner may have been damaged during the period of operating with such contaminated fuel. For example, the solid contaminants may have caused erosion/corrosion/blockage? of the burner fuel tips.

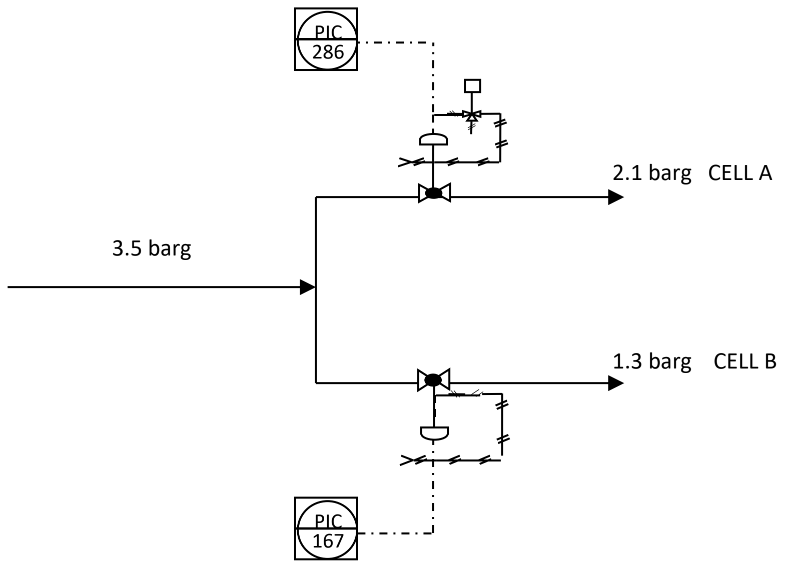
6.3. Such damage to the tips may result in an excess of fuel being introduced into the furnace, giving rise to local sub-stoichiometric combustion conditions.

6.4. There could be other mechanical aspects of the burner that have been damaged resulting in the imbalance between fuel and air. Whilst there were no immediately apparent external malfunction characteristics, often such problems are identified during shutdown periods when the burners can be more closely inspected.

7. Fuel Pressure

7.1. During the site survey, it was observed that Cell A was being provided with 2.1 barg fuel gas pressure whilst Cell B was only being provided with 1.3 barg, despite the process outlet temperatures and flow rates at each cell being equal (418oC). Although the flame lengths and diameters were not noticeably different, the flames in cell B were slightly more luminous than those in Cell A. The luminescence of the flame is an indicative measure of oxygen availability for combustion, since flames with high O2 availability are less luminous.

7.2. Despite the valves having very similar open positions, there was a discrepancy between the downstream pressures of each valve. The different fuel supply pressures under isothermal conditions would mean that different amounts of fuel flow rates are being provided to each cell. It was calculated that the cell with the lower pressure would actually have a greater fuel flow than the higher pressure cell since the fuel will have a reduced path of resistance via the low pressure route (note: as the valves have essentially the same %open position, the pressure drop across each can be assumed to be equal).



7.3. Considering that the valves are in the same position, equal pressure losses would apply to each valve and the incoming flow has the same flow area across the valve in either branch. Thus, the valves are not consequential in the analysis and the incoming flow of gas is more likely to flow down the greater pressure gradient in an attempt to equalise the pressure.

Assumptions:

- Fuel piping serving each cell is in a general symmetrical arrangement
- All manual valves in the fuel line are open
- Elevation changes and liquid slug formation is negligible

Calculations:

Difference in density between 2.1 barg and 1.3 barg

PV = nRT (Ideal Gas Law Equation)

(P * Mw) / RT = (n * Mw) / V = density (g/m3)

Cell A (@ 2.1 barg)	**Cell B (@ 1.3 barg)**
Mw= 21.1	Mw= 21.1
P = 310,000 Pa (a) (2.1 barg)	P = 230,000 Pa (a) (1.3 barg)
R = 8.314	R = 8.314
T = 288 K (ambient temperature)	T = 288 K (ambient temperature)
(310000 * 21.1) / (8.314 * 288) = 2732 g/m3	(230000 * 21.1) / (8.314 * 288) = 2027 g/m3
=> 2.73 kg/m3	=> 2.03 kg/m3

7.4. Difference between the two densities at the respective conditions:

7.5. Density difference = 2.73 – 2.03 = 0.7 kg/m3

7.6. In an attempt to equalise the pressure, there will be an additional 0.7 kg per m3 flowing to CELL B instead of CELL A. Of course, because the system is continuous the pressure will never equalise and there will remain a discrepancy in the flow.

7.7. So let's say the actual fuel flow rate required in Cell A is: 0.636 kg/s

7.8. Density: 2.73 kg/m3

7.9. Volume flow = 0.636 / 2.73 = 0.233 m3/s

7.10. Remembering that there will be an additional 0.7 kg per m3 flowing to CELL B instead of CELL A

7.11. Then additional mass flow to Cell B = 0.7 * 0.233 = 0.1631kg/s

7.12. So mass flow to cell B = 0.636 + 0.1631 = 0.8 kg/s

7.13. LHV of Fuel: 41,837 kJ/kg

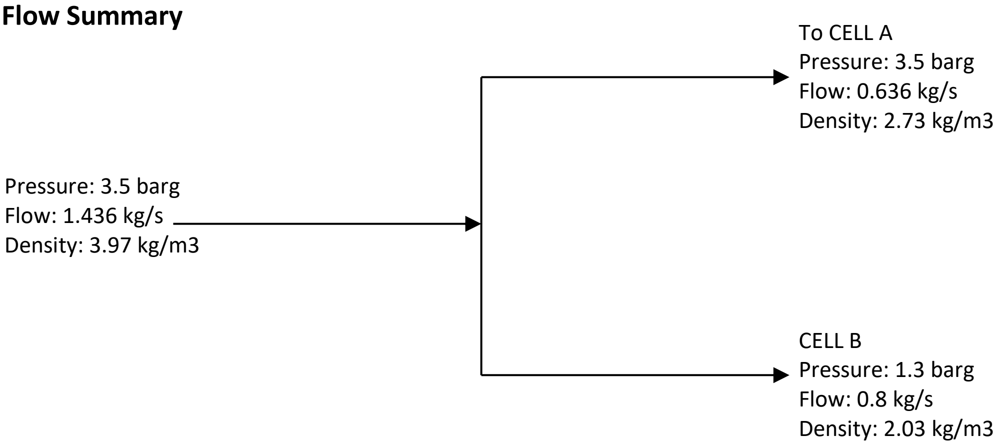
7.14. Minimum Air Fuel Ratio (AFR) = 13.9 (for stoichiometric combustion)

7.15. Maximum Air Flow Rate into each cell @ design duty: 11.05 kg/s

7.16. Cell A AFR: 11.05 / 0.636 = 17.4 (above 13.9, thus Combustion conditions OK)

7.17. Cell B AFR: 11.05 / 0.8 = 13.8 (below 13.9, CO production will to occur in real operating scenario)

Fuel Flow Summary



The above conclusion also explains why Cell B consistently has a lower measured O2 reading in comparison to Cell A.

Accounting for the additional heat release

7.18. The calculations above demonstrate that there is a distinct mass flow imbalance between the two cells which gives rise to the production of CO at the higher operating ranges of the heater. However, it is important to realise that the fuel flow imbalance means that the cells will have different absorbed duties.

Heat Release = Fuel Flow (kg/s) * LHV (kJ/kg)

Cell A Heat Release = (0.636 * 41837) = 26.6 MW

Cell B Heat Release = (0.79 * 41837) = 33.05 MW

(* Note that for Cell B, the total flow of 0.8kg/s is not completely burnt due to insufficient air, thus 0.79 kg/s fuel noted above can be burnt completely at best)

7.19. Nonetheless, the measured process outlet temperatures for Cell A and Cell B were 418°C and 422°C respectively. Usually, this discrepancy between the temperature transmitters can be neglected, however in the case whereby one cell is being fired at a greater rate than the other, this difference would also be reflected in the measured process outlet temperatures of each cell.

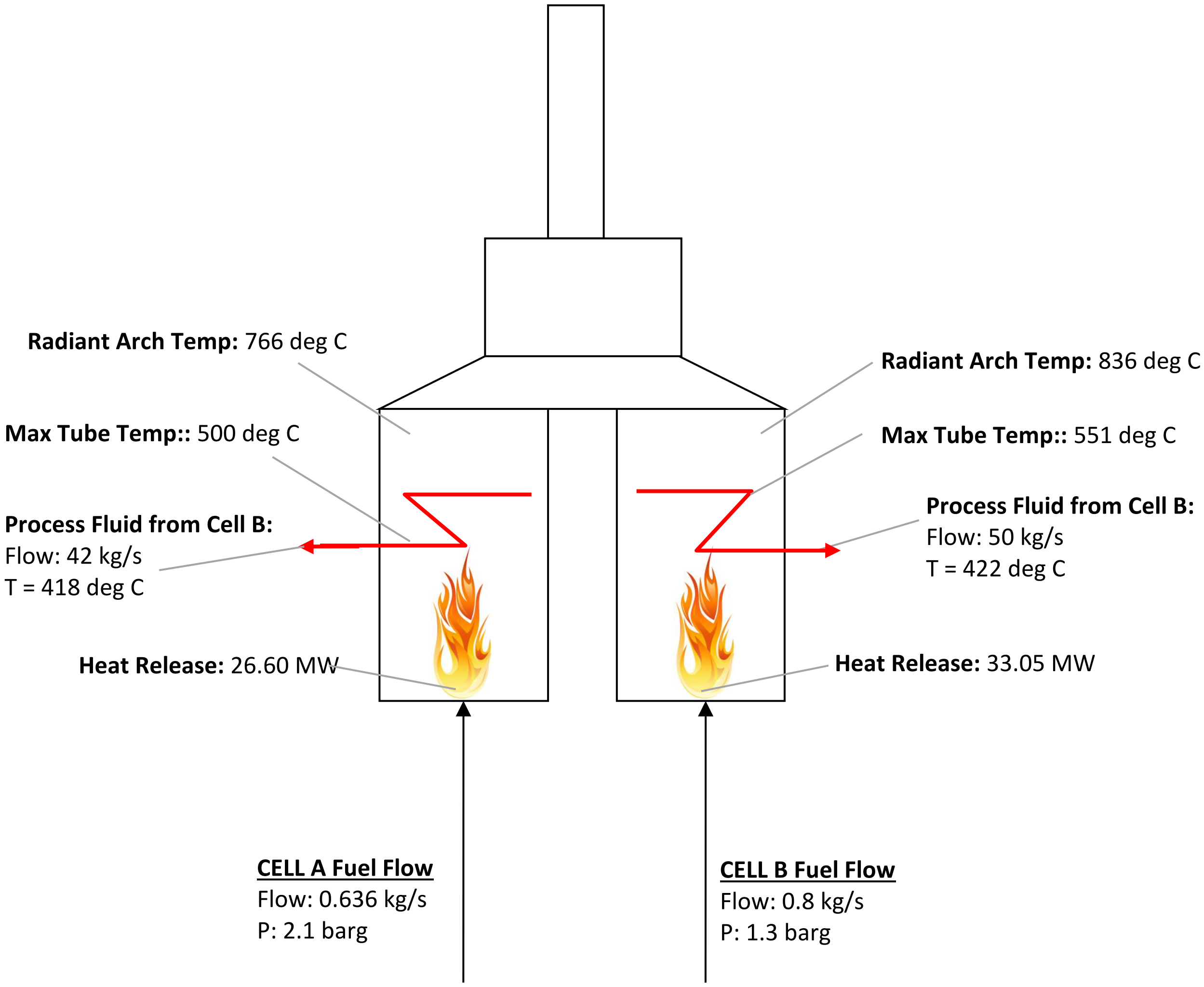
7.20. These measured temperatures suggest that there is an imbalance in flows between the process passes. Several simulation models were prepared in order to determine the extent of the mal-distribution and the results are summarised below:

Current Operation Simulation Results of Each Cell

Item	Cell A	Cell B
Total Heat Absorbed, MW	16.25	19.27
Heat Release, MW	26.60	33.05
Process flow, kg/s	42	50
Temp. at arch, °C	766	836
Max Tube Temp. deg C	500	551
Avg. Radiant Flux W/m2	23,963	28,957
Combustion Air flow, kg/s	11.05	11.05
Fuel gas flow rate, kg/s	0.636	0.8
Excess Air, %	25	0

7.21. It is considered fortunate that cell B with a greater firing rate also has a greater mal-distributed process flow rate. The process fluid measured temperature discrepancy would be more severe if Cell B had the lower process flow rate and could potentially result in disturbance in downstream process units/equipment.

7.22. Summary Model of Current Furnace Operation:



8. Discussion

8.1. This report has detailed the analysis conducted by HeaterSIM in relation to excessive CO emissions of the 1105-01 Vacuum Heater at the CLIENT Refinery. Our analysis has highlighted that the imbalanced fuel pressures supplied to each radiant cell (despite having the same % open positions) to be the cause for the fuel rich conditions in Cell B, thus leading to CO production.

8.2. From discussion with CLIENT site engineers, we understand that there has been recent fouling of the fuel lines by an unknown solid contaminant. It is therefore reasonable to expect that these solid contaminants may have eroded/corroded the burner fuel tips, which would mean that a significant amount of fuel gas is passed through the burner tips than intended at a given pressure, giving rise to poor air/fuel mixing and fuel rich combustion conditions.

8.3. Such deductions are also consistent with the difference in fuel line pressures downstream of the respective PCVs that have essentially the same % open positions. We have presented a quantitative analysis of the operating conditions that could arise from the discrepancy in fuel pressures and our results are consistent with the measured data from site.

8.4. We have also considered other possible causes for the excessive CO production which have been discussed within the report, including internal tube coking and burner malfunction. However, analysis of these aspects from collected data and visual inspection has not currently identified any credible issues that would give rise to the excessive CO production reported on site.

8.5. However, despite our analysis and presentation that the imbalanced fuel pressure to each cell is the likely cause for the CO production, the investigation has proved quite complex and there are a number of other issues which may be responsible for the excessive CO levels measured. Thus, we have prepared a list of recommendations which should be carried out or investigated at the earliest opportunity, in accordance with site convenience, shutdown periods and safety considerations:

8.5.1. **Replace burner fuel tips on all burners:** It is understood from discussions with site engineers that there are sufficient spare tips in storage, thus such an action can be carried out quickly and with minimal cost. It is our expectation that such action would significantly reduce the discrepancy between the fuel pressures supplied to each radiant cell.

8.5.2. **X-Ray Analysis of all fuel lines:** In order to identify possible blockages contributing to mal-distribution of fuel.

8.5.3. **Emission levels of the other heaters:** As per CLIENT request, this report assumes that the other heaters are operating correctly. However, as the CO measurement is recorded in the main stack, it is of considerable importance to confirm the emission levels of each heater over a sustained period, to ensure that this assumption is correct.

8.5.4. **Maintenance check on PCV 286 and PCV 167:** To ensure correct operational performance

8.5.5. **Examine Coded Calculations for PIC control loops:** In order to ensure that the correct pressure is being supplied for a given heat requirement. All measuring device elements and transmitters should be also be checked.

8.5.6. **Check CO emissions analyser:** Although the trends provided with a number of variables against CO emissions have been helpful, there is no clear and consistent relationship demonstrated with CO emissions that would usually be expected. Thus, a general check should be undertaken to ensure that the CO analyser is working correctly or measurement readings taken with another device to ensure accuracy and consistency.

8.5.7. **Fuel Composition:** It has been noted that the fuel composition contains 0.8% mole of CO. A general check of the fuel composition should be carried out over time to ensure that the level of CO within the fuel is maintained at acceptable levels.

8.5.8. **Close Inspection of burners:** To be carried out during shutdown period in order to identify damage (e.g. blocked fuel tips and/or blockages in air duct/windbox).