IMPROVING HEATING PLANT EMISSIONS USING FLUE GAS CARBON MONOXIDE MONITORING

A thesis presented in partial fulfilment of the requirements for the degree of
Masters of Engineering in Automation and Control at Massey University

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SUMMARY

RCR Energy Systems builds industrial heating plants and their control systems. In these the excess air (above the stoichiometric ratio) for combustion is a process variable and its setpoint is determined using a look-up table. RCR aims to improve the efficiency of wood-fired, thermal-oil heating plants by using a combination of carbon monoxide monitoring and oxygen trim control to automatically adjust the excess air setpoint.

Heating plants require the correct amount of oxygen for combustion. Too little excess air does not allow complete combustion, producing a loss in efficiency and wasted fuel. Too much excess air reduces the flame temperature with a consequent drop in heat transfer rate and loss of efficiency.

The aim of the project was to explore the advantages of carbon monoxide monitoring and oxygen trim control, as well as its application, design and implementation in trimming excess oxygen setpoint, to a lower, but still safe operating level.

Various carbon monoxide monitoring and oxygen trim control schemes were researched with the most suitable being implemented on an industrial system using a combined carbon monoxide and oxygen measurement analysers. This scheme was then tested on the heating plants at Hyne & Son in Tumbarumba, Australia. The tests proved that the excess air setpoint could be successfully reduced by 2%, leading to an approximate 3 – 5% improvement in efficiency.

ACKNOWLEDGEMENTS

I am grateful to my parents for giving me the opportunity to study a Masters degree in New Zealand. I would also like to thank my supervisor Dr Huub Bakker for his help and advice throughout my academic career. Thanks also to my mentor Allen Keogh, automation and electrical manager at RCR Energy Systems, for his support while working on the project. My gratitude extends to Nick Martin and Kelly Williams, engineers at RCR Energy Systems, for putting up with me and providing me with a lot of help and knowledge which assisted with the project.

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NOMENCLATURE

SYMBOL	DESCRIPTION	UNIT
a_1	Carbon content of grate ash, %wgt	%
a_2	Carbon content of fly ash , %wgt	%
CO	Carbon monoxide	ppm
$COSP_{HP1}$	Heating plant 1 carbon monoxide setpoint	ppm
$COSP_{HP2}$	Heating plant 2 carbon monoxide setpoint	ppm
COT_{PH1}	Heating plant 1 carbon monoxide transmitter	ppm
COT_{PH2}	Heating plant 2 carbon monoxide transmitter	ppm
Cp_{AmbHP}	Heating plant ambient temperature specific heat capacity	J/kg. °C
$Cp_{FlueHP1}$	Heating plant 1 flue gas temperature specific heat capacity	J/kg. °C
$Cp_{FlueHP2}$	Heating plant 2 flue gas temperature specific heat capacity	J/kg. °C
$Cp_{FlueNewHP}$	Heating plant flue gas temperature specific heat capacity with increased 2% in excess air	J/kg. °C
$Cp_{FurnHP1}$	Heating plant 1 furnace air temperature specific heat capacity	J/kg. °C
$Cp_{FurnHP2}$	Heating plant 2 furnace air temperature specific heat capacity	J/kg. °C
$Cp_{FurnNewHP}$	Heating plant furnace air temperature specific heat capacity with increased 2% excess air	J/kg. °C
Cp_{HEHP}	Heating plant heat exchanger outlet air temperature specific heat capacity	J/kg. °C
$Cp_{HENewHP}$	Heating plant heat exchanger outlet air temperature specific heat capacity with 2% increase in excess air	J/kg. °C
$Cp_{OilHP1(33\%Texa+67\%Prf)}$	Heating plant 1 heat transfer oil specific heat capacity (33% Texatherm 32 + Perfecto HT12)	J/kg. °C
$Cp_{OilHP2(33\%Texa+67\%Prf)}$	Heating plant 2 heat transfer oil specific heat capacity (33% Texatherm 32 + Perfecto HT12)	J/kg. °C
$Cp_{OilInHP1Prf}$	Heating plant 1 Perfecto HT12 inlet oil specific heat capacity	J/kg. °C
$Cp_{OilInHP1Texa}$	Heating plant 1 Texatherm 32 inlet oil specific heat capacity	J/kg. °C
$Cp_{OilInHP2Prf}$	Heating plant 2 Perfecto HT12 inlet oil specific heat capacity	J/kg. °C
$Cp_{OilInHP2Texa}$	Heating plant 2 Texatherm 32 inlet oil specific heat capacity	J/kg. °C
$Cp_{OilOutHP1Prf}$	Heating plant 1 Perfecto HT12 outlet oil specific heat capacity	J/kg. °C
$Cp_{OilOutHP1Texa}$	Heating plant 1 Texatherm 32 outlet oil specific heat capacity	J/kg. °C
$Cp_{OilOutHP2Prf}$	Heating plant 2 Perfecto HT12 outlet oil specific heat capacity	J/kg. °C
$Cp_{OilOutHP2Texa}$	Heating plant 2 Texatherm 32 outlet oil specific heat capacity	J/kg. °C
E_{gr}	Thermal efficiency	%
E_{HP1}	Heating plant 1 efficiency improvement	%
E_{HP2}	Heating plant 2 efficiency improvement	%
F	The flowrate of the fluid	Kg/s
F_{AirHP1}	Heating plant 1air flow rate	kg/s
$F_{AirHP1+2\%}$	Heating plant 1 air flow rate with 2% increase in excess air	kg/s

F_{AirHP2}	Heating plant 2air flow rate	kg/s
$F_{AirHP2+2\%}$	Heating plant 2 air flow rate with 2% increase in excess air	kg/s
F_{OilHP1}	Heating plant 1 oil flow rate	kg/s
$F_{OilHP1(33\%Texa+67\%Prf)}$	Heating plant 1 oil flow rate (33% Texatherm 32 + Perfecto HT12)	kg/s
F_{OilHP2}	Heating plant 2 oil flow rate	kg/s
$F_{OilHP2(33\%Texa+67\%Prf)}$	Heating plant 2 oil flow rate (33% Texatherm 32 + Perfecto HT12)	kg/s
$F_{OilInHP1Prf}$	Heating plant 1 Perfecto HT12 inlet oil flow rate	kg/s
$F_{OilInHP1Texa}$	Heating plant 1 Texatherm 32 inlet oil flow rate	kg/s
$F_{OilInHP2Prf}$	Heating plant 2 Perfecto HT12 inlet oil flow rate	kg/s
$F_{OilInHP2Texa}$	Heating plant 2 Texatherm 32 inlet oil flow rate	kg/s
$F_{OilOutHP1Prf}$	Heating plant 1 Perfecto HT12 outlet oil flow rate	kg/s
$F_{OilOutHP1Texa}$	Heating plant 1 Texatherm 32 outlet oil flow rate	kg/s
$F_{OilOutHP2Prf}$	Heating plant 2 Perfecto HT12 outlet oil flow rate	kg/s
$F_{OilOutHP2Texa}$	Heating plant 2 Texatherm 32 outlet oil flow rate	kg/s
FR_{HP1}	Heating plant 1 firing rate	%
FR_{HP2}	Heating plant 2 firing rate	%
H	Hydrogen content of fuel as fired, %wgt	%
K_1	Coal constant. typical value of k_1 for coal is 63 in accordance with British standard 845-1:1987	-
K_2	Weight basis percentage of the fuel	-
K_{gr}	Constant Siegert (based on calorific value)	-
L_{1gr}	Losses due to sensible heat in dry flue gases	%
L_{2gr}	Losses due to enthalpy in water vapour in the flue gases	%
L_{3gr}	Losses due to unburned gases in the flue gases	%
L_{4gr}	Losses due to combustible matter in ash and riddling	%
L_{5gr}	Losses due to combustible matter in grit and dust	%
L_{6gr}	Radiation, convection and conduction losses	%
L_{Tgr}	Total losses	%
M_f	Mass of solid fuel fired	kg
mH_2O	Moisture content of fuel as fired, %wgt	%
N_2	Nitrogen content in the flue gas	%
O_2	Oxygen content in the flue gas	%
O_2SP_{HP1}	Heating plant 1 oxygen setpoint	%
O_2SP_{HP2}	Heating plant 2 oxygen setpoint	%
O_2T_{HP1}	Heating plant 1 oxygen transmitter	%
O_2T_{HP2}	Heating plant 2 oxygen transmitter	%
$p_{OilHP1(33\%Texa+67\%Prf)}$	Heating plant 1 oil density (33% Texatherm 32 + Perfecto HT12)	kg/m^3
$p_{OilHP2(33\%Texa+67\%Prf)}$	Heating plant 2 oil density (33% Texatherm 32 + Perfecto HT12)	kg/m^3
$p_{OilInHP1Prf}$	Heating plant 1 Perfecto HT12 inlet oil density	kg/m^3
$p_{OilInHP1Texa}$	Heating plant 1 Texatherm 32 inlet oil density	kg/m^3

$p_{OilInHP2Prf}$	Heating plant 2 Perfecto HT12 inlet oil density	kg/m^3
$p_{OilInHP2Texa}$	Heating plant 2 Texatherm 32 inlet oil density	kg/m^3
$p_{OilOutHP1Prf}$	Heating plant 1 Perfecto HT12 outlet oil density	kg/m^3
$p_{OilOutHP1Texa}$	Heating plant 1 Texatherm 32 outlet oil density	kg/m^3
$p_{OilOutHP2Prf}$	Heating plant 2 Perfecto HT12 outlet oil density	kg/m^3
$p_{OilOutHP2Texa}$	Heating plant 2 Texatherm 32 outlet oil density	kg/m^3
$Q_{AirinHP1}$	Heating plant 1 air inlet power	MW
$Q_{AirinHP2}$	Heating plant 2 air inlet power	MW
$Q_{AirinNewHP1}$	Heating plant 1 air inlet power with 2% increase in excess air	MW
$Q_{AirinNewHP2}$	Heating plant 2 air inlet power with 2% increase in excess air	MW
$Q_{CombHP1}$	Heating plant 1 power generated in combustion zone	MW
$Q_{CombHP2}$	Heating plant 2 power generated in combustion zone	MW
$Q_{CombNewHP1}$	Heating plant 1 power generated in combustion zone with 2% increase in excess air	MW
$Q_{CombNewHP2}$	Heating plant 2 power generated in combustion zone with 2% increase in excess air	MW
Q_{gr}	Gross calorific value of fuel	kJ/kg
Q_{HP1}	Heating plant 1 output power	MW
Q_{HP2}	Heating plant 2 output power	MW
Q_{NewHP1}	Heating plant 1 output power with 2% increase in excess air	MW
Q_{NewHP2}	Heating plant 2 output power with 2% increase in excess air	MW
$Q_{SteamHP1}$	Heating plant 1 steam power	MW
$Q_{SteamHP2}$	Heating plant 2 steam power	MW
$Q_{SteamNewHP1}$	Heating plant 1 steam power with 2% increase in excess air	MW
$Q_{SteamNewHP2}$	Heating plant 2 steam power with 2% increase in excess air	MW
t_3	Heating plant exit temperature	°C
t_a	Ambient temperature	°C
T_{AmbHP1}	Heating plant 1 ambient temperature	°C
T_{AmbHP2}	Heating plant 2 ambient temperature	°C
$T_{FlueHP1}$	Heating plant 1 flue gas temperature	°C
$T_{FlueHP2}$	Heating plant 2 flue gas temperature	°C
$T_{FlueNewHP1}$	Heating plant 1 flue gas temperature with 2% increase in excess air	°C
$T_{FlueNewHP2}$	Heating plant 2 flue gas temperature with 2% increase in excess air	°C
$T_{FurnHP1}$	Heating plant 1 furnace air temperature	°C
$T_{FurnHP2}$	Heating plant 2 furnace air temperature	°C
$T_{FurnNewHP1}$	Heating plant 1 furnace air temperature with 2% increase in excess air	°C
$T_{FurnNewHP2}$	Heating plant 2 furnace air temperature with 2% increase in excess air	°C
T_{HEHP1}	Heating plant 1 heat exchanger outlet air temperature	°C
T_{HEHP2}	Heating plant 2 heat exchanger outlet air temperature	°C
$T_{HENewHP1}$	Heating plant 1 heat exchanger outlet air temperature with 2% increase in excess air	°C

$T_{HENewHP2}$	Heating plant 2 heat exchanger outlet air temperature with 2% increase in excess air	°C
T_{HHP1}	Heating plant 1 heater outlet air temperature	°C
T_{HHP2}	Heating plant 2 heater outlet air temperature	°C
T_{in}	Inlet fluid temperature	°C
$T_{OilInHP1}$	Heating plant 1 inlet oil temperature	°C
$T_{OilInHP2}$	Heating plant 2 inlet oil temperature	°C
$T_{OilInNewHP1}$	Heating plant 1 inlet oil temperature with 2% increase in excess air	°C
$T_{OilInNewHP2}$	Heating plant 2 inlet oil temperature with 2% increase in excess air	°C
$T_{OilOutHP1}$	Heating plant 1 outlet oil temperature	°C
$T_{OilOutHP2}$	Heating plant 2 outlet oil temperature	°C
$T_{OilOutNewHP1}$	Heating plant 1 outlet oil temperature with 2% increase in excess air	°C
$T_{OilOutNewHP2}$	Heating plant 2 outlet oil temperature with 2% increase in excess air	°C
T_{out}	outlet fluid temperature	°C
UA_{HP1}	Heating plant 1 heat transfer coefficient x Area	W/°C
UA_{HP2}	Heating plant 2 heat transfer coefficient x Area	W/°C
VCO	Volume of carbon monoxide, %mol	%
VO_2	Heating plant excess oxygen, %mol	%
ΔT_{HP1}	Heating plant 1 log temperature difference	°C
ΔT_{HP2}	Heating plant 2 log temperature difference	°C

CONTRIBUTIONS

The major contribution of this thesis has been to apply the technique of carbon monoxide monitoring trim control to a heating plant. While this technique has been known for some time, the implementation using a specific analyser on a PLC (Programmable logic control) controller has not previously been done within New Zealand industry. Specifically, RCR Energy Systems Limited has had no previous experience with carbon monoxide trim control nor carbon monoxide online analysers.

The specific contributions described in this thesis and made by the author, are:

1. A literature review of boiler combustion with regard to production/control of carbon monoxide and excess air,
2. The analysis of carbon monoxide control loop structures leading to a design of one for this project,
3. An analysis of two online, carbon monoxide analysers leading to a choice of one for this project,
4. Implementation of the control loop in the Sequential Function Chart (SFC) and Structure Text programming languages for a PLC control,
5. Implementation of the analyser and control loop on a heating plant in Tumarumba, Australia (with assistance),
6. An analysis of the data from the investigation of the performance heating plants prior to implementing the trim control,
7. An analysis of the operation of the analyser and control loop on the heating plants,
8. An analysis of the mass and heat balances of the heating plants,
9. A financial analysis of the payback period for such control on a boiler plant from historical data.

INTRODUCTION

RCR Energy Systems build and automate industrial heating plants. A heating plant is an industrial facility that uses waste energy to produce heat, electricity, etc... RCR as is common practice in industry, controls the flow of air to the furnace of the heating plant to maintain a set level of excess air (air beyond that required to meet the stoichiometric requirements). The setpoint for this control comes from a look-up table.

The company now wishes to improve on this by trimming the excess air setpoint by measuring the flue gas carbon monoxide in addition to the oxygen levels. The test case will be the wood fired thermal-oil heating plants at the Hyne & Son heating plants in Tumbarumba, Australia.

Heating plants require the correct amount of oxygen for combustion, too much or little can cause undesirable effects thus reducing heating plant efficiency.

The aim of this project is to design, implement and test a carbon monoxide monitoring and oxygen trim control system to trim the percentage oxygen setpoint for combustion.

This thesis is divided into four chapters.

Chapter 1 describes the background and the research which made this project necessary. It illustrates the importance of improving a heating plant's performance by running regular efficiency tests and its impact on efficiency and savings. The chapter also includes different methods to measure and control excess air.

Chapter 2 includes the trials and investigations of heating plants' performance before implementing the trim control.

Chapter 3 focuses on the trim control specification and methods to determine if it meets the specifications and generic design. In addition, it includes the implementation and the process function description of the trim control system.

Chapter 4 provides the results and discussion from performing the experiments outlined in the methodology section. In addition, an example is given to support the ability of carbon monoxide monitoring and oxygen trim control to optimise the efficiency of a heating plant.

Finally, the conclusion lists the project objectives that were met and the knowledge gained from the research. A further section on recommendations and unresolved issues is included.

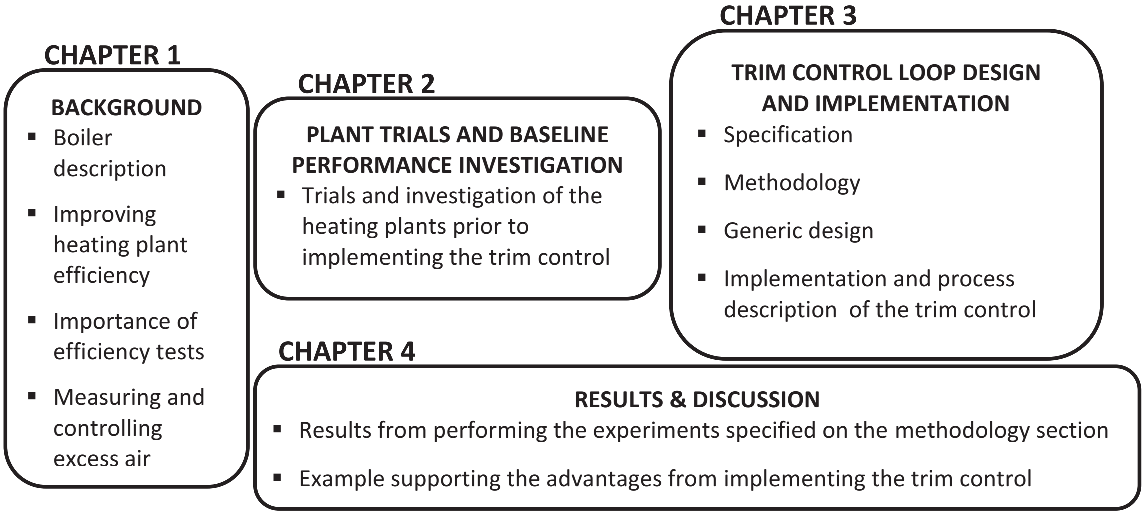


Figure 1: Thesis structure

CHAPTER 1: BACKGROUND

Chapter 1 includes the literature review and the background material required to understand the work done for this thesis. Aside from describing the increase in the efficiency of a heating plant by improving the control of excess air, it includes other techniques for measuring and optimising the performance of a heating plant. In addition it describes various types of analysers and trim control strategies for measuring and controlling excess air.

1.1 BOILER DESCRIPTION

A brief description of a boiler is provided rather than a heating plant for completeness because a boiler includes equipments such as an economiser and steam drum, which most heating plants do not. A description of a boiler will provide a better understanding of the importance of a boiler or heating plant efficiency in further sections.

A boiler is a system which heats water or other type of fluid in a closed vessel. The heated fluid exists the boiler and can be used in various heating applications (Steingress, 2001).

Different boilers use different type of fuels such as biomass, wood, coal, oil and natural gas (Babcock & Wilcox Company, 1992).

The general process function of a boiler is described and is presented in Figure 2:

- The forced draft fan (FD fan) is located within the ductwork before the boiler, taking ambient air and blowing it to the furnace for combustion. (American Society of Civil Engineers. Air and Gas Duct Structural Design Committee, 1995; Babcock & Wilcox Company, 1992).
- Air supplied by the forced draft fan (FD fan) is preheated by the flue gases. The temperature varies for different types of boilers (Ibid).
- Fuel is burned in the furnace to further heat the air (ibid).
- Hot air produced from burning the fuel, heats the flowing fluid medium which could be water or oil. The fluid medium is heated to a high temperature that is dependent on the type of boilers and production purposes (Ibid).

  The heat transfer oil, at Hyne & Son heating plant 1, is heated to approximately 250 °C. The generated heat from the heat transfer oil is converted into power (Watt), where Q is the heat flow, T_{in} is the temperature of the oil flowing through the system, T_{out} is the temperature of the oil exiting the system, Cp_F is the specific heat capacity and F is the flowrate.

  $$Q = (T_{In} - T_{Out}) \times Cp_{\,F} \times F \qquad (1.1.1)$$

  This energy is used for various industrial applications such as graining machines, wood treatment, generating electricity, etc...
- The economiser is located at the rear of the boiler and it is used to preheat the fluid in boilers, using the flue gases. It is normally used in steam boilers (Ibid).
- The steam drum is located at the top of the water tubes and acts as a reservoir. It separates the water and steam mixture. The difference in densities between hot and cold water helps provide an accumulation of water and saturated steam in the drum (Babcock & Wilcox Company, 1992; Heselton, 2004).
- The cyclone is a dust collector and is located before the induced draft fan. It helps to protect the boiler's equipment from being damaged by particulates in the flue gas (American Society of Civil Engineers. Air and Gas Duct Structural Design Committee, 1995; Babcock & Wilcox Company, 1992).
- The induced draft fan (ID fan) is located within the ductwork downstream of the boiler close to the stack. It removes flue gases from the furnace and induces it to exit out of the stack (Ibid).

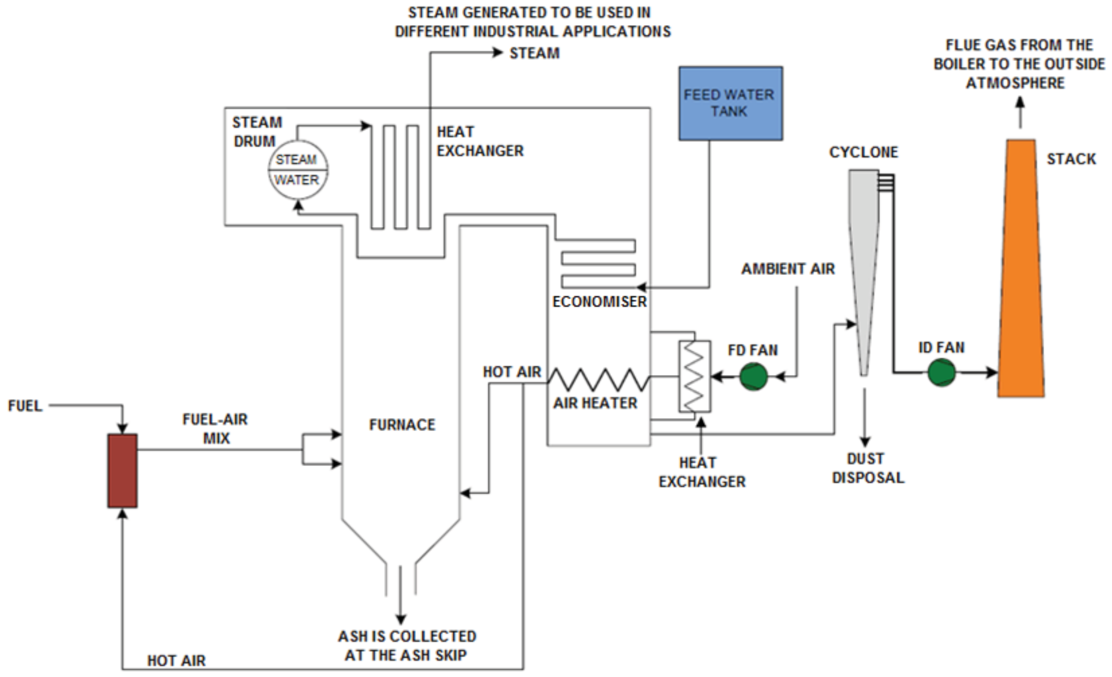


Figure 2: Steam boiler

1.2 HYNE & SON HEATING PLANT PROCESS FUNCTION DESCRIPTION

Hyne & Son in Tumbarumba, Australia hold two thermal-oil heating plants. Heating plant 1 is rated at 12.5 MW and heating plant 2 at 15MW. The heating plants produce energy for wood treatment. A heating plant is a cogeneration operation which uses heat to generate electricity and useful heat. The process function of Hyne & Son heating plants is the same and the process is shown in Figure 3:

1. Wood chip fuel is supplied from the surge bin at an ambient temperature into the vibrating grate in the furnace (A grate is a frame that holds the fuel for fire in the furnace).
2. The fuel in the furnace is burned, producing hot air and gases known as flue gases. The temperature of the air in the furnace is approximately 1060°C.
3. A grate shake occur at approximately uniform intervals to distribute the fuel evenly across the area. The grate ash conveyor continuously removes the burned ash from the grate and places it in the ash skip. It prevents the blockage of the grate and allows new fuel to take its place and to be burnt. The burnt ash collected in the skip will be mixed with the new fuel to be burned again.
4. The air cooling dampers are for cooling the furnace. They open when the heat temperature of the furnace exceeds the specified operation value.
5. The excess air is supplied by the forced draft fan. Before excess air is supplied for combustion it is heated first through the heat exchanger at an approximate temperature of 60°C.

   The heat exchanger is an air preheater. It uses the hot air from the flue gases to heat the excess air. Installing a preheater in a heating plant reduces heat and energy losses through the stack (American Society of Civil Engineers: Air and Gas Duct Structural Design Committee, 1995).

6. The excess air is further heated by the flue gas air through the air heater to an approximate temperature of 230°C.
7. The hot air heats the oil which flows through the radiant and convection coils. The area where this occurs is also known as the combustion zone. The oil flows in a closed loop. It enters at an approximate temperature of 240°C and is heated through the convection and radiant coils to an approximate temperature of 260°C.

   The heating plants are operating using two types of mineral based heat transfer oil, a mixture of 33% of Caltex Texatherm 32 and 67% Castro Perfecto HT12. Hyne & Son uses a blend of both oils to provide the heating plants with the performance required to deliver specified output power.
8. The induced draft fan sucks the emission and sucks the flue gas, which has an approximate temperature of 160°C, through the stack.
9. The hopper collects dust and fly ash from the heating system which is removed using the fly ash conveyor.
10. The fly ash conveyor removes the fly ash which is collected (in the hopper) from the heating plant by a high efficiency cyclone. The conveyor contains a pugmill which sprays water on to the fly ash to prevent it from blowing into the atmosphere.

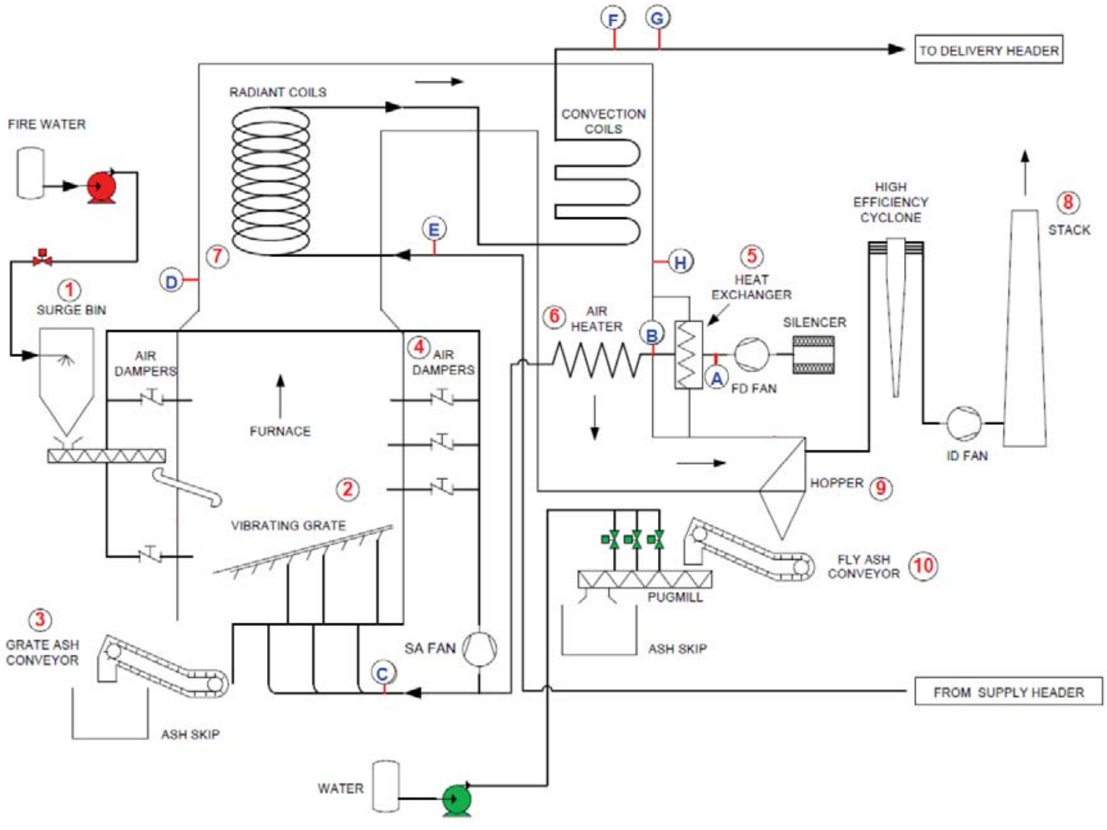


Figure 3: Hyne and Sons' heating plant diagram (1 to 10 refer to process function in Chapter 1, section 1.2, page 16. A to H refer to data log measuring points which are listed in Table 5 in Chapter 4, section 4.2.1, page 55) (after RCR Energy Systems Limited, 2002)

1.3 ENERGY EFFICIENCY

Manufacturers in industry are interested in increasing the energy efficiency of heating plants, and are continuously looking at ways of improving the combustion process and flue gas emissions. Energy efficiency is a critical heating plant specific characteristic as it directly affects the largest cost in many heating plants, that of the fuel. There are several factors that need to be considered in assessing it. Some of these are outlined below (Energy Efficiency Guide for Industry in Asia, 2006):

Stack temperature

The energy loss in the stack gases consists of waste heat and moisture losses. Most industrial boilers operate with high stack gas temperatures (204°C- 300°C), which result in large flue gas losses when not equipped with heat recovery equipment such as economisers and air preheaters (Ibid, Payne, 1996).

It is important for the stack temperature to be at a minimum level, but not so low as to allow condensation to form on the exhaust duct resulting in sulphur dew point corrosion. A stack temperature above 200 °C is considered to be too high and an indication of wasted heat. The heat can be retained by retuning and recalibrating the heating plant (Energy Efficiency Guide for Industry in Asia, 2006).

Traditionally large utility boilers were not designed with advanced combustion control. Boilers operated with high level of excess air (20% - 60%) causing high dry flue gas losses. The latent heat of water vapour covers a large portion of the total efficiency losses. Losses resulting from the latent heat of water can be minimised by allowing the water vapour to condense out before the flue gases leave the boiler (Payne, 1996).

Minimising the exit flue gas temperature and excess air level will help to optimise a boiler's overall efficiency (Ibid).

Minimum flue gas temperatures are limited by corrosion and the condensation of the sulphuric acid in the cold end areas of a boiler. It is suggested that heat recovery equipment should have a minimum average cold end temperature depending of the sulphur level in the fuel. Minimum average cold end temperatures are suggested as 65.5°C for normal gas, 79.44°C for oil fuel and 85°C for coal fuel (Ibid).

For boilers without heat recovery equipment, the minimum exit gas temperature is fixed by the boiler operating pressure which also defines the steam temperature. Usual design practices result in an outlet gas temperature above saturation temperature of approximately 65.5°C (Ibid).

Economiser

The wasted heat can be utilized by pre-heating the feed water of a heating plant thus lowering the input energy required to heat the fluid and decreases the firing rate required to achieve a specific output. This will in return increase the overall thermal efficiency of the heating plant (Energy Efficiency Guide for Industry in Asia, 2006).

Economisers are devices that are intended to reduce energy consumption and increase the overall thermal efficiency of a heating plant. Economisers heat fluids that are used as a flowing medium in a heating plant, usually water (for steam boilers). The fluid in the economiser is usually heated above 100 °C (for boilers) using exhaust flue gases (Ibid).

Some heating plants, mainly older models, produce flue gas exit temperatures of above 200°C. As mentioned before, this is an indication of wasted heat (Ibid).

Economisers may cause the flue gas temperature to drop too low resulting in condensation which can lead to corrosion and damage to the equipment. Therefore, care must be taken with the design and specifications of the heating plant (Ibid).

Combustion preheating air

The air pre-heater device is similar to an economiser. It recovers the heat losses from the flue gas and heats the air which goes into combustion. In the same way as an economiser it increases the overall thermal efficiency of a heating plant by increasing the air temperature for combustion; higher combustion air temperature lowers the energy input that is required to heat the air for combustion. This achieves the required efficiency output with lower energy input (Payne, 1996, Ibid).

Radiation and convection heat losses

The external surfaces of a heating plant are at a higher temperature than the surroundings. The heat losses will depend on the surface area of the heating plant and the difference in temperature between the surface and the surroundings. Heat losses can be minimized by covering the heating plant walls and piping with insulation (Payne, 1996; Spirax Sarco, 2010, Ibid)).

Scaling and soot

Scaling appears in water systems as calcium particulates while soot is the result of incomplete combustion. Build-up of scaling and soot acts as an insulator against heat transfer. High exit flue gas temperature might be considered as an indication of soot build-up and scaling of water. This results in poor heat transfer through the system. Flue gas temperature should be regularly monitored as an indication of soot and scaling deposits (Energy Efficiency Guide for Industry in Asia, 2006).

Operating load

It has been suggested the optimum efficiency of a heating plant is achieved at two-thirds of a heating plant operating load. However, the optimal operating load is different for different types of heating plants. It depends on the design, fuel type and operation specifications of a heating plant (Ibid). Some heating plants in industry, such as those built by RCR Energy Systems, achieve maximum efficiency at full operating load.

Incomplete combustion

Incomplete combustion may be the result of inadequate combustion air or poor mixing of fuel and air. In both cases it leads to incomplete burning of fuel resulting in high levels of combustible gases, high emissions and soot. Usually incomplete combustion is indicated by the colour or smoke intensity of the fire in the burner (Payne, 1996).

Excess air

An accurate measurement of the amount of excess air is essential to ensure complete combustion. The efficiency of a heating plant can be achieved if the losses due to incomplete combustion and flue gas heat are kept at minimum levels (Energy Efficiency Guide for Industry in Asia, 2006).

There has been economic pressure for manufacturers in the industry to produce and control heating plants with low gas emissions. Heating plants with high gas emissions are indicative of poor performance and unsafe procedures (Ibid).

Emissions generated from heating plants are directly linked to combustion factors which include furnace temperature, unburned fuel and heat loss through the stack. These factors in return depend on the amount of excess air which is required for combustion in the furnace. The correct amount of oxygen excess air for a particular heating plant and fuel is fundamental in emission reduction (Bailey, 1926).

The optimum level of excess air varies with furnace design, type of burner, fuel and process variables. Optimum operating levels of excess air for specific heating plants can be determined by conducting tests and trials (Ibid).

This project specifically focuses on improving the efficiency of a heating plant by improving the process control of excess air.

1.4 TESTING ENERGY EFFICIENCY

A regular efficiency test is very important when managing a heating plant. For heating plants that have been operating for a long period of time, it is not uncommon to find the efficiency has dropped. A small amount of 5% or 10% of efficiency drop may result in significant costs (Wulfinghoff, 1999).

Efficiency tests provide a good study of a heating plant's economic performance and whether there are any opportunities for potential improvement or adjustments of the instruments. It can also identify a heating plant's problems (Payne, 1996, Ibid).

Heating plants are very sensitive to the surrounding conditions such as weather, tubes fouling, corrosion of instruments, etc. It is therefore, essential to run several types of efficiency tests to get a full picture of a heating plants' performance. Some of these are listed below (Wulfinghoff, 1999):

Combustion test

The combustion test is the most important test of a heating plant's performance. It is possible to achieve accurate results when using good quality measurements. Combustion efficiency is tested by measuring oxygen content or carbon dioxide content in the flue gases. The oxygen test provides an accurate measure of air/fuel ratio of a specific operating load for a specific heating plant and type of fuel. This can be achieved by placing an analyser and a transmitter at the flue gas duct. Carbon dioxide tests can be done using a similar method (Ibid).

The specifications of a combustion test must meet the following conditions (Ibid):

- Completely burned fuel.
- Fuel completely burned with minimum excess air.
- Heat extracted as much as possible from the combustion gases.

The combustion tests analyse flue gases and provide an indication of whether the efficiency of a heating plant meets the combustion specifications (Ibid).

Test for incomplete combustion

Incomplete combustion, as mentioned in previous sections, is usually associated with insufficient excess air in a furnace for combustion and can result in significant cost and energy losses. Any given combustion requires a certain amount of air. Despite the importance of maintaining low levels of excess air, it must be a positive amount for successful combustion (Ibid).

To prevent incomplete combustion, good control of excess air is vital (Ibid).

Two types of tests can be performed to detect incomplete combustion; the smoke opacity test and the carbon monoxide test (Ibid).

The two types of test are listed below:

1. *Smoke opacity test*

The smoke opacity test is the measure of the smoke emerging from the stack. In the past, the smoke was measured by observing its colour. For each specific fuel at an optimum combustion, the emerging smoke would have a specific colour. For example, for a heating plant burning heavy oil the colour of the smoke should be a light brown haze. Under conditions in which incomplete combustion occurs, the colour of the smoke would differ from its usual colour. However, this method is no longer popular and has been replaced by density measures of the smoke which vary depending on the type of fuel density. Nevertheless, this method is suitable for heavy grades of oil and solid fuels, but is not reliable for gaseous and light oil fuels, as the residue of these fuels is only visible when air is very deficient (Payne, 1996, Ibid).

2. *Carbon monoxide test*

Carbon monoxide is a direct measure of incomplete combustion for all types of fuels, as long as it contains carbon. High levels of carbon monoxide indicates incomplete burning of the fuel, thus making it an excellent indicator of incomplete combustion (Wulfinghoff, 1999).

High levels of carbon monoxide in a heating plant operating with the correct level of excess air for a specific operating load, but nevertheless displaying incomplete burning of the fuel, suggests a defect within a boiler. For example, a carbon monoxide test could indicate a fouled burner or a poor match of a burner assembly and the firebox causing a portion of the flame to hit a surrounding surface. When the flame temperature decreases it results in incomplete combustion, leaving carbon monoxide and other intermediate products in the flue gas (Ibid).

Specific environmental pollutants test

According to environmental regulations, flue gases must be tested for specific pollutants such as nitrogen oxides (NO_x), sulphur oxides (SO_x), hydrogen sulphide (H_2S) and chlorine (Cl). These emission gases must be maintained within specific limits. However, controlling these emissions requires procedures which might affect the unit efficiency such as recirculation of flue gases, increasing air flow or adjusting the burner flame. It is therefore important to find methods that would cause the minimum drop in the heating plant's efficiency (Ibid).

Habib et al (2007) performed a study which numerically investigated the formation of NOx in a mathematical model of a 160MW industrial boiler. They found that, at constant fuel flowrate, NOx emissions increased with increases in excess air. Conversely, when holding the air flowrate constant, increasing excess air (i.e. reducing the fuel flowrate and therefore the load) decreased the amount of NOx emitted.

From this we can say that being able to reduce the excess air, by including CO trim control, will also reduce the amount of NOx emitted at a given fuel flowrate (load) (Ibid).

1.5 ENVIRONMENT OFFENCES AND PENALTIES

Heating plants and boilers in Australia, such as Hyne & Sons, are required by government laws and regulations to operate under air emission standards.

In Australia, the Department of the Environment, Water, Heritage and the Arts produced Emission Estimation Technique (EET) manuals to assist Australian manufacturing, industrial and service facilities to operate according to the emission standards listed in the National Pollutant Inventory (NPI)

(Australian Governement: Department of the Environment, Water, & Heritage and the Arts, 2010).

The EET manual includes emission factors for various fuels, process and control configurations for certain NPI listed substances (Ibid).

The emission factor is defined as the weight of a substance released per activity and it is calculated by multiplying the substance specific emission by the activity (Ibid).

There is uncertainty related to the emission factors due to the degree of difference between the equipment or process from which the factor was derived and the equipment/process to which the factor is being applied. The uncertainties are rated alphabetically to indicate the degree of accuracy (Ibid),

A – Excellent

B – Above Average

C – Average

D – Below Average

E – Poor

U – Unrated

The EET manual includes emission factors for various fuels, process and control configurations for certain NPI listed substances. Table 1 presents the emission required to operate combustion boilers in Australia (Ibid).

If the heating plants in New South Wales, such as the Hyne & Sons' heating plants in Tumbarumba breach the emission standards, penalties and fines listed under the Environmental Offences and Penalties Act 1989 and Protection of the Environment Operations Act 1997, sections 124 -126, 132 are enforced. Protection of the Environment Operations Act 1997 – section 132 states "Maximum penalty for air pollution offences: A person who is guilty of an offence under this Division is liable, on conviction:

(a) in the case of a corporation-to a penalty not exceeding $1,000,000 and, in

Table 1: Emission factors for wood/bark fired boilers (after Ibid).

Emission Substance	**Emission Factor (kg/t)**	**Emission Factor in ppm/t and %**	**Emission Factor Rating (EFR)**
Carbon monoxide	4.08	4,223.60 ppm/t 0.42 %/t	D
Oxides of nitrogen	1.49	NO 1439.13ppm/t 0.14%/t NO_2 938.67ppm/t 0.093%/t	D
Particles matter ≤10.0 µm		-	
Uncontrolled	3.24		D
Multicyclones with fly ash reinjection	2.73		D
Multicyclones without fly ash reinjection	0.86		D
Wet scrubber	0.22		D
Particles matter ≤2.5 µm		-	
Uncontrolled	2.74		D
Multicyclones with fly ash reinjection	1.62		D
Multicyclones without fly ash reinjection	0.43		D
Wet scrubber	0.22		D
Sulfur dioxide	0.17	76.89 ppm/t 0.008 %/t	A

the case of a continuing offence, to a further penalty not exceeding $120,000 for each day the offence continues, or

(b) in the case of an individual-to a penalty not exceeding $250,000 and, in the case of a continuing offence, to a further penalty not exceeding $60,000 for each day the offence continues" (New South Wales Government, 1997).

1.6 AIR REQUIRED FOR COMBUSTION

This section describes the importance of availability of air in completing combustion. In addition, different techniques are described for measuring and controlling excess air for maximum heating plant efficiency.

1.6.1 Stoichiometric air for combustion

No heating plant is capable of burning fuel and complete combustion without sufficient air to do the job. The calculated air level, using combustion chemistry formulas, required for combustion is known as stoichiometric air or theoretical air (Dukelow, 1991).

If the fuel analysis is known, the theoretical amount of oxygen can be calculated based on the chemical reactions between the elements and oxygen. The amount of oxygen can be converted to the corresponding amount of theoretical air required for combustion. Ideally, the calculated stoichiometric air should be sufficient for complete combustion, producing carbon dioxide and water vapour. However, in practice, if only stoichiometric air was supplied for combustion, some of the fuel would not burn due to a short reaction time or insufficient time to mix well with the oxygen before the combustion gases cool down. Incomplete combustion results in a high level of carbon monoxide (Ibid, Payne, 1996).

Incomplete burning of the fuel can be resolved with additional amounts of combustion air known as excess air (Ibid; Siemens Energy & Automation, 2005).

1.6.2 Excess air for combustion

To ensure complete combustion additional air is required. This is known as excess air and it is measured as a percentage (%) of the total flow. The total air required for combustion:

$$Total\ air\ for\ complete\ combustion = Theoretical\ air\ (Stoichiometric\ air) + Excess\ air \tag{1.6.1}$$

It is essential for the amount of excess air to be accurate for the specific operating load of a heating plant using a particular type of fuel. Insufficient excess air will result in incomplete combustion, efficiency loss and wasted fuel. High excess air will result in a drop in efficiency, as the flame temperature will decrease and reduce the heating plant's heat transfer rate (Dukelow, 1991).

Incomplete burning of fuel produces high levels of carbon monoxide as shown in the chemical reaction, equation 1.6.2 (Dukelow, 1991; Tapline, 1991).

$$Carbon\ + Oxygen \longrightarrow Carbon\ Monoxide \tag{1.6.2}$$

$$2C + O_2 \longrightarrow 2CO$$

Adding the correct amount of excess air for combustion results in complete burning of the fuel and thus most of the carbon monoxide being converted to carbon dioxide, as in equation 1.6.3 (Ibid).

$$Carbon\ Monoxide\ +\ Oxygen \longrightarrow Carbon\ Dioxide + Heat \tag{1.6.3}$$

$$2CO\ + O_2 \longrightarrow 2CO_2 + Heat$$

If the percentage of oxygen is known or can be measured in the flue gas, the percentage excess air can be calculated using the following equation,

$$Excess\ air = K_2 \times \left(\frac{21}{21 - O_2\%} - 1\right) \times 100 \qquad (1.6.4)$$

K_2 is the weight basis percentage of the fuel. O_2 is the percentage of the oxygen in the flue gas.
Equation 1.6.4 is useful for calculating excess air when tables or curves are not available. The excess air is calculated based on wet basis percentage oxygen (Dukelow, 1991).

1.6.3 Excess air and combustible gas relationship at various operating loads

Figure 4 describes the relationship of excess air and the combustible gases at various operating loads. Running a heating plant at a higher operating load is more efficient than that of a lower operating load. At a high operating load, better mixing of the air and fuel and therefore smaller amount of excess air are required to complete combustion (Dukelow, 1991).

The levels of excess air and carbon monoxide vary as the operating load changes. The optimum operating excess air setpoint at different operating loads, is at the intersection between the combustible gas curves and the "fuel loss from air" curves (Ibid).

The arrows in Figure 4 indicate the direction in which carbon monoxide increases and the corresponding increase in fuel losses. A high level of carbon monoxide indicates partial combustion due to incomplete burning of the fuel. This is due to there being insufficient air to burn the rest of the carbon monoxide and convert it to carbon dioxide (Ibid).

Flue gas temperature is high at higher operating loads with a gain of 0.1% in oxygen. Therefore, the optimum carbon monoxide level is greater at higher operating loads than that of lower loads (Ibid).

The shape of the combustible gas curves stays the same at all operating loads. However, for some boilers, the shape of the curves change and shift to the right as the operating load is reduced (Ibid).

Note that the curves and levels of oxygen and carbon monoxide vary with different types of boilers (Ibid).

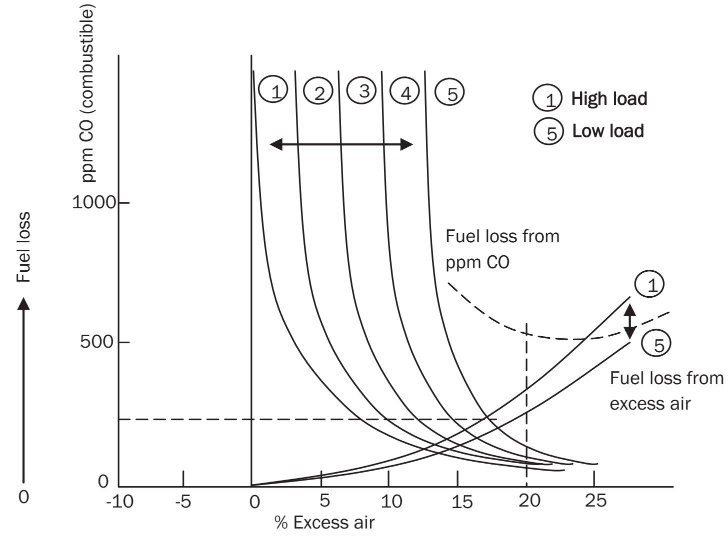


Figure 4 Relationship between excess air and combustible gas (after Dukelow, 1991)

1.6.4 Increasing heating plant efficiency by operating at a minimum excess air

Maintaining a minimum excess air for combustion is an effective technique which can be performed without high costs. The performance of a heating plant is sensitive to the level of excess air used for combustion (Tapline, 1991).

Maintaining minimum excess air results in (Ibid):

- Lower heat and energy losses through the stack.
- A decrease in flue gas velocity resulting in more time available for heat transfer in the heating plant.
- The flame temperature in the furnace increasing which raises the radiant heat transfer in the combustion zone. The radiant heat transfer becomes more efficient and reduces the heat losses through the stack.
- Reduction in pollution as less fuel is required to produce the desired output energy.
- Savings in fuel costs. Less fuel is needed to produce the required energy output.
- Reduction in the cost of the input energy required to produce the desired output energy therefore, increasing productivity.

It is therefore very important to maintain optimum excess air levels for combustion.

1.6.5 Non-optimum excess air level

Many boilers are operating at a non-optimum excess air level for reasons may not be apparent initially. The reasons that may include (Payne, 1996):

- Air in-leakage upstream of the plant oxygen analyser,
- Incorrect calibration of the oxygen analyser,
- Insufficient combustion air supplied at a full operating load,
- A non-optimum placement of the oxygen analyser in the flue gas duct.

Industrial boilers are designed to balance the draft. The operation of the forced draft fan and induced draft fan are designed to create a slight negative pressure in the furnace. The negative pressure prevents hazards due to hot flue gas leaking into the boiler house if any leaks in the boiler or duct work (to the induced draft fan) due to air leakage to the flue gas steam. However, the air infiltration through the oxygen analyser may cause it to record higher values than the actual readings. Air leakage may cause significant combustible losses in the form of carbon monoxide or high ash carbon content (Ibid).

A non-optimum excess air could also be due to accumulation of dust and fly ash on the oxygen sensor cavity or corroded sample lines. An oxygen analyser may be in error by several percent below the normal readings because the sensor has become plugged with fly ash. This would be apparent to an operator that a boiler is operating at a lower excess air than that required. This can result in high levels of carbon monoxide or ash carbon (Ibid).

1.7 MEASURING EXCESS AIR

There are a range of analysers available in the industry which can be used to analyse and detect oxygen in the furnace. An in-situ analyser is the most commonly used for excess air trim control (Lindsley, 2000).

The in-situ method is used to measure emissions. It continuously takes a sample of gas from the flue gas stream and analyses it. This analysis provides average figures of gas composition (e.g. process combustion efficiency, inlet/outlet temperature, oxygen and carbon monoxide levels) across the diameter of the gas stream. It has a fast response time since there are no sampling system delays (Ibid; Siemens Energy & Automation, 2005).

1.7.1 Selecting a suitable analyser

As the aim of this thesis is to control the excess air based upon measurements of both oxygen (excess air) and carbon monoxide, a suitable analyser must be chosen.

Prior to this work, research by RCR Energy Systems it was concluded that two industrial analysers might be feasible for installation in the heating plants at Hyne & Son; the ABB SMA 90 Stack from ABB and the OCX 88A from Emerson.

The final selection of one of these two units was decided by the author based on a number of factors; price, number of output signals, lag time and delivery period.

Table 2 displays the comparison between the ABB and Emerson unit analysers.

Despite Emerson being cheaper and providing a higher accuracy than the ABB analyser, the number of signal outputs is very limited and the lag time very long for the performance of the heating plants at Hyne & Son.

The ABB analyser, besides having the output signals of oxygen and carbon monoxide, also includes process combustion efficiency (based upon the flue gas combustion efficiency) as an output signal. In addition, the analyser includes four relay alarms for each analogue output and a single alarm for fault and calibration. ABB has a short lag time of less than one minute. There is a short delay between a change in airflow and the corresponding response change in the flue gas. It also has a faster sampling response time than that of the Emerson analyser. An analyser that produces a short lag time, results in a better control response, tighter control of excess air, and therefore higher plant efficiency. From these descriptions it is clear that the ABB analyser was more suited to the heating plants' performance.

Table 2: Comparison between ABB and Emerson analysers (ABB Ltd, 2010b; Emerson Process Management, 2005)

	ABB (ABB SMA 90 Stack)	**Emerson (OCX 88A)**
Price	NZ$33,565.00	NZ$18,307.00
Signals	**4 analogue outputs:** AO1: Process O_2 AO2: Process CO_e AO3: Inlet/Outlet temperature AO4: Process combustion efficiency	**2 analogue outputs:** AO1: O_2 AO2: CO_e
	6 relay alarm outputs: DO1: Process O_2 DO2: Process CO_e DO3: Process temperature alarm DO4: Combustion efficiency alarm DO5: Analyser fault alarm DO6: Calibration in progress	**2 relay alarm outputs:** DO1: O_2 DO2: CO_e
Sampling response time	O_2 <3.5s CO<13s	O_2 = 10s CO = 25s
Lag time	< 1 minute	Approx. 5 minutes
Delivery period	6 weeks	10 weeks
Accuracy	O_2 ± 2.5% of range CO ± 20 ppm	O_2 ± 0.75% of range CO ± 20 ppm

1.7.2 ABB SMA90 stack gas monitoring system

Two ABB SMA90 analysers were used for this project. The analyser units were installed at Hyne & Son heating plants 1 and 2.

Figure 5 shows the analyser unit assembly. The electronic assembly is located in the MCC room (Motor Control Centre room) and the sensor assembly is installed at the actual heating plants close to the stack (see Appendix 4 for the analyser units installed in heating plant 2 photos, figures 33, 34 and 35).

Samples are continuously drawn in via a filter probe placed in the flue gas stream. The sample is then analysed by the sensor assembly. Electrical outputs from the sensor are fed through the interconnecting flexible cable to the electronics assembly for interpretation (ABB Ltd, 2010a).

The analyser has four analogue outputs; process oxygen, process carbon monoxide, inlet/outlet temperatures and the combustion efficiency (see Appendix 3 for the features). The output values are sent to the PLC (Programmable Logic Controller) and controlled by the trim control loop. The values from the analysis are displayed on the unit's display screen and on the HMI screen (Human Machine Interface) (Ibid).

The analyser units contain an automatic sensor calibration feature which uses zero and span gases of known concentrations to calibrate both sensors and ensure continual accuracy (Ibid).

The span Gas contains a specific amount of impurities and is used to check the linearity of a system (Martyr & Plint, 2007). The span test gas is required to be a balance of oxygen/carbon monoxide/nitrogen. The oxygen/carbon monoxide concentrations are required to be 80-100% of the used range. It is required for the test gas to be approved for both oxygen and carbon monoxide content (Ibid).

Zero gas is a purified gas that is clear of any materials that might affect the instrument. This gas is used for both instrument calibration and component testing (Emerson Process Management, 2005). The zero gas is required to be at one percent oxygen/nitrogen balance. The test gas has to be approved for oxygen content (ABB Ltd, 2010a).

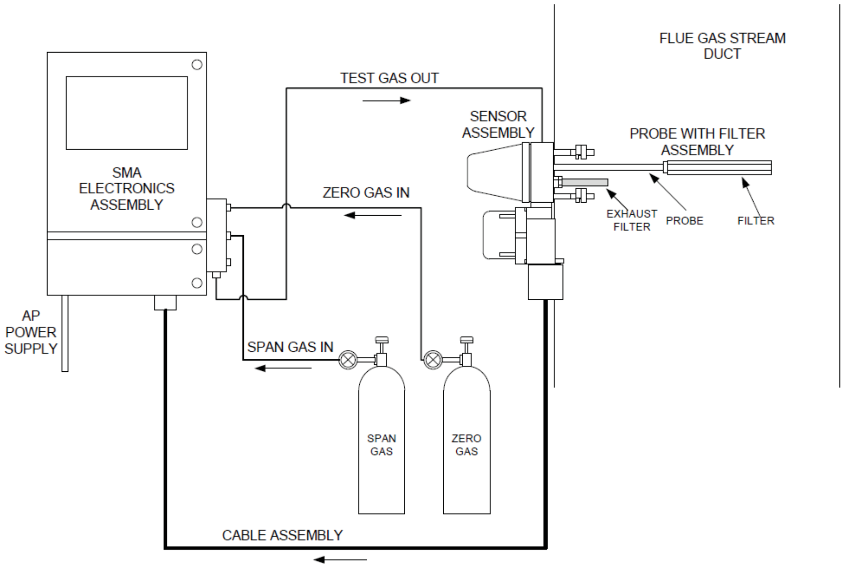


Figure 5: ABB analyser unit (after ABB Ltd, 2010a)

1.7.3 Optimum location for trim control sensor in the plant

Usually analysers are placed in the convection zone since it is easier to access. However, the ideal location for measuring combustible gases and oxygen is directly in the furnace (see Figure 6) for a number of reasons. These are listed below (Wildy, 2000):

- Oxygen reading measurements are more precise in the furnace than the convection section. This is because air leakages occur in the convection section (Ibid).
- Combustible gas measurement is different in the convection zone compared to the furnace. This is because the combustible gases burn further in the hot tubes of the convection section (Ibid).
- Oxygen reading in the burner is required for combustion efficiency and safety purposes. Oxygen reading in the convection section cannot be linked to what is happening in the furnace (Ibid).

Using oxygen analysers in the furnace is insufficient to indicate burner and process problems. Using a zirconia probe (used at the in-situ or ex-situ methods) will also provide an indication of the level of the excess air in the furnace (Ibid).

1.8 CONTROL STRATEGY FOR TRIMMING EXCESS AIR FOR COMBUSTION

It is common to determine heating plants' and boilers' excess air for combustion for a specific furnace using specific fuel type using a look-up table which is based on the heating plant firing rate or operating load. At present however, excess air in the furnace can be controlled and trimmed using a trim control.

The author reviewed the literature review on two of the possible trim controls that can be implemented in a heating plant: 1) an oxygen trim control and 2) carbon monoxide monitoring and oxygen trim control. In addition, the limitations of only using oxygen trim control and the benefits of using another parameter such as carbon monoxide were also investigated.

1.8.1 Oxygen trim control

Oxygen trim is used to automatically control the excess air to optimize the air/fuel ratio in order to maximise combustion efficiency. A sample from the flue gas in the furnace or the outlet of the heating plant is analysed for oxygen level in an analyser. The analyser sends the corresponding signal to a controller to modify the air/fuel ratio in the furnace to

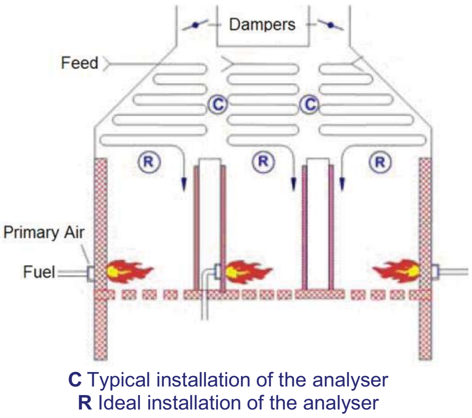


Figure 6: Location of trim control sensor in the plant (modified from Wildy, 2000)

maintain the oxygen percentage to a specified setpoint. The setpoint of the excess oxygen varies with the load (Heselton, 2004).

Oxygen trim control operates within upper and lower limits and they include alarms to protect against malfunction within the heating plant. Most of them do not have a precise setpoint as the setpoint changes with the load variations. The setpoint can be generated by a function which is characterized from the steam flow, heat demand, excess air, fuel analysis, flue gas temperature and heating plant testing (Ibid).

From the literature, several oxygen trim control schemes were found with very similar operating strategies and produced by different manufacturers and researchers (Ibid).

The application of oxygen trim control

Figure 7 is an example of an oxygen trim control scheme presented in Dukelow's book (1991) and also in Siemens Energy Automation manual (2005).

An oxygen transmitter installed on the furnace is continuously measuring the oxygen percentage. The oxygen setpoint is controlled based on the firing rate (operating load). The oxygen PI controller (Proportional-Integral controller) will manipulate the forced draft fan which supplies the excess oxygen in the furnace (Ibid).

The oxygen trim controller is tuned for a low gain and slow integral response to obtain control stability. The low gain is the result of the relationship between the airflow change and percentage oxygen change while the slow integral is a result of the accumulated time constants in the control loop (Ibid).

Dukelow (1991) has stated that the slow integral tuning requirement is due to the accumulated time constant within the control loop. The time constant is a sum of the time constants from controller, controlled devices, transport time from the control dampers and valves through to the combustion process to the analyser and the delays in the analyser itself.

An operator can manipulate the setpoint signal using a manual adjustable bias. This also provides compensation for controlling carbon monoxide emissions (Ibid; Siemens Energy & Automation, 2005).

A limit output for the trim control is used to protect against analyser failure. The limits can be implemented as the limiter to the controller output (Ibid).

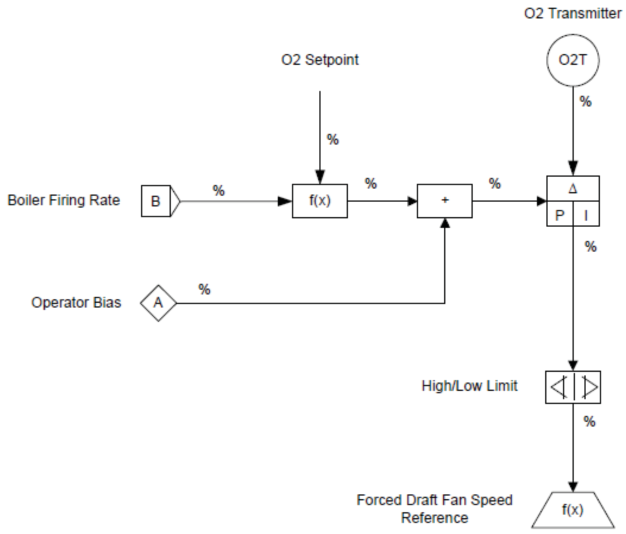


Figure 7: Oxygen trim control loop (after Dukelow, 1991; Siemens Energy & Automation, 2005)

Limitation of oxygen trim control

When other disturbances are introduced to the heating plant, the oxygen trim control is not as efficient in determining the excess air for combustion.

The excess air level depends on the type of heating plant, fuel type, burner type, humidity changes in the air, moisture content changes in the fuel, operating loads, fouling of the burner system and mechanical wear of combustion equipment. These factors continuously change as the load changes thus causing the amount of the oxygen to change as well. For these reasons it is strongly recommended to monitor other parameters such as flue gas composition, unburned hydrocarbons, opacity or carbon monoxide (Yokogawa, 2008).

1.8.2 Carbon monoxide monitoring and oxygen trim control

The solution to some problems with oxygen trim control is to control excess air based on another parameter such as carbon monoxide. Carbon monoxide is a direct indicator for incomplete combustion. For these reasons, including a control measure of carbon monoxide is an efficient method for determining the correct oxygen setpoint for combustion (Yokogawa, 2008).

As the carbon monoxide level increases beyond the specified range it manipulates the oxygen controller to allow more oxygen. This result in an increase in the air/fuel ratio which increases turbulence for a better air fuel mixing process and allowing the rest of the carbon monoxide to be oxidised producing carbon dioxide. This is a secondary effect since it requires a lot more air to change the mixing much, say 10-20%. The most important is that there is more oxygen present where the combustion is taking place. An increase in air/fuel ratio should be adequate to complete combustion and reduce carbon monoxide concentration in the flue gas. A air/fuel ratio higher than that required to complete combustion can reduce the flame temperature with a consequent drop in heat transfer rate and loss in efficiency (Siemens Energy & Automation, 2005).

Different approaches of carbon monoxide monitoring and oxygen trim control loop

From the literature review on carbon monoxide monitoring and oxygen trim control, there were only four possible, simple control arrangements (leaving out more complex methods like Smith predictors or model predictive control). These are; feed-forward trim control, cascade-loop trim control, a single controller arrangement and Rosemount Analytical trim control.

The control loops are listed below:

1. *Feed-forward trim control*

Figure 8 shows the feed forward trim control configuration introduced by Colannino (2006).

The controller tries to maintain the optimum air/fuel ratio based on the oxygen setpoint. When the air density or fuel composition varies, the controller tries to retain optimum oxygen level and therefore furnace efficiency (Ibid).

The controller continuously compares the carbon monoxide setpoint with that from the furnace. When the carbon monoxide is at a very low level it will manipulate the oxygen setpoint to decrease and vice-versa. The relationship between carbon monoxide and oxygen can be built in directly into the logic or it can be derived from collecting data at different temperatures (Ibid).

The system can be controlled using a distributed control system (DCS) or a programmable logic controller (PLC) (Ibid).

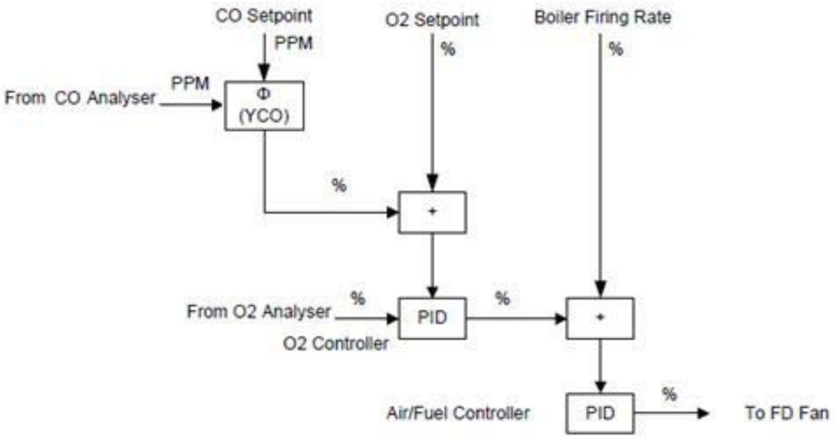


Figure 8: Colannino's "feed-forward" trim control (after Colannino, 2006)

1. Cascade loop trim control

Figure 9 is a cascade control arrangement. This method uses carbon monoxide to manipulate the oxygen setpoint. When the carbon monoxide percentage varies during the operating process, it will bias the oxygen controller. The oxygen controller will then manipulate the forced draft fan speed which supplies air in the furnace for combustion. Both oxygen and carbon monoxide have separate controllers (Dukelow, 1991).

The function generators are responsible for setting carbon monoxide and oxygen setpoints based on the operating load of the heating plant (Ibid).

The setpoints can be modified using the operator adjustable bias. For safety practices, a limiter is essential to prevent a controller action from causing unsafe heating plant operation (Ibid).

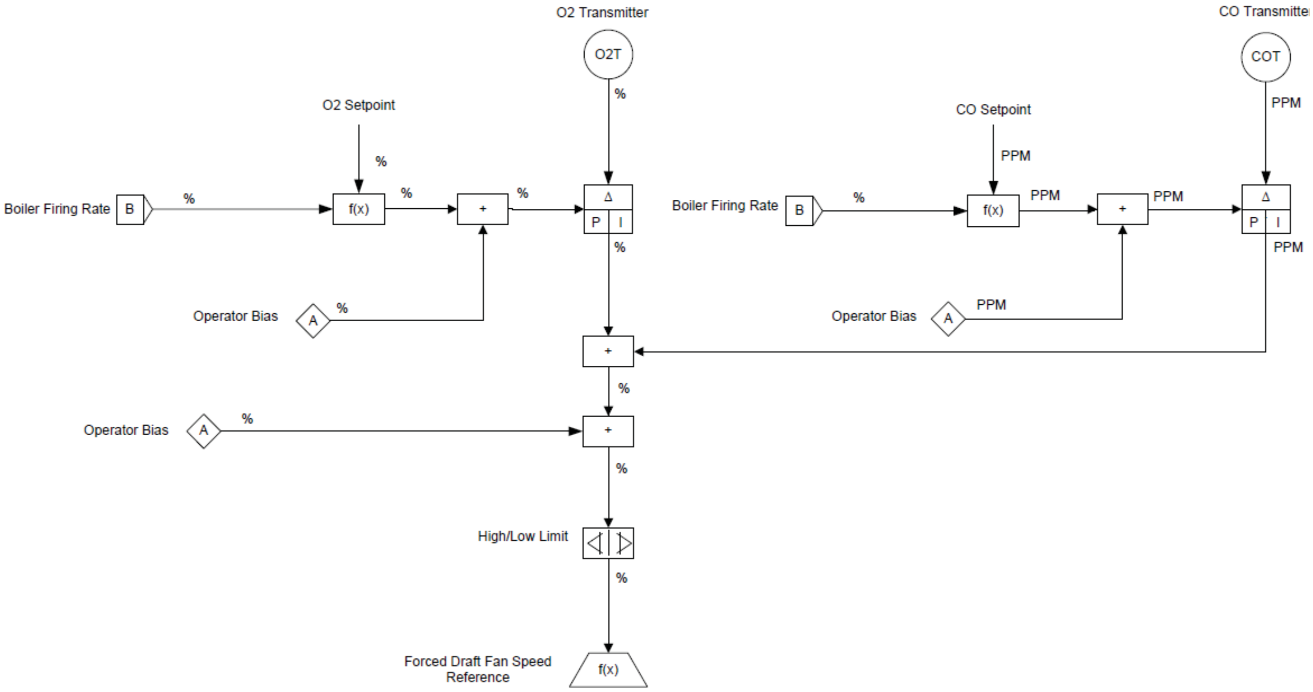


Figure 9: Carbon monoxide monitoring and oxygen trim control using cascade control arrangement (after Dukelow, 1991)

3. *Single controller*

Figure 10 shows the single controller arrangement for both oxygen and carbon monoxide. If any changes occur to the levels of oxygen or carbon monoxide, it will cause a change in the other variable (Dukelow, 1991).

The oxygen and carbon monoxide setpoints are generated by a function generator. The oxygen setpoint is based on a relationship function between the firing rate versus oxygen level. The relationship function is a low limit of oxygen level which is determined based on the data collected during testing a heating plant's performance. An error calculation is done between the specified oxygen setpoint and the one measured from the furnace. The error signal is then entered into the function block and the upper limit of the oxygen band width is calculated (Ibid).

Carbon monoxide is measured in the furnace by a transmitter. The error between the carbon monoxide signal measured from the furnace and the setpoint from the function generator is calculated. Then the carbon monoxide signal is inverted and matched to the percentage oxygen signal in the negative proportional logic. Since the carbon monoxide signal is not linear, it is linearised (Ibid).

The operator is able to manipulate the carbon monoxide setpoint via the adjustable bias. The oxygen and carbon monoxide signals will then enter the high and low selectors and the desired error signal will be selected. This then enters the controller logic to produce a trimming control signal (Ibid).

The control logic has a high and low limiter as a safety precaution in case the flue gas analyser system fails to operate (Ibid).

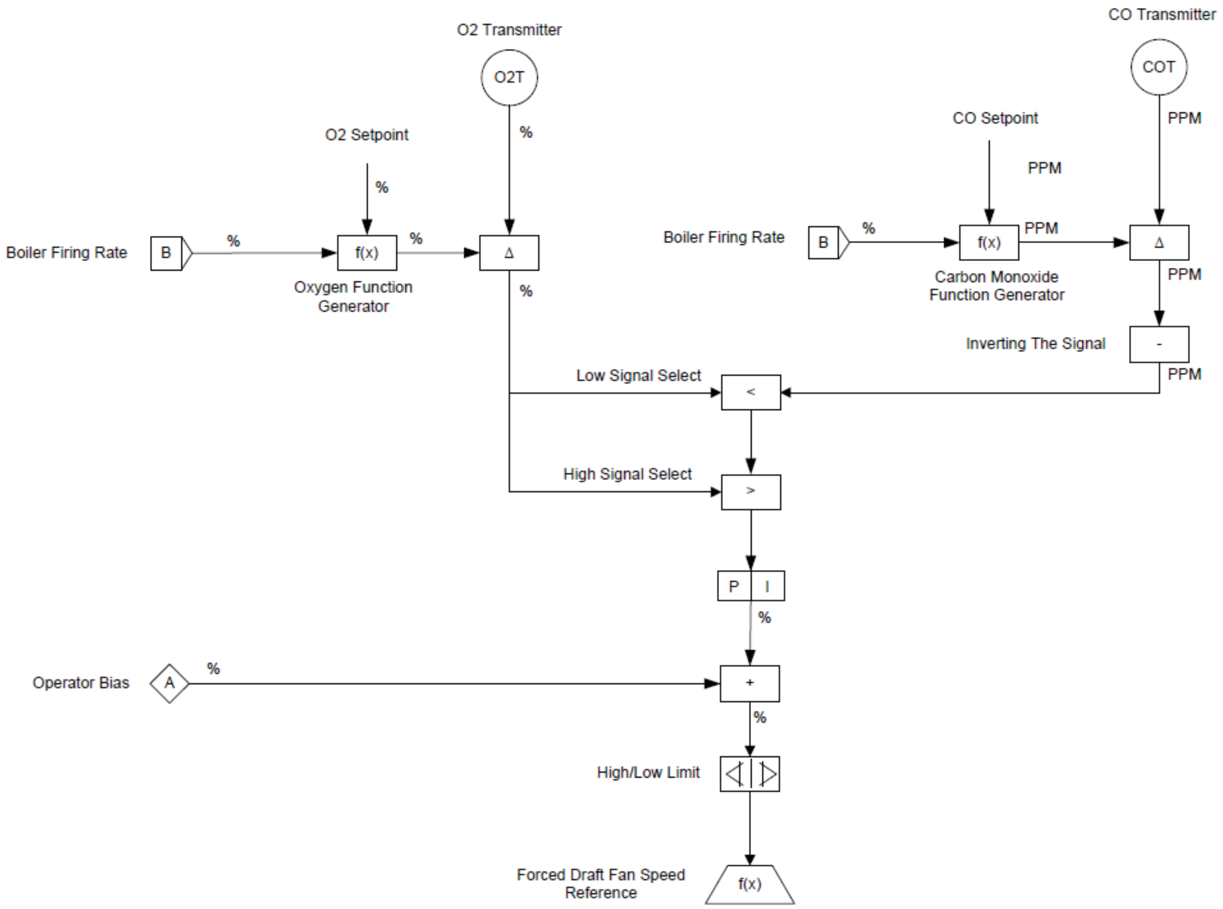


Figure 10: Carbon monoxide monitoring and oxygen trim control using single controller (after Dukelow, 1991)

2. *Rosemount Analytical trim control*

Figure 11 is the model introduced by Rosemount Analytical Inc. Carbon monoxide acts as a primary controller when the excess air is within the upper and lower bound. The trim control will switch to oxygen if the required excess air has reached the limit due to rapid load change (Rosemount Analytical, 1995).

The controller has a faster response when excess air has reached the limit compared to variations in carbon monoxide (Ibid).

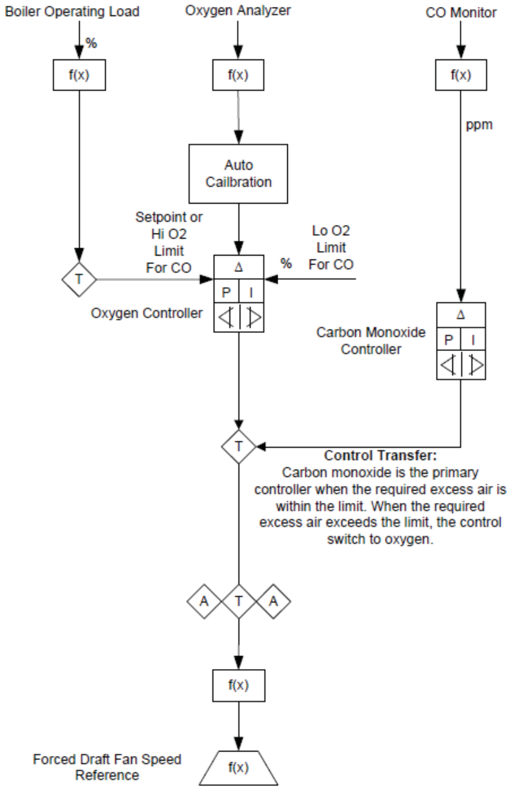
The controller will continually tune the air/fuel ratio to the optimum level for better combustion. However, there are other factors such as a dirty burner which may result in an increase in the carbon monoxide level. In this case the carbon monoxide controller will demand more air and the oxygen control will take over as the oxygen limit is reached. When transfer occurs between controllers, the system alerts the operator to take correct action (Ibid).

Rosemount Analytical suggests that the carbon monoxide monitoring and oxygen control can be configured to suit other combustion processes (Ibid).

Limitations of carbon monoxide monitoring and oxygen trim control

Although carbon monoxide monitoring and oxygen trim control have solved the issues of oxygen trim control, it does have limitations:

- It is often impossible to use carbon monoxide monitoring and oxygen trim control in refinery heating plants. As conditions change in the plant it causes the fuel hydrogen content to undergo significant changes. This may result in dramatic changes to the theoretical air requirement. When changes to theoretical air requirement occurs, the oxygen percentage will fluctuate between 0% and 3% for a given heat and airflow. Having zero



Control Transfer:
Carbon monoxide is the primary controller when the required excess air is within the limit. When the required excess air exceeds the limit, the control switch to oxygen.

Figure 11: Rosemount Analytical trim control (after Rosemount Analytical, 1995)

oxygen percentage for combustion will result in high levels of carbon monoxide. Further additional minor adjustment of the oxygen setpoint would be ineffective. Therefore, carbon monoxide monitoring and oxygen trim control are not usually suitable for refinery heating plants, instead airflow ratios or an air register adjustment of the burners are more appropriate (Colannino, 2006).

- Refinery heaters cannot control both oxygen level and draft using manual carbon monoxide monitoring and oxygen trim control, as the furnace would require lots of adjustments to retain a precise oxygen level. It would be more efficient using an automated stack damper control and an automated air register adjustment of the burners. Manual carbon monoxide trim control adjustments are not suited for furnaces which require various adjustments to retain accurate oxygen level on a continual basis (Ibid).

1.9 LIMITING FACTORS IN REDUCING EXCESS AIR IN HEATING PLANT FURNACES

A study by Bailey (1926), involving 4000 boilers and more than 75,000 flue gas analyses, showed the importance of the furnace temperature, unburned fuel and heat loss in the chimney gases with relation to percentage excess air.

It was important to include in the background section (Chapter1) the boiler study that was done by Bailey (1926). He presented a detailed study of a wide range of boilers. Nowhere else in the studied literature is there a comparable source of such fundamental data, hence the reliance on this source in the following sections despite its age. While the efficiencies of boilers will have increased since this article was written, the comparisons between boiler types, and the shapes of the various curves, so still hold true today.

The following sections describe the limiting factors in reducing excess air in the furnace for combustion.

1.9.1 Excess air required for different types of furnaces

Bailey (1926) has presented a summary of 3,767 combustion tests representing average excess air at the best operating conditions for different types of furnaces over 10 years (see Figure 12). (Note that there was no indication of the scatter of the data or goodness of fit in the original.)

The top plot in Figure 12 shows the percentage of excess air required for different types of furnaces. Wood refuse has the maximum excess air percentage of around 61%; while gas fired boilers have the lowest average excess air percentage of approximately 19%. Under feed stocker is 45%, Pulverised coal at 28% (Ibid).

The lower plot in Figure 12 shows the rate of heat absorption by the boiler and super heater per cubic foot of furnace volume. The wood refuse has the minimum heat absorption rate of approximate 14 Btu/hr/Ft^3, while the hand fired boiler has the maximum of 40 Btu/hr/Ft^3 (Ibid).

1.9.2 Limiting factors for further reduction of excess air

Figure 13 shows the same data as that shown in Figure 12 but with additional limiting factors which prevent further reduction of excess air (Bailey, 1926).

As can be noted from Figure 13:

- Carbon monoxide is the dominant limiting factor for most types of coal burned in fuel beds and gas fired boilers.
- Smoke determines the minimum excess air for oil fired boilers.

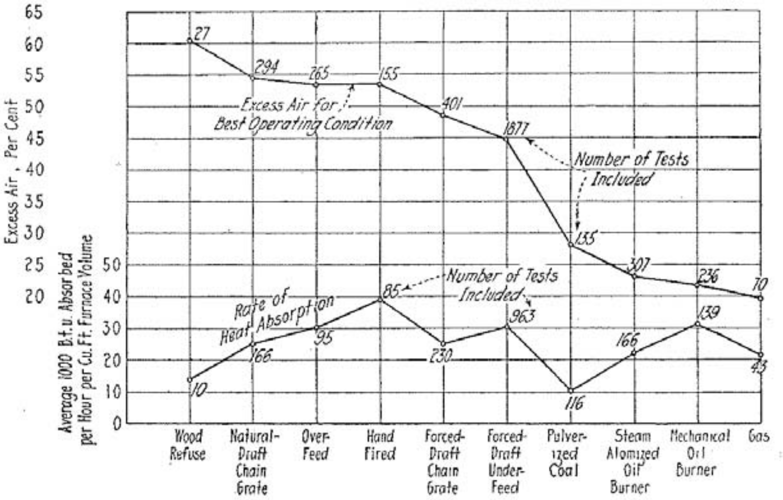


Figure 12: Average excess air at best operating conditions for different types of furnaces (Bailey, 1926)

- Ashpit loss is considered as an important factor in mechanical and more modern types of stokers.
- Refractories are significant in modern types of stokers where high excess air exists.
- Refractories are the dominant factor for further reduction of excess air in pulverised coal fired boilers (Ibid).

1.9.3 Relationship between excess air and carbon monoxide loss

Figure 14 shows the relationship of excess air versus carbon monoxide loss.

The upper curves show the percent by volume of flue gas analysis versus total air required for combustion. Curve **A** represents theoretical conditions with perfect mixture and reduction in excess air. Further reduction of excess air will result in unburned fuel and the formation

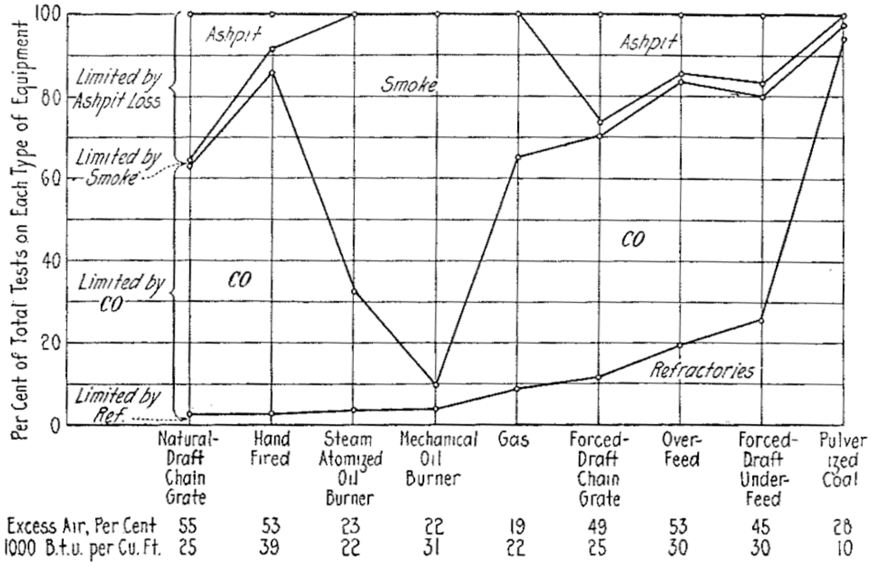


Figure 13: Relative frequency of occurrence of the various limiting factors at normal ratings on different types of fuels-burning equipment (Bailey, 1926)

of carbon monoxide and hydrocarbons as well as increases in the rate of heat loss of approximately 14 times for each percentage drop in excess air. Curves **B**, **C** and **D** show the rate at which carbon monoxide starts to increase with a drop in excess air (Ibid).

The lower set of curves show heat losses versus excess air. A perfect mixing of air and fuel cannot be obtained. This is shown in curves **B**, **C** and **D** which are for different types of furnaces. Each of these curves shows a point where carbon monoxide starts to appear. The efficient combustion excess air level for furnace **B** is at approximate 12%, furnace **C** at 30% and furnace **D** at 70% (Ibid).

Carbon losses need to be monitored on all types of stokers and pulverised coal to prevent them from reaching an undesired level without showing any sign of smoke. Any form of smoke resulting from pulverised coal is a sign of greater loss than that resulting from any other type of fuel combustion (Ibid).

1.9.4 The relationship between combustion theoretical temperatures and percentage excess air

Figure 5 in Bailey's paper (1926) shows a loss in heat from flue gases at different excess air values and unburned gases. In addition the figure also shows a decrease in furnace temperature as the excess air drops. A 10% reduction in excess air results in an increase in theoretical

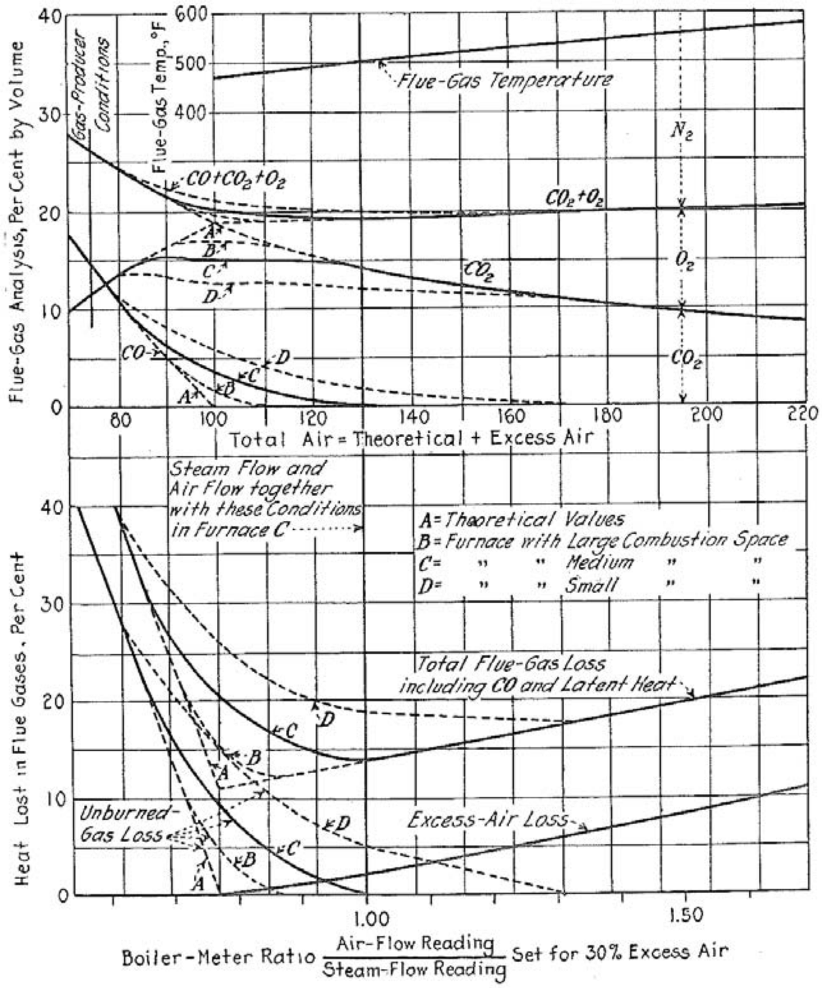


Figure 14: Relation between excess air and carbon monoxide loss (Bailey, 1926)

temperature of combustion of about 200°C. Thus controlling percentage excess air is a key factor in controlling furnace temperatures for a given set of furnace conditions. A higher furnace temperature provides greater combustion efficiency as the heat is transmitted faster and more efficiently at a higher furnace temperature than when it is lower.

An increase in flue gas temperature occurs with an increase in percentage excess air. This is due to the higher gas velocity flowing through the boiler and a drop in the heat transfer rate by radiation when the initial temperatures are lower (Ibid).

1.9.5 The relation of carbon dioxide and oxygen with excess air for various fuels

Figure 8 in Bailey's paper (1926) demonstrates the relationship between carbon dioxide and excess air for various fuels. The figure shows carbon dioxide percentage varies by more than 1% for the same excess air for different types of coal fuel.

Due to the common practice of changing the fuel types burned in the same furnace, it is essential for the fuel to be analysed with further tests besides carbon dioxide to determine the suitable excess air for combustion (Ibid).

It has been suggested for all types of fuels except blast-furnace gas, that the percentage excess air can be determined from the following formula,

$$Excess\ Air = 100 \times \left(\frac{O_2\%}{0.264N_2\% - O_2\%}\right) \tag{1.9.1}$$

1.10 SUMMARY

This chapter has described boilers in general, factors that affect their energy efficiency and how to test the energy efficiency. It has described the required amount of air for combustion including the concept of excess air and how this is measured.

Methods for controlling excess air were then covered as well as possible methods for including carbon monoxide measurements in this control.

Finally, limitations on how much excess air can be reduced were described.

CHAPTER 2: PLANT TRIALS AND BASELINE PERFORMANCE INVESTIGATION

Chapter 2 describes the trials and investigations of Hyne & Son heating plants' performance before implementing the trim control system

2.1 INVESTIGATING THE HEATING PLANT PERFORMANCE

Prior to implementing the trim control it was important to investigate the performance of both heating plants at Hyne & Son as this provided a better representation of how the control loop would respond and fit into the overall heating plant process. The investigation was conducted by the author with help from Nick Martin and Kelly Williams of RCR.

Figure 15 and 16 demonstrate the performance of Hyne & Son's heating plants 1 and 2 performances before implementing the trim control. Tables 3 and 4 include comments of the recorded data during the investigation.

The heating plants did not include a trim controller. The excess air setpoint was determined by a look-up table based on the firing rate.

Trials and investigations were conducted by applying changes to the heating plants such as altering air flows, pressure, fuel feed screws and the rate of the grate shakes (Grate shake is the movement applied to the frame that holds the fuel in the furnace to distribute the fuel evenly).

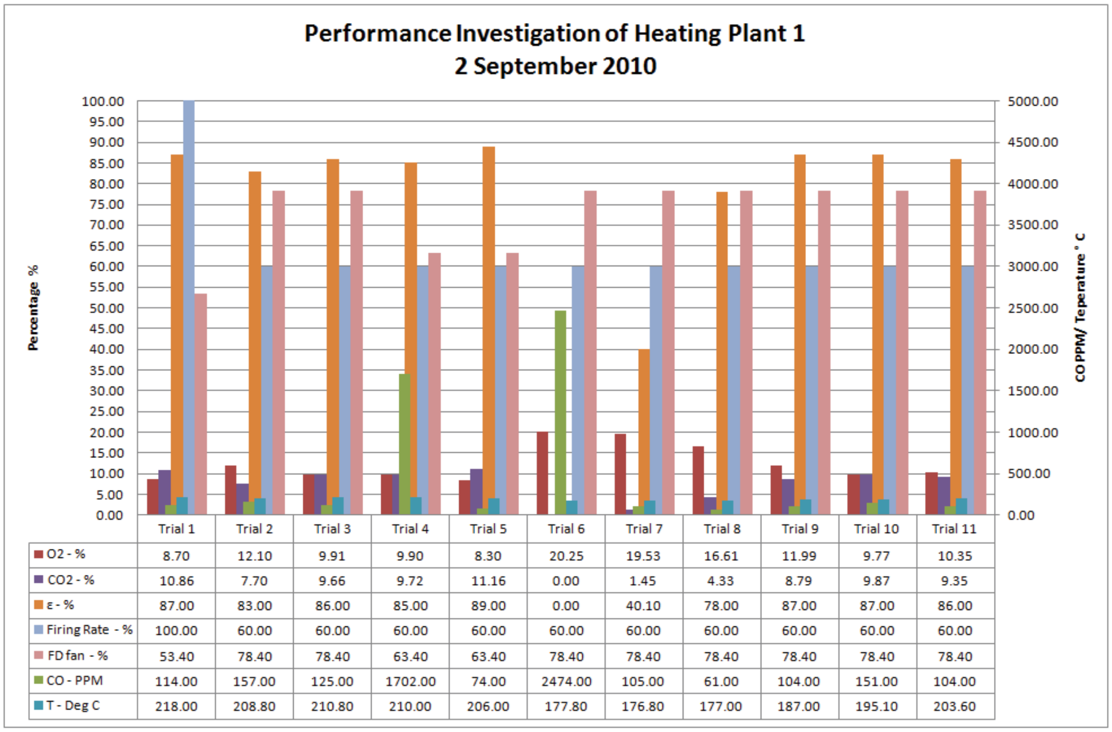
During trials and investigation measurements were taken for oxygen, carbon monoxide, carbon dioxide, flue gas temperature and flue gas efficiency using a combustion analyser and a pressure measuring instrument.

It has been noted that there are a number of factors that influence the change of oxygen, carbon monoxide, carbon dioxide, flue gas temperature and flue gas efficiency;

- Comparing the performance of the heating plant 1 (Figure 15) in Trial 1 and 2, when the forced draft fan rate was low in Trial 1, it led to a drop in oxygen and carbon monoxide levels. On the other hand in Trial 2, when the rate of the forced draft fan was increased, it result an increase in both oxygen and carbon monoxide levels and a drop in efficiency. This indicates oxygen was higher than that required for complete combustion. High level in oxygen for combustion may decrease the furnace temperature and therefore leads to incomplete burning of the fuel and increase in carbon monoxide. This is also shown in Figure 16, Trial 2.
- When setting the heating plant to operate at a low firing rate as seen in Figure 15, Trial 2, the furnace temperature decreases and therefore fuel is not completely and efficiently burnet. In complete burning of the fuel leads to an increase in carbon monoxide level and a drop in efficiency. It has also been observed that the firing in the furnace appears to be very smoky.
- When a grate shake occurs, it generates a sudden increase in the carbon monoxide level in the furnace. Spikes generated from grate shakes are very short and they are usually overlooked and not considered as smothering as seen in Figure 15, Trial 4.
- Smothering may occur when fuel piles up in the furnace. In return firing in the furnace becomes very smoky which is an indication of a bad combustion as seen in Figure 15, Trial 6. The heating plant was recovered from smothering by pressing the smothering button in the HMI screen. When the smothering button pressed, it reduced the fuel feed screw rate and therefore decreased fuel pile up and the firing the in the furnace

improved as shown in Figure 15, Trial 7.

- When the furnace pressure was increased from -5mmH_2O to +7mmH_2O in heating plant 2 (Figure 16, Trial 3), the oxygen level decreased and resulted carbon monoxide to decrease. On the other hand, when the furnace pressure was reduced from +7mmH_2O to +5mmH_2O (Figure 16, Trial 4), the oxygen level increased and resulted the carbon monoxide to increase in the flue gas, due to inefficient burning of the fuel, which led the efficiency to drop. This indicates high furnace pressure does affect the level of oxygen in the furnace and therefore the carbon monoxide level and efficiency of the flue gas.
- The secondary air damper is controlled as a digital input (on/off). In cases where cooling air dampers are opened there would be an increase in excess oxygen in the furnace and a decrease in carbon monoxide level. However, as the excess oxygen continues to increase in the furnace it may cause the carbon monoxide to increase as well. This is because the heat transfer in the furnace will cool the combustion gases down too far resulting in incomplete burning of the fuel. It would be better to control the secondary air cooling process control by analogue control over the top cooling air damper, with a PID control, rather than digital control and setpoint.



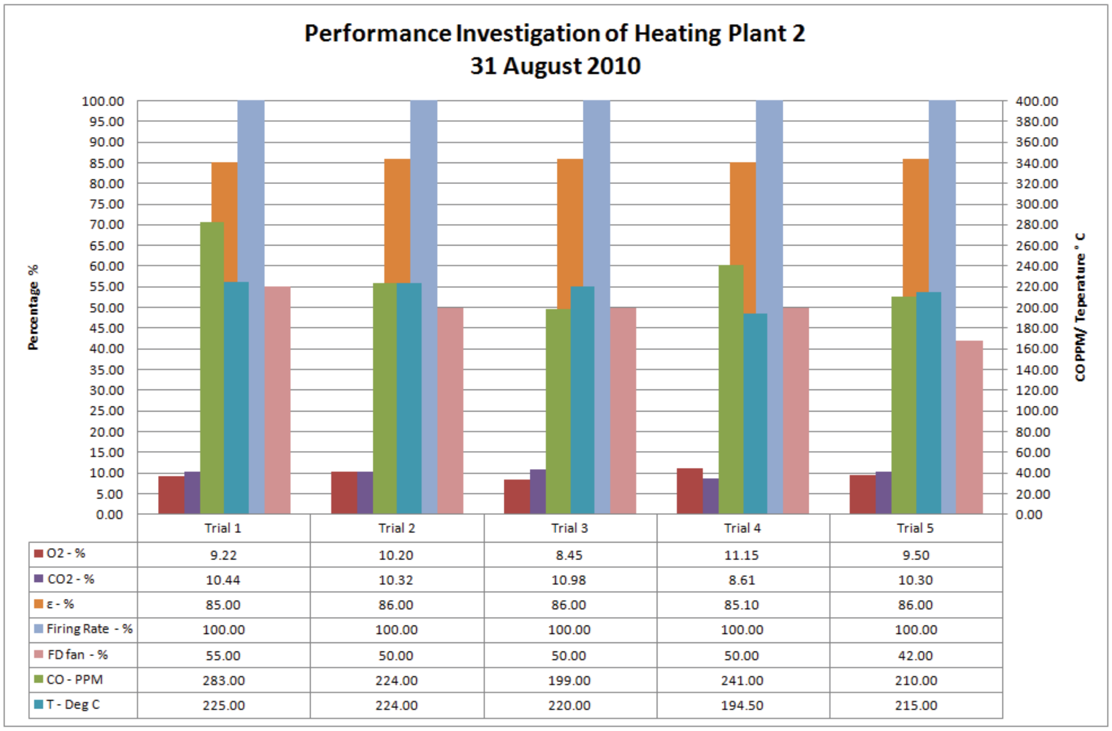
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10	Trial 11
■ O2 - %	8.70	12.10	9.91	9.90	8.30	20.25	19.53	16.61	11.99	9.77	10.35
■ CO2 - %	10.86	7.70	9.66	9.72	11.16	0.00	1.45	4.33	8.79	9.87	9.35
■ ε - %	87.00	83.00	86.00	85.00	89.00	0.00	40.10	78.00	87.00	87.00	86.00
■ Firing Rate - %	100.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00
■ FD fan - %	53.40	78.40	78.40	63.40	63.40	78.40	78.40	78.40	78.40	78.40	78.40
■ CO - PPM	114.00	157.00	125.00	1702.00	74.00	2474.00	105.00	61.00	104.00	151.00	104.00
■ T - Deg C	218.00	208.80	210.80	210.00	206.00	177.80	176.80	177.00	187.00	195.10	203.60

Figure 15: Performance investigation of heating plant 1

Table 3: Heating plant 1 performance investigation comments

Trial	Comments
1	Recorded data at 53.4% FD fan rate and 100% firing rate
2	
	Changed FD fan from 53.4% to 78.4%
	Reduced firing rate to 60 %, 61 Hz

	Firing at the furnace very smoky suggested bad combustion
3	
	Firing in the furnace and efficiency improved. No fuel mounting
	Increased feed screws to 30%
4	
	Decreased FD fan from 78.4%% to 63.4%
	Spike occurred due to grate shake
	Increased furnace pressure from -5 to 2mm
5	
	Further data recorded of the performance of the heating plant
6	
	Increased FD fan from 63.4% to 78.4%
	Furnace pressure 2mm
	Firing at the furnace very smoky indication of bad combustion
7	
	Pressed smothering button at the control room (at the HMI)
	Firing in the furnace became less smoky and the combustion is improved
	The efficiency improved
8	
	Recorded data when very intense fire at the side of the grate
9	
	Further data recorded of the performance of the heating plant
10	
	Recorded data when the intensity of the fire in the furnace increased at the side of the grate
11	
	Further data recorded of the performance of the heating plant



	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
🟥 O2 - %	9.22	10.20	8.45	11.15	9.50
🟪 CO2 - %	10.44	10.32	10.98	8.61	10.30
🟧 ε - %	85.00	86.00	86.00	85.10	86.00
🟦 Firing Rate - %	100.00	100.00	100.00	100.00	100.00
🟥 FD fan - %	55.00	50.00	50.00	50.00	42.00
🟩 CO - PPM	283.00	224.00	199.00	241.00	210.00
🟦 T - Deg C	225.00	224.00	220.00	194.50	215.00

Figure 16: Performance investigation of heating plant 2

Table 4: Heating plant 2 performance investigation comments

Trial	Comments
1	
	Recorded data at 55% FD fan rate and 100% firing rate
2	
	Reduced FD fan from 55% to 50%
3	
	FD duct front Pressure: -10 mmH_2O
	FD duct ground Pressure: 8.9 mmH_2O
	Change furnace pressure SP from -5 to +7
	FD duct front Pressure: 0 mmH_2O
	FD duct ground Pressure: -5 mmH_2O
	ID fan: -296 mmH_2O
4	
	Firing rate controller changed from 0.03Deg C/s to 0.1 Deg C/s
	ID fan: -246 mmH_2O
	Changed furnace pressure SP from +7 to +5
	Pressure at burner: -10 mmH_2O
5	
	Reduced FD fan from 50% to 42%

2.2 SUMMARY

This chapter has shown the results and analysis of the trials to record the baseline behaviour of the heating plants before the introduction of the carbon monoxide analyser and the author’s new excess-air, trim controller.

CHAPTER 3: TRIM CONTROL LOOP DESIGN AND IMPLEMENTATION

Chapter 3 includes carbon monoxide monitoring and oxygen trim loop specifications, methods used to determine if the trim control meets the specifications and the generic design. In addition, it includes the implementation and the functional description of the trim control system.

3.1 SPECIFICATIONS

As mentioned in the Introduction chapter, the aim of the project was to design, and test, a better trim control using measurements of the carbon monoxide level in the flue gas.

The trim control was designed to meet the following specifications derived from discussions between the author and RCR:

1. Improve the efficiency of the heating plants.
2. Maintain carbon monoxide at a desired level by trimming the excess oxygen setpoint to a required level.
3. Perform specific operations to restore normal operation when smothering is detected.
4. Improve the efficiency of the heating plants after implementing the carbon monoxide monitoring and oxygen trim control.
5. Implement on the plant system used by RCR, which requires the code to be written in IEC61131-3 standard.

3.2 METHODS

This section outlines the methods and experiments to determine if the product will meet the specifications laid out in the previous section. The following methods were derived from the discussion between the academic supervisor, author and RCR.

Specification 1:

Improve the efficiency of the heating plants.

Method1:

Run the trim controller in normal operating mode and observe the carbon monoxide concentration and excess air setpoint.

Expected result:

The carbon monoxide concentration is returned to near the excess air setpoint. The speed of the response is as fast as possible without unduly affecting the excess air control.

Specification 2:

Maintain carbon monoxide at a desired level by trimming the excess oxygen setpoint to a required level.

The carbon monoxide look-up table will include three limit levels as shown in Figure 17. ‘Ideal’ is the required carbon monoxide level to be achieved, ‘upper limit normal’ is the maximum normal operating level for carbon monoxide and ‘upper limit alarm’ is for detecting smothering.

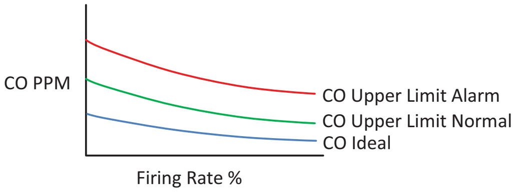


Figure 17: Carbon monoxide look-up table

Specification 2 is divided into two parts, Method 2A and 2B:

Method 2A:

Decrease oxygen percentage gradually when the carbon monoxide level is below the upper limit normal.

Expected result:

When the carbon monoxide process variable is below the upper limit normal (above which the combustion is no longer considered complete), the excess oxygen setpoint will be lowered, as it suggests that there is more oxygen than is required for complete combustion.

Method 2B:

Increase oxygen percentage when the carbon monoxide level is above the upper limit normal.

Expected result:

When the carbon monoxide process variable exceeds the upper limit normal level, the excess oxygen setpoint will be increased gradually to overcome the increase in carbon monoxide, which should drop close to the ideal level.

Specification 3:

When the carbon monoxide level increases above the upper limit alarm level (Smothering):

- Perform a grate shake in order to distribute the fuel evenly across the grate and to optimize the fuel burning process.
- Decrease the feed rate of the fuel screws. This will reduce the input fuel which in turn will improve the air/fuel mixing process.

Method 3:

A smothering event will be simulated by lowering the forced draft fan rate, decreasing the air flow into the furnace and therefore decreasing excess oxygen available for combustion. Also, by increasing the fuel feed screws, the air/fuel ratio for combustion will be minimized leading to a smothering event and subsequent rise in carbon monoxide levels. This will lead the control system to perform a grate shake and reduce the fuel feeder speeds.

Expected result:

A decrease in the fuel feed screws should be observed. This should overcome smothering and decrease the carbon monoxide level.

Specification 4:

Improve the efficiency of the heating plants after implementing the carbon monoxide monitoring and oxygen trim control.

Two possible methods could be applied to determine the efficiency improvement of implementing the trim control;

Method 4A

Comparing the flue gas efficiency measured by ABB analyser unit with and without the trim control.

A. With trim control

1. Switch the trim control to auto.
2. Apply a step change of carbon monoxide every 30 minutes over a three hour period.
3. Measure flue gas efficiency.

B. Without trim control

1. Switch the trim control to manual. The excess air setpoint for a specific firing rate will be determined by a look-up table.
2. Apply a step change of carbon monoxide every 30 minutes over a three hour period.
3. Measure flue gas efficiency.

Method 4B:

Assess the heating plants' efficiency based on the British standard for assessing thermal performance of heating plants for steam, hot water and high temperature heat transfer fluids.

Expected result:

The same expected result in both methods 4A and 4B that is increase in efficiency after implementing the carbon monoxide monitoring and oxygen trim control. Implementing the trim control will eliminate the addition of excess air. Thus, increasing the efficiency of the flue gas and the overall heating plant performance.

Specification 5:

Implement on the control system used by RCR, which requires the code to be written in IEC61131-3 standard.

Method 5

The trim control will be implemented in heating plant 1 and 2 by RCR. The code will be written in IEC61131-3 standard using RSLogix5000 from Rockwell software.

3.3 GENERIC DESIGN

The trim control loop design was created based on the carbon monoxide/oxygen control arrangements suggested in the literature in Section 1.8.2. However, the control loops were unnecessarily complicated in the implementation and did not account for the asymmetric response of carbon monoxide to incomplete combustion. The author created the design of the trim controller following discussions with RCR. The final design can be seen in Figure 18.

The feed-forward controller arrangement is limited (Figure 8, page 31). It does not take in to account smothering conditions. The description of the control loop did not include a description of how the carbon monoxide and oxygen levels were based on the firing rate or how they should be calculated. The strategy of adding a sum of firing rate and the oxygen PID controller output to the air/fuel controller is complicated and impractical.

The cascade control loop (Figure 9, page 31) is less complicated than the rest of the control loops introduced in the literature review Section 1.8.2. However, the trim control loop includes a carbon monoxide controller. The level of the carbon monoxide changes very rapidly compared to the oxygen level. For this reason, the carbon monoxide controller will be tuned with a lower gain than the oxygen controller. Tuning two controllers in a trim control may result in feedback instability.

In the case of Hyne & Son's plant, while the oxygen level is controlled and therefore requires a controller, the carbon monoxide need not be controlled but only used to adjust the excess-oxygen, trim controller setpoint. A second controller is not, therefore, necessary.

The single controller arrangement (Figure 10, page 32) is particularly complex as it requires one single controller that reacts to the effects of both oxygen and carbon monoxide and switches from control of one to the other. This process makes the control loop inefficient and, in practice, it is difficult to implement.

The Rosemount Analytical control loop (Figure 11, page 33) runs a transfer mode strategy between oxygen and carbon monoxide controllers and requires operator intervention and is, therefore, hardly ideal. This arrangement is not ideal because it requires an operator intervention. The trim control is required to trim the excess air setpoint automatically. Operator interference with the trim control may create some instability within the system because of the shifting mode. Heating plants are sensitive to very small variations. It is important to implement a reliable and stable control loop which suits the dynamics and the size of a heating plant. Similarly to the cascade loop arrangement, this model includes a carbon monoxide controller. The process of the trim control loop is simpler and provides better performance without including this controller. Instead the excess oxygen, trim controller setpoint will be adjusted based on the carbon monoxide measurements.

The design of the trim control for Hyne & Son heating plants was simplified as shown in Figure 18. Readings of oxygen and carbon monoxide will be directly measured from the flue gas stream through probes placed between the convection coils and the hopper. Carbon monoxide readings will be compared with a setpoint generated based on the firing rate from the look-up table. The level of the carbon monoxide measurement compared with the ideal limits will manipulate the oxygen PID controller. If the measured carbon monoxide remains low (compared to setpoint) the oxygen setpoint bias will gradually be reduced. If the carbon monoxide level increases then the oxygen setpoint bias is stepped up.

When the furnace temperature exceeds the specified operating limit, the cooling air dampers are opened to reduce the heat. Opening the cooling air damper can affect the level of excess air in the furnace. It is therefore, added to the oxygen setpoint to be stepped up when this occurs.

Smothering is corrected by reducing the speed of the fuel feed screws until the carbon monoxide level comes back into the normal range at which point the feeder screw speeds will slowly return to the original value.

Finally, the oxygen trim PID controller manipulates the forced draft fan which supplies excess air in the furnace for combustion.

An operator may bias the oxygen trim percentage if required using a manual bias input.

The trim control shown in Figure 18, as designed by the author, is considered to be the most suitable. It takes into account smothering conditions and the air added from secondary air fan cooling. It does not include a PID controller for the carbon monoxide, only for the excess air, making it a simpler and more stable controller.

3.4 THE IMPLEMENTATION OF THE TRIM CONTROL

The implementation of the trim control can be divided into two parts: software and hardware.

The author implemented the design as a

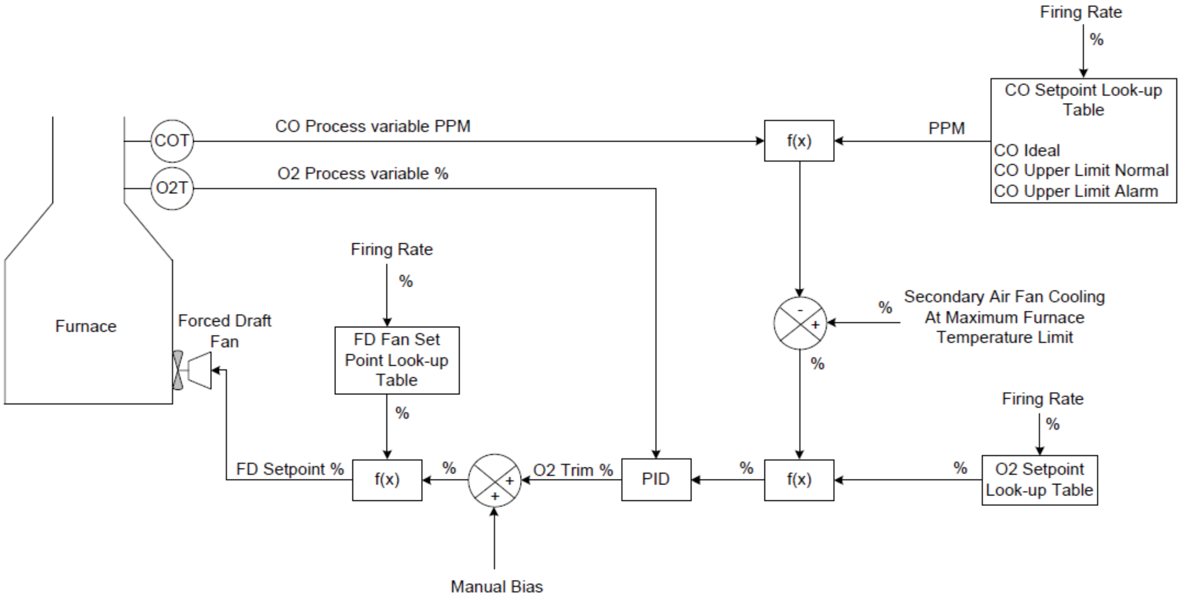


Figure 18: Excess-air, trim control scheme resulting from changes made by the author to previous schemes

program in Sequential Function Chart (SFC) and Structured Text based on the IEC61131-3 standard using an RSLogix5000 PLC from Rockwell (see Appendix 1 for the algorithm and program). As stated in the previous section, the program was based on the control loops introduced by Dukelow (1991) and redesigned by the author. The author's design was somewhat further modified by RCR staff for the Hyne & Son heating plants as shown in Figure 19.

The hardware installation of the carbon monoxide analyser was done by ABB. The electronic assembly was located in the MCC room while the analyser's sensor assembly was placed at the heating plants close to the stack, as shown in Appendix 4 figures 33, 34 and 35.

The author felt that the ideal location of the sensor assembly should be after the combustion area but, because of high temperatures and therefore difficulties in implementation, RCR decided to locate it close to the stack. RCR believed that placing the sensor assembly close to the stack would provide measurements close to the accurate readings without adding undue delay into the control loop.

3.5 THE PROCESS FUNCTION OF THE TRIM CONTROL

The operation of the analyser and trim control loop on the heating plants was analysed by the author with assistance from RCR staff.

The process function of the trim controller can be divided into two parts: oxygen trim control and carbon monoxide trim control.

The oxygen trim control

The oxygen trim controller uses a PI controller with a setpoint generated by a lookup table based on the firing rate to add a trimming bias onto the forced draft fan speed.

When the cooling air damper is open, it can affect the desired oxygen setpoint in the furnace. An offset is therefore added to the oxygen PID controller set point in order for this to be taken into account when this happens.

Carbon monoxide trim control

The carbon monoxide setpoint is generated by a look-up table based the on the firing rate. This determines the ideal level of carbon monoxide, the upper limit of the normal range and the alarm range at which smothering may occur (Figure 19).

Carbon monoxide control does not use a PID controller. Rather the system takes appropriate discrete actions when the carbon monoxide process variable exceeds the “CO upper limit normal” or alarm levels.

If the carbon monoxide process variable exceeds the “CO upper limit normal”, the excess oxygen setpoint will increase significantly to overcome the high level of carbon monoxide. On the other hand, if the carbon monoxide process variable is less than the “CO upper limit normal”, the excess oxygen setpoint will slowly decrease. This results in the system running at an excess air level just above the value which will result in inefficient combustion.

If the carbon monoxide process variable is higher than the “CO upper limit alarm”, the speed of the fuel feed screws will reduce until the carbon monoxide level comes back into the normal range at which point the feeder screw speeds will slowly return to the original value.

Grate shakes generate very short carbon monoxide spikes. Therefore, if a manual or automatic grate shake occurs, high carbon monoxide is disregarded for 60 seconds before any action is taken.

Figure 19 summarises the carbon monoxide monitoring and oxygen trim control.

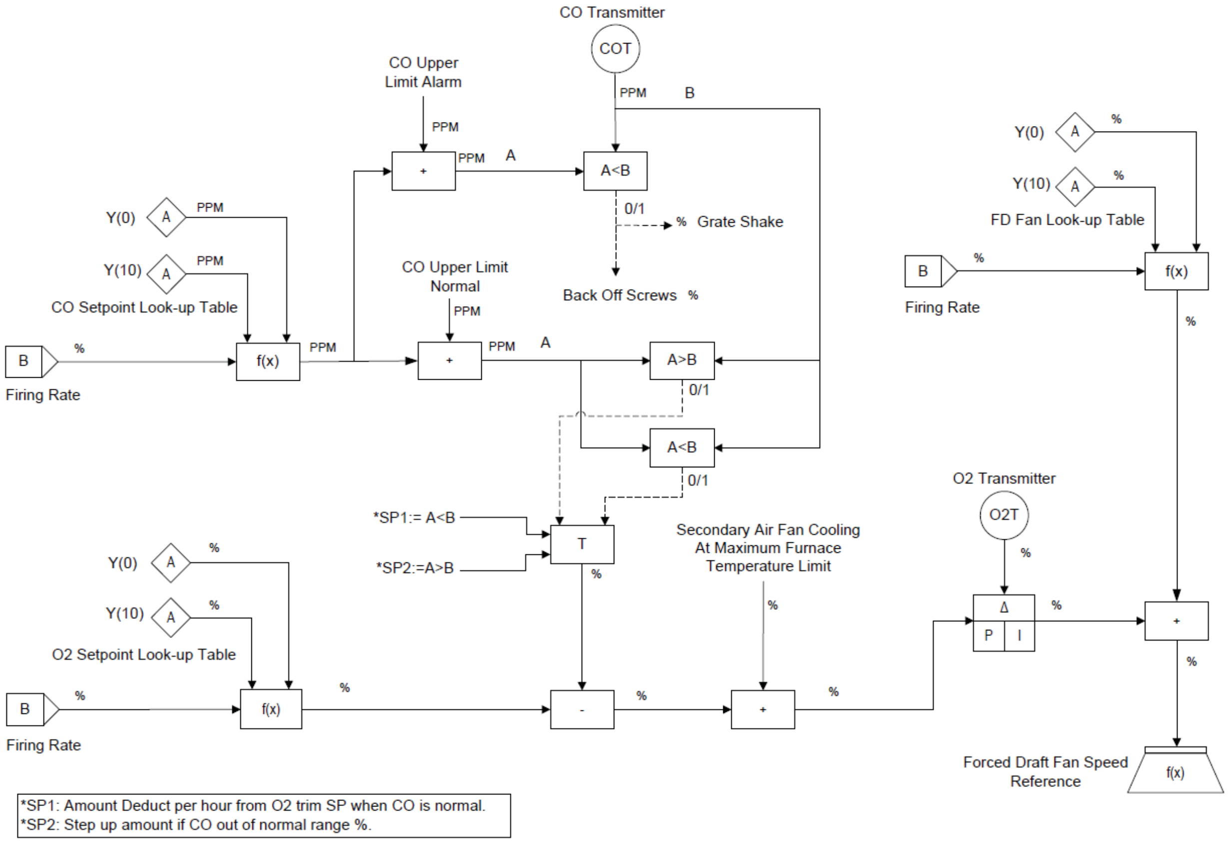


Figure 19: Carbon monoxide monitoring and oxygen trim control

3.6 SUMMARY

In this chapter the specifications for the final controller design are listed as well as the testing methods required to confirm that the specifications have been met. The competing controller design schemes are then discussed leading to the description of the author's control scheme for incorporating carbon monoxide measurement into the excess air, trim controller. The ability of this controller to recover from smothering is also described.

Finally, the process function and the implementation of the trim control loop into the heating plants were explained.

CHAPTER 4: RESULTS AND DISCUSSION

Chapter 4 provides the results and discussion for the experiments specified in the Method section in Chapter 3.

4.1 TESTING THE PERFORMANCE OF THE CARBON MONOXIDE MONITORING AND OXYGEN TRIM CONTROL

This section discusses the performance of the trim control system in maintaining carbon monoxide at a desired level by trimming the excess oxygen setpoint. In addition, its ability to restore normal operation when smothering is measured.

The performance of the trim control systems at the heating plants was tested by Nick Martin of RCR with oversight from the help of Kelly Williams and the author. The data produced were then analysed by the author.

The first trial of the controller could not be carried out as planned due to a failure of the ABB analyser installation. Instead the trim control loop was tested and the process conditions were simulated as shown in Figure 20.

After the ABB units were repaired, the trim control system was tested under the actual process conditions of the heating plants as shown in figures 21 and 22.

Testing the trim control without the ABB analyser

This was achieved by creating an artificial carbon monoxide input to test the functionality of the trim control without the ABB analyser and having to wait for specific process conditions. This was performed in simulation mode only where values for the carbon monoxide concentration were entered manually into the system. The data performance of the carbon monoxide was manually input to the trim control loop. This method was only tested on Methods 1 and 2 (Chapter 3, Section 3.2) within a period of approximately 2 hours.

Figure 20 is a plot of data recorded by the data log (Hyne & Son Pty Ltd - Tumbarumba, 2010) while running the trials.

As can been seen from Figure 20, from 4:12:00 PM to 4:48:00 PM, the carbon monoxide level was set, by hand, between the ideal and upper limit normal (above which the combustion is no longer considered complete) at approximately 250 ppm. The oxygen setpoint was decreased gradually by the trim controller by a small amount because there was more oxygen than that required to complete combustion. In a real process the reduction of the oxygen setpoint, in this mode, is set to 1% per hour.

As the level of carbon monoxide was increased, by hand, to 500 ppm, which was above the upper limit normal as seen at 4:48:00PM, the oxygen setpoint was increased by the trim controller to overcome the high level of carbon monoxide and convert more carbon monoxide to carbon dioxide.

When the carbon monoxide level was increased further (to approximately 1080 ppm) above the upper limit normal as seen at 5:12:01 PM, the excess oxygen setpoint continues to increase to reduce the formation of high levels of carbon monoxide.

Testing the trim control with the ABB analyser

This section shows the results of the experiments outlined in Methods 1, 2 and 3 (see Chapter 3, Section 3.2). For these trials the carbon monoxide analysers were repaired and working. Figures 21 and 22 show the performance of the carbon monoxide monitoring and oxygen trim control during the actual heating plant process conditions.

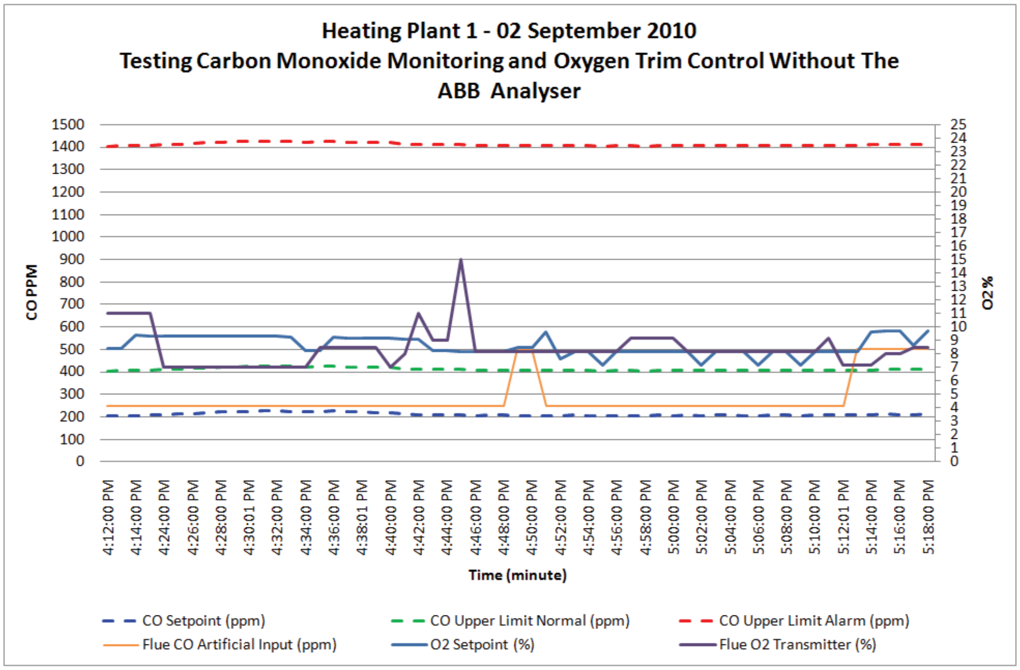


Figure 20: Carbon monoxide monitoring and oxygen trim control performance without the ABB analyser, using an artificial carbon monoxide input, i.e. the carbon monoxide concentration was input by hand (Heating plant 1- 2 September 2010)

Figure 21 shows the regular spikes, for example the occurrence at 8:54:30 AM, 9:49:30 AM and 10:20:30 AM. These spikes are generated by grate shakes (a grate is a frame that holds the fuel for fire in the furnace and it shakes at approximately uniform interval to distribute the fuel evenly). The carbon monoxide level is above the upper limit alarm when the grate shake spikes occur. These spikes are not considered to be due to smothering as they are very short (and are ignored by the trim controller. (Note that this is the equivalent of using a spike filter.)

A smothering condition is considered to be when the level of carbon monoxide stays at a higher level for a period over 60 seconds. Figure 21 shows these smothering events at 10:28:30 AM, 10:42:30 AM and 4:30:30 PM where the plant is brought back to normal operation by the smothering control algorithm. This result is proof of meeting Specification 3. The smothering control algorithm reduces the fuel feed screws until carbon monoxide level comes back into the normal range. As the carbon monoxide level returns to the normal range, the feeder screw speed will slowly be returned to the original value.

Proof of meeting specification 2A can be seen in Figure 21 where the carbon monoxide level is below the ideal setpoint such as that at 1:34:30 PM (at 4:23:30 AM in Figure 22) and where the carbon monoxide level is between the ideal setpoint and upper limit normal as seen at 11:56:30 AM in Figure 21 (at 2: 51:30 AM in Figure 22). When the carbon monoxide process variable is below the upper limit normal (above which the combustion is no longer considered complete), the excess oxygen setpoint will be lowered at a rate of 1% per hour, as it suggests that there is more oxygen than is required for complete combustion.

The oxygen setpoint was not lowered below 6.5% when the carbon monoxide process variable dropped well below the ideal set point as seen at 1:34:30 PM Figure 21 and 4:23:30 AM Figure 22.

Although the carbon monoxide level can be well below the setpoint, the heating plant would still require positive amount of air to burn the fuel efficiently and create turbulence. A heating plant cannot burn the fuel efficiently with 0% oxygen as stated in the literature, Chapter 1, section 1.4 on "Test for complete combustion". In heating plant 2 an oxygen level of 6.5%, is the minimum amount that it can burn the fuel efficiently. The trim control was programmed to trim the oxygen setpoint to a minimum of 6.5%. The minimum operating oxygen setpoints for Hyne & Sons' heating plants were determined, by Kelly Williams, based on the heating plants' performance.

When the carbon monoxide process variable exceeds or almost at the upper limit normal as seen in Figure 22 at 1:15:30 AM to 1:39:30 AM, the excess oxygen setpoint was increased gradually at 1:19:30 AM to overcome the increase in carbon monoxide, which should drop close to the ideal level. This result a proof of meeting Specification 2B.

The trim control loop was designed and programmed for the carbon monoxide limits to change with the ideal setpoint by same amount as seen at the start of Figure 21 and at 3:47:30 AM at Figure 22. The carbon monoxide setpoint change based on the heating plants' firing rate as seen on the control loop diagram, Figure 19. For heating plant 2, the upper limit normal and the upper limit alarm are set to be 200ppm and 300ppm, respectively, higher than the ideal set point. These limits were determined, by Kelly Williams, based on standard authorized emission levels and heating plants' performance.

The overall performance of the carbon monoxide monitoring and oxygen trim control has proved to meet specifications 1, 2 and 3 (Chapter 3, Section 3.2). The trim control improved the heating plants' performance. The carbon monoxide concentration is returned to near the setpoint by adjustment to the excess air setpoint. The speed of the response is as fast as possible without unduly affecting the excess air control.

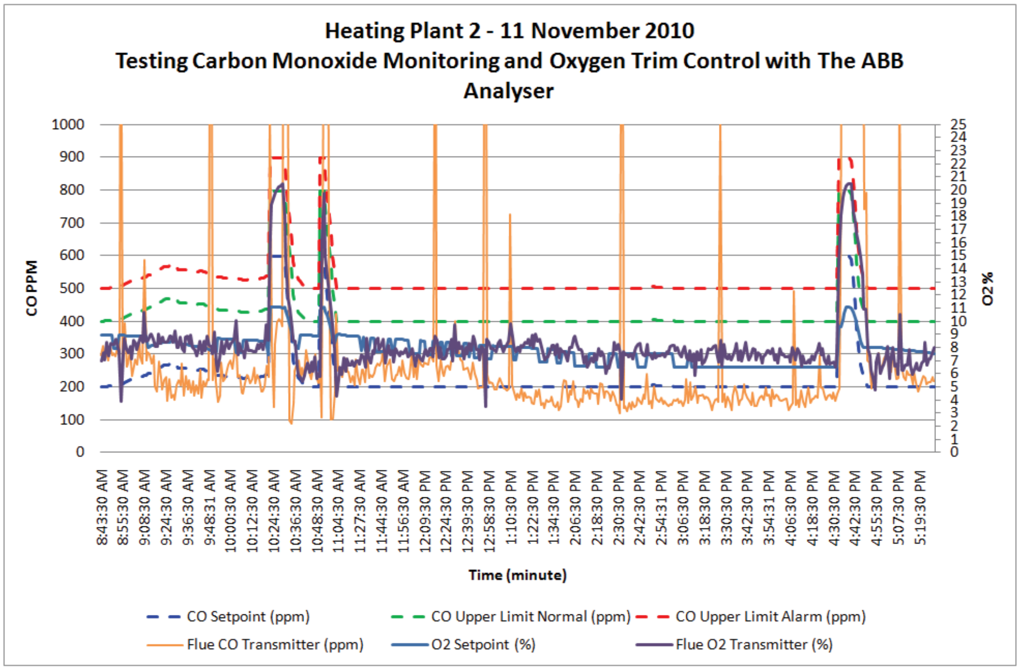


Figure 21: Carbon monoxide monitoring and oxygen trim control performance with the ABB analyser during the actual heating plant process conditions, i.e. after the repair of the carbon monoxide analysers (Heating plant 2 – 11Novemeber 2011)

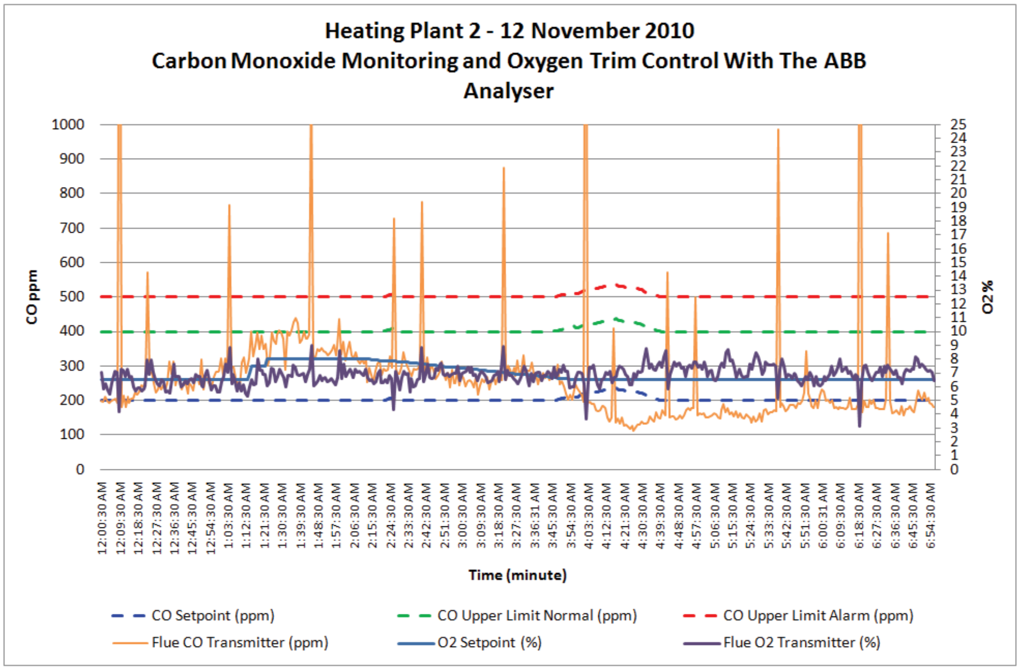


Figure 22: Carbon monoxide monitoring and oxygen trim control performance with the ABB analyser during the actual heating plant process conditions, i.e. after the repair of the carbon monoxide analysers (Heating plant 2 – 12Novemeber 2011)

For these trials the excess air setpoint was dropped by 2% i.e. a 2% reduction in air inflow. The satisfactory performance of the trim control scheme shown here proves an immediate increase in the efficiency of the plant. (Before implementing the trim control in the heating plants, the excess air setpoints were estimated based on the firing rate using a look-up table.)

4.2 EFFICIENCY IMPROVEMENT CALCULATIONS

It was not possible to perform to direct trials to prove whether the trim control improved the heating plants' efficiency as specified in Chapter 3, Section 3.2, Method 4. At the time of the trials just referred to, the method for testing the efficiency improvement had not been determined and it was therefore too late to be tested on the heating plants. The location of the heating plants in Australia made it difficult to run the required number of trials. In addition, resource requirements in the plant (personnel and lab testing) to run the tests and process disruption for the client were lacking. Additionally, the client was more interested in reducing particulate emissions which can be seen to have reduced by looking at the stack and are tested annually. According Kelly Williams of RCR, the particulate emissions were seen to be reduced after implementing the trim control.

While specific trials could not be performed to measure the efficiency gains directly, the author estimated these by analysing the mass and heat balances of the heating plants.

The heat energy calculation results showed the heating plants' efficiency improvement from implementing the trim control. Since the excess air setpoint had been lowered by 2% when the trim controller was installed, the efficiency improvement was calculated between the output power, with and without the 2% of the extra excess air. The calculated output power with an increase of 2% excess air was calculated from the data imported while the trim control was implemented. This was done by increasing air inflow by 2% which causes an increase in furnace air temperature, flue gas temperature, inlet and outlet oil temperatures and the final output power. These variables need to be recalculated. The output power with a 2% excess air increase could have been imported while the trim control is set in manual mode but at the time of the trials the method for testing the efficiency improvement had not been determined and it was therefore too late to be tested on the heating plants.

Appendix 5a includes the description of the variables, heat energy functions and calculations of the efficiency improvement from implementing the carbon monoxide monitoring and oxygen trim control.

4.2.1 Variables required for calculation

The calculations were applied to both heating plants at Hyne & Son.

Variables required for the efficiency improvement calculations were obtained from;

- Heating plants data log (Hyne & Son Pty Ltd - Tumbarumba, 2010)
- Calculated based on imported variables from the data log
- Standard thermal property tables and nomograph (Perry & Chilton, 1973; Perry, Green, & Maloney, 1997; Turns & Kraige, 2007)
- Recalculated variables with increased 2% excess air.

The uncertainties of all variables were calculated using the standard error method of the set of data at steady state. A 95% confidence interval was calculated for the final efficiency values for both heating plants (E_{HP1} & E_{HP2}).

Variables imported from the heating plants' data log

Table 5 lists the variables from the heating plants' data log and are referenced in Figure 23. Hyne & Sons' heating plants in Tumbarumba have the same construction as that shown in Figure 23, however, heating plant 1 is 12.5 MW and heating plant 2 is 15 MW.

Calculated variables

Table 6 includes variables required for the heat energy calculation and which were calculated in Appendix 5a using the imported variables from the heating plants data log.

Table 5: Variables imported from the data log

Location on Figure 23	Variable	Description	Value	Unit
A	T_{AmbHP1}	Heating plant 1 ambient temperature	23.30 ± 0.12	°C
A	T_{AmbHP2}	Heating plant 2 ambient temperature	21.13 ± 0.03	°C
B	T_{HEHP1}	Heating plant 1 heat exchanger outlet air temperature	82.92 ± 0.04	°C
B	T_{HEHP2}	Heating plant 2 heat exchanger outlet air temperature	66.62 ± 0.13	°C
C	T_{HHP1}	Heating plant 1 heater output air temperature	251.95 ± 0.09	°C
C	T_{HHP2}	Heating plant 2 heater output air temperature	270.37 ± 0.24	°C
D	$T_{FurnHP1}$	Heating plant 1 furnace air temperature	1,077.97 ± 2.98	°C
D	$T_{FurnHP2}$	Heating plant 2 furnace air temperature	1,073.10 ± 4.94	°C
E	$T_{OilInHP1}$	Heating plant 1 inlet oil temperature	224.59 ± 0.07	°C
E	$T_{OilInHP2}$	Heating plant 2 inlet oil temperature	222.58 ± 0.18	°C
F	$T_{OilOutHP1}$	Heating plant 1 outlet oil temperature	251.38 ± 0.27	°C
F	$T_{OilOutHP2}$	Heating plant 2 outlet oil temperature	251.56 ± 0.38	°C
G	F_{OilHP1}	Heating plant 1 oil flow rate	679.95 ± 0.76	m^3/h
G	F_{OilHP2}	Heating plant 2oil flow rate	907.77 ± 0.54	m^3/h
H	$T_{FlueHP1}$	Heating plant 1 flue gas temperature after combustion zone	292.64 ± 0.12	°C
H	$T_{FlueHP2}$	Heating plant 2 flue gas temperature after combustion zone	387.32 ± 0.78	°C
	Q_{HP1}	Heating plant 1 output power	10.11 ± 0.18	MW
	Q_{HP2}	Heating plant 2 output power	14.46 ± 0.30	MW

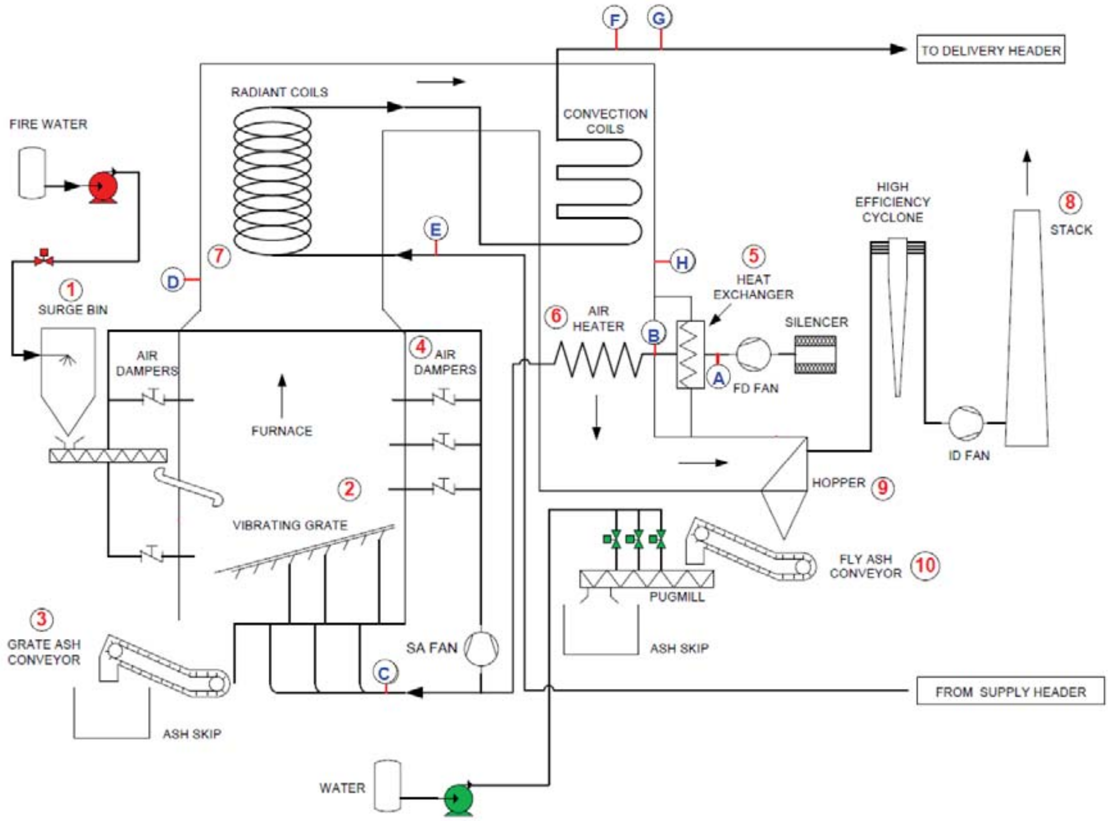


Figure 23: Hyne and Sons' heating plant diagram (1 to 10 refer to process function in Chapter 1, section 1.2, page 16. A to H refer to data log measuring points which are listed in Table 5 in Chapter 4, section 4.2.1, page 55) (after RCR Energy Systems Limited, 2002)

Table 6: Variables calculated based on the imported heating plants data log

Variables	Description	Value	Unit
F_{AirHP1}	Heating plant 1air flow rate	- 9.77 ± 0.15	kg/s
F_{AirHP2}	Heating plant 2 air flow rate	-15.98 ± 0.24	kg/s
UA_{HP1}	Heating plant 1 heat transfer coefficient x Area	37719.99 ± 606.68	W/°C
UA_{HP2}	Heating plant 2 heat transfer coefficient x Area	37104.74 ± 604.06	W/°C
ΔT_{HP1}	Heating plant 1 log temperature difference	268.08 ± 0.41	°C
ΔT_{HP2}	Heating plant 2 log temperature difference	389.53 ± 1.87	°C

Variables determined from standard thermal properties and nomograph

The heat transfer oil thermal properties (density and specific heat capacity) and flow rate used in the heating plants were required to complete the efficiency improvement calculations. The heating plants were operating based on a mixture of 33% of Caltex Texatherm 32 and 67% Castrol Perfecto HT12 of mineral based heat transfer oils. The thermal properties of both oils were obtained from their product data sheet (Castrol, 2007; ChevronTexaco, 2003). The thermal properties and flow rates at the required temperature were interpolated and calculated in Appendix 5b.

The specific heat capacities for the flue gas and furnace air temperatures were calculated based on the percentages of the composition elements. The percentages of the compositions were provided by RCR. The gas composition depends on the type of the fuel burned. The composition elements produced from burning biomass fuel at Hyne & Son heating plants; consist of nitrogen (N_2), carbon dioxide (CO_2), carbon monoxide

(CO), sulphur dioxide (SO_2) and vapour (H_2O).

The specific heat capacities of those elements were determined from standard thermal property tables and nomogram. The percentage of each element was then multiplied by its specific heat capacity. The sum of the total gas compositions was then presented as a final specific heat capacity as shown in Appendix 5c.

Table 7 includes flue gas and furnace air thermal properties. It also includes heat transfer oil thermal properties and flow rates values.

Recalculated variables with increased 2 % excess air

Before implementing the trim control, the excess air was an additional 2% higher than that required for complete combustion to prevent smothering and incomplete burning of the fuel. The difference would have caused changes to air flow rate, furnace air temperature, flue gas temperature, inlet and outlet oil temperatures and the final output power. These variables need to be recalculated.

Table 8, includes the recalculated variables with 2% increase in excess air. Appendix 5a includes the calculations of the recalculated variables.

Table 7: Heat transfer oil, flue gas and furnace air thermal properties

Variables	Description	Value	Unit
$Cp_{FlueHP1}$	Heating plant 1 specific heat capacity of the flue gas	1219.95 ± 0.37	J/kg. °C
$Cp_{FlueHP2}$	Heating plant 2 specific heat capacity of the flue gas	1224.24 ± 0.25	J/kg. °C
$Cp_{FurnHP1}$	Heating plant 1 specific heat capacity of the furnace air specific heat capacity	1414.53 ± 0.32	J/kg. °C
$Cp_{FurnHP2}$	Heating plant 2 specific heat capacity of the furnace air specific heat capacity	1413.62 ± 1.45	J/kg. °C
$Cp_{OilHP1(33\%Texa+67\%Prf)}$	Heating plant 1 oil specific heat capacity (33% Texatherm 32 + Perfecto HT12)	2647.87 ± 31.05	J/kg. °C
$Cp_{OilHP2(33\%Texa+67\%Prf)}$	Heating plant 2 oil specific heat capacity (33% Texatherm 32 + Perfecto HT12)	2627.47 ± 4.21	J/kg. °C
$F_{OilHP1(33\%Texa+67\%Prf)}$	Heating plant 1 oil flow rate (33% Texatherm 32 + Perfecto HT12)	141.30 ± 0.16	kg/s
$F_{OilHP2(33\%Texa+67\%Prf)}$	Heating plant 2 oil flow rate (33% Texatherm 32 + Perfecto HT12)	188.78 ± 0.10	kg/s
$p_{OilHP1(33\%Texa+67\%Prf)}$	Heating plant 1 oil density (33% Texatherm 32 + Perfecto HT12)	748.11± 0.08	kg/m^3
$p_{OilHP2(33\%Texa+67\%Prf)}$	Heating plant 2 oil density (33% Texatherm 32 + Perfecto HT12)	748.67 ± 0.07	kg/m^3

Table 8: Calculated variables for energy efficiency improvement calculations with 2% increase in excess air

Variables	Description	Value	Unit
$F_{AirHP1+2\%}$	Heating plant 1 air flow rate with 2% increase in excess air	-9.97 ± 0.15	kg/s
$F_{AirHP2+2\%}$	Heating plant 2 air flow rate with 2% increase in excess air	-16.30 ± 0.24	kg/s
Q_{NewHP1}	Heating plant 1 output power with 2% increase in excess air	9.65 ± 0.16	MW
Q_{NewHP2}	Heating plant 2 output power with 2% increase in excess air	14.01 ± 0.29	MW
$T_{FlueNewHP1}$	Heating plant 1 flue gas temperature after combustion zone with 2% increase in excess air	287.36 ± 0.11	°C
$T_{FlueNewHP2}$	Heating plant 2 flue gas temperature after combustion zone with 2% increase in excess air	380.14 ± 0.76	°C
$T_{FurnNewHP1}$	Heating plant 1 furnace air temperature with 2% increase in excess air	1057.29 ± 2.92	°C
$T_{FurnNewHP2}$	Heating plant 2 furnace air temperature with 2% increase in excess air	1052.47 ± 4.84	°C
$T_{HENewHP1}$	Heating plant 1 outlet air temperature from the heat exchanger with 2% increase in excess air	81.75 ± 0.04	°C
$T_{HENewHP2}$	Heating plant 2 outlet air temperature from the heat exchanger with 2% increase in excess air	65.73 ± 0.13	°C
$T_{OilInNewHP1}$	Heating plant 1 inlet oil temperature with 2% increase in excess air	224.25 ± 0.13	°C
$T_{OilInNewHP2}$	Heating plant 2 inlet oil temperature with 2% increase in excess air	222.19 ± 0.28	°C
$T_{OilOutNewHP1}$	Heating plant 1 outlet oil temperature with 2% increase in excess air	250.16 ± 0.25	°C
$T_{OilOutNewHP2}$	Heating plant 2 outlet oil temperature with 2% increase in excess air	250.42 ± 0.35	°C

4.2.2 Efficiency improvement

The efficiency improvement based on the output power difference with, and without the 2% increase in excess air for heating plant 1 and 2 were calculated to be E_{HP1}= 4.78 ± 0.39% and E_{HP2} = 3.24 ± 0.07% respectively. Appendix 5a includes the details of the equations and calculations of the efficiency improvement percentage.

The calculated efficiency improvement values suggest that the carbon monoxide monitoring and trim control have improved the heating plants efficiency. By increasing the efficiency of a heating plant, operating costs such as fuel costs and input energy required to produce a specific output can be reduced as stated in section 1.6.4.

The efficiency improvement percentages also indicate that the heating plant performance efficiency is sensitive to a small change in excess air.

4.3 EXAMPLE OF EFFICIENCY IMPROVEMENT BY REDUCING EXCESS AIR

To complete the analysis of the use of trim control on a boiler it is necessary to calculate the savings made due to the increased efficiency. This was not possible for the plant under study since the major cost benefit, the reduction in fuel costs, was not an issue. Hyne & Son used waste wood to fire the boilers, the fuel therefore cost them virtually nothing.

This section provides an example of the efficiency analysis performed by RCR on a 37MW coal fired boiler at Fonterra, Edendale. This was used by the author to recalculate the thermal efficiency improvement by reducing the boiler excess air from 7% to 5% then calculating the payback savings and internal rate of return in such a situation. Permission was granted by Fonterra to use the data from 37MW Edendale boiler.

4.3.1 The calculation of thermal efficiency

The boiler was operating under the following conditions:

- Boiler: Fonterra Edendale
- Boiler size: 37MW
- Firing rate: 100%
- Steam pressure: 42 bar
- Boiler output: 56,600 kg/hr
- Drum pressure: 41.5 bar G
- Steam flow: 56,567 kg/hr
- Feed water flow: 57,167 kg/hr
- Average grate temperature: 245 ˚C

The thermal efficiency calculation was performed at 7% and 5% excess air using the British Standards For Assessing Thermal Performance Of Heating Plants For Steam, Hot Water And High Temperature Fluids – Part 1 (British Standards Institution, 1987). The thermal efficiency calculation is based on losses calculation and provides results within ± 2% tolerance. The losses calculations in percentage are:

- Losses due to sensible heat in dry flue gases (L_{1gr}).
- Losses due to enthalpy in water vapour in the flue gases (L_{2gr}).
- Losses due to unburned gases in the flue gases (L_{3gr}).
- Losses due to combustible matter in ash and riddling (L_{4gr}).
- Losses due to combustible matter in grit and dust (L_{5gr}).
- Radiation, convection and conduction losses (L_{6gr}).

The total losses (L_{Tgr}) are then calculated by adding up all the individual losses. The thermal efficiency (E_{gr}) percentage is calculated by subtracting the total losses in percentage from 100. Appendix 6a includes heat losses and efficiency calculations. The calculations are based on gross calorific value of the fuel.

Table 9 includes a comparison of the losses and thermal efficiency calculations for Fonterra Edendale coal fired boiler when the boiler operates at excess air of 7% and 5%.

When reducing excess air from 7% to 5%, changes occur in the losses due to sensible heat in dry flue gases (L_{1gr}) and losses due to unburned gases in the flue gases (L_{3gr}). This is because both functions include the excess air variable. Increasing excess air results in an increase in both L_{1gr} and L_{2gr}. This increases the overall total losses and therefore, decreases the thermal efficiency percentage.

Losses due to radiation, convection and conduction (L_{6gr}) were selected from British Standard manual, Appendix C, Table 3. (BS845 1:1987). It was therefore, specified to be the same whether a heating plant operates at excess air of 7% or 5%.

The analyses show that by reducing excess air from 7% to 5%, the thermal efficiency of a heating plant increases. The improvement due to a 2% reduction in excess air is 1.1% (the difference of the calculated efficiency improvement between 7% and 5%).

Table 9: Thermal efficiency comparison of a coal fired boiler at Fonterra, Edendale (RCR Energy Systems Limited, 2009)

	7% Excess Air	**5% Excess Air**
L_{1gr}	9.0%	7.9%
L_{2gr}	11.7%	11.7%
L_{3gr}	0.1%	0.1%
L_{4gr}	0.002%	0.002%
L_{5gr}	3.4%	3.4%
L_{6gr}	0.3%	0.3%
L_{tgr}	24.5%	23.4%
E_{gr}	75.5%	76.6%

4.3.2 Payback savings and internal rate of return of fuel saving cost from implementing carbon monoxide monitoring and oxygen trim control

Heating plants usually operate continuously at higher excess air than that required to complete combustion, to eliminate any potential smothering or incomplete combustion. This was the case at the Hyne & Son heating plants. Therefore, implementing trim control improved the control of excess air for combustion since it controls the excess air setpoint based on the carbon monoxide level in the flue gas. Because of these changes a heating plant will not be operating continuously at higher excess air. Excess air will be maintained at a lower level and varied continuously with the change in carbon monoxide.

When the thermal efficiency of a heating plant improves, it reduces operating costs by reducing the fuel consumption required to produce a desired output power and therefore fuel costs. For some biomass heating plants, the fuel is not purchased since the fuel used is from heating plant wood waste, as in the case at Hyne & Son. Therefore, no savings will be gained from the fuel; however, the overall efficiency of a heating plant will be achieved. For coal fire heating plants, savings from fuel costs can be achieved.

The payback savings can be calculated for the 37MW Fonterra boiler in Edendale thermal efficiency improvement of 1.1% (the difference of the calculated efficiency improvement between 7% and 5%).

Appendix 6b includes the calculations of the payback savings of the fuel cost from implementing the trim control.

The cost of implementing the carbon monoxide monitoring and oxygen trim control is as follows:

- The trim control transmitter: NZ$30,000

- Installation: NZ$5,000
- Software: NZ$5,000
- Calibration per a year: NZ$1,500

The 37MW Fonterra boiler in Edendale consumes coal fuel as follows:

- Fuel cost: 0.12 $/kg (typical price paid over the 2009 period)
- Fuel consumed per hour: 8,131 kg/h
- Fuel cost: NZ$0.12/kg
- Fuel cost per hour: 975.71 NZ$/h

Table 10 summarizes the saving payback over a period of two years for 37MW Fonterra Edendale boiler. It also includes the payback saving if the trim controller was implemented on smaller sized boilers such as 10MW and 20MW. The payback saving is higher for a bigger size boiler than that of a smaller size.

The cost of implementing the trim control is the same for different size boilers or heating plants. The same transmitter, installation, software and calibration can be done for different sized heating plants and boilers.

The payback periods for a 37MW Fonterra Edendale boiler is calculated at approximately five months; while for a heating plant size of 10MW it is approximately 18 months. The fuel costs savings increases in proportion to the size of the heating plant, because of the higher fuel consumption.

Internal rate (IRR) of return analysis was done over a time frame of two years as shown in Figure 24. A 37MW Fonterra Edendale boiler has an IRR % of 216%, 94% for 20MW, and 16% for a 10MW. Appendix 6c includes the internal rate of return cash flow calculations.

Table 10: Payback savings over a period of two years for Fonterra Edendale and smaller sized boilers

Fonterra Edendale				
Period (Year)		**0**	**1**	**2**
	Costs NZ$	40,000	1,500	1,500
37MW	Fuel cost savings NZ$	0	97,442	97,442
	Net savings NZ$	0	95,942	95,942
Example of small sized boilers				
	Costs NZ$	40,000	1,500	1,500
10MW	Fuel cost savings NZ$	0	26,336	26,337
	Net savings NZ$	0	24,836	24,836
20MW	Fuel cost savings NZ$	0.00	52,671.21	52,671.21
	Net savings NZ$	0	51,171	51,171

Net savings NZ$ = Fuel cost savings NZ$ – costs NZ$

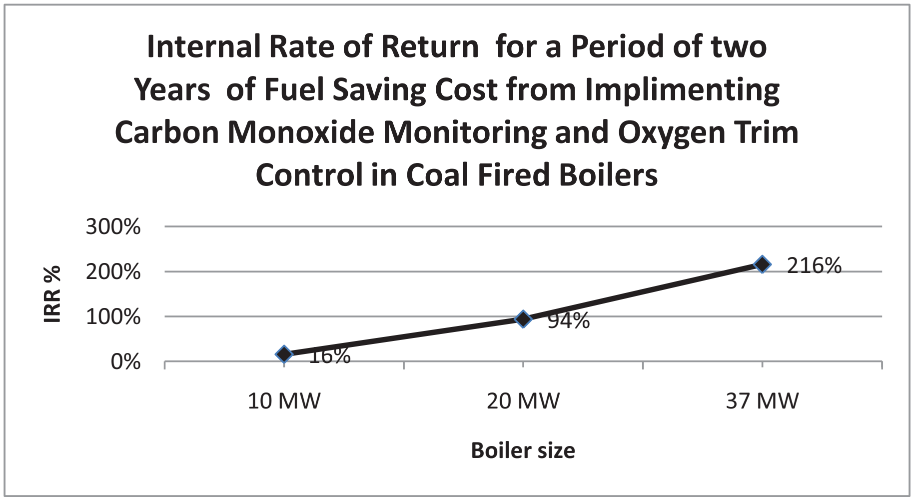


Figure 24: Internal rate of return for a period of two years of fuel saving cost after implementing carbon monoxide monitoring and oxygen trim control in coal fired boilers

Despite high values for the payback saving calculations and internal rate of return analysis, these figures are based on calculations and not experimental data. Also, the carbon monoxide monitoring and oxygen trim control is not suitable for all types of boiler and heating plants as stated in the literature review, Chapter 1, Section 1.8.2 on “Limitations of carbon monoxide monitoring and oxygen trim control”. There are risks that must be considered and therefore, various tests and analyses are required to investigate whether the carbon monoxide monitoring and oxygen trim control is suitable and can provide optimum performance for a specific boiler or heating plant.

4.4 SUMMARY

This chapter has shown the analyses, results and discussion of the experiments and methods outlined in Chapter 3. The carbon monoxide monitoring and oxygen trim control was tested with and without the ABB analyser based on the specifications outlined in Chapter 3, section 3.1.

Efficiency improvement calculations were completed for Hyne & Sons’ two heating plants to determine the improvement by reducing excess air by 2% after implementing the carbon monoxide monitoring and oxygen trim control.

An example shown on payback savings and internal rate of return analyses of the fuel costs if the carbon monoxide monitoring and oxygen trim control was implemented in coal fired boilers.

CONCLUSIONS

Most project objectives were achieved. They are listed below:

- The heating plants at Hyne & Son were upgraded by implementing carbon monoxide monitoring and oxygen trim control to trim excess air for combustion.
- Based on the experiments performed on the heating plants, the trim control was shown to be performing according to the specifications outlined. The specifications derived from discussions with RCR were as follows:
    1. Improve the efficiency of the heating plants.
    2. Maintain carbon monoxide at a desired level by trimming the excess oxygen setpoint to a required level.
    3. Perform specific operations to restore normal operation when smothering is detected.
    4. Improve the efficiency of the heating plants after implementing the carbon monoxide monitoring and oxygen trim control.
    5. Implement on the plant system used by RCR, which requires the code to be written in IEC61131-3 standard.
- The design of the trim control loop was initially based on the control methods provided in Section 1.8.2. However it was discovered that these control methods were too impractical and complicated to be implemented on a real heating plant. The information provided was inadequate and a lot of significant information was missing, such as the function generators and the equations required to solve the optimum carbon monoxide to oxygen ratio.

  The design of the trim control was developed to be simple and suitable for Hyne & Son's heating plants.
- The original look-up tables which were used to generate the oxygen setpoint for the heating plants were found to be unnecessarily conservative and provided a less precise amount of air than that strictly required for combustion.

  Using carbon monoxide to manipulate and control the setpoint of the excess air for combustion has improved the heating plants efficiency. As carbon monoxide is a direct measure of incomplete combustion and unburnt fuel, it sets the oxygen setpoint to the optimal percentage to complete combustion.
- The heat energy efficiency calculations have shown, by implementing the carbon monoxide monitoring and oxygen trim control, an improvement in the heating plants efficiency by approximately 3% in heating plant 1 and approximately 5% in heating plant 2.
- Efficiency calculations for a 37MW coal fired boiler in Edendale, Fonterra, have shown that by reducing excess air by 2 %, a boiler's efficiency increases by 1.1%. Reduction in excess air may be achieved by implementing a carbon monoxide monitoring and oxygen trim control.

RECOMMENDATIONS

Despite achieving important results from the project, there are number of areas in which more work can be done, these are detailed below:

Confirming the improvement of trim control

Standard trials and analysis can be done to show that for specific sites the efficiency of the carbon monoxide monitoring and oxygen trim control can be improved. This can be done by one of two methods. Firstly, by comparing the flue gas efficiency when running the heating plant with the trim control and when the trim control is turned off or set to manual. Secondly, by running the tests on the heating plant using the British Standards For Assessing Thermal Performance Of Heating Plants For Steam, Hot Water And High Temperature Fluids – Part 1.

The heat energy calculations contain some specified values, as some of the variables could not be obtained directly. In addition, an operating heating plant undergoes a lot of variations which cannot be determined and therefore considered in the calculations. It is therefore, important to perform real world tests on actual sites to reinforce and complement the standardised analysis that are normally done.

Calibration of the trim control

The trim control would require calibration once a year. A heating plant is sensitive to a lot of variations influenced by the fuel composition, ambient temperature and conditions, moisture, humidity, etc... As these factors change, new settings for the trim control may be required. This would ensure the heating plants maintained maximum efficiency.

Regular efficiency tests

As mentioned in Section 1.4, regular efficiency tests are very important when managing an industrial heating plant. Carrying out continuous efficiency tests provides a good study of a heating plant's performance and an indication of whether there is any room for improvement or adjustment to a heating plant's instruments. It also indicates faults that may exist within a heating plant.

A small change in a heating plant's efficiency may have a significant impact on the cost and the economic performance of the heating plant (Wulfinghoff, 1999).

APPENDICES

In developing the carbon monoxide monitoring and oxygen trim control a lot of research was undertaken by the author into developing the most suitable control method for Hyne & Son's heating plants. Below are the algorithms that were transformed from the process diagrams introduced by Dukelow (1990) (figures 25, 27 & 28).

Dukelow's trim control loops were the starting point in developing the programming of the trim control. The programming codes were created in Sequential Function Chart (SFC) and Structure Text. The codes were created based on IEC61131-3 standard using RSLogix5000 from Rockwell software.

Figure 29 is a smothering algorithm which was suggested by RCR Energy Systems.

The following algorithms were used to assist in developing the final model.

Carbon monoxide monitoring and oxygen trim control (cascade control loop)

Working strategy of the trim control arrangement is shown in Figure 25:

- Is connected in a cascade loop.
- The setpoints for both carbon monoxide and oxygen is determined by the specified heating plant operating load signal.
- The output from the carbon monoxide controller manipulates the oxygen setpoint. The output from the carbon monoxide controller acts as a manipulated variable for the oxygen setpoint.
- The oxygen setpoint can be determined by multiplying the output from the carbon monoxide controller based on the specified ratio between carbon monoxide and oxygen. The ratio is determined from the heating plant performance.
- The trimmed signal from the oxygen controller will bias the force draft fan which produce air for combustion in the furnace.
- The carbon monoxide controller to be tuned with a smaller gain compare to that of the oxygen controller. Since carbon monoxide variable is very sensitive, the difference between low levels (<200ppm) and high levels (>2000ppm) can be 0.1% to 0.2 % mole fraction of oxygen.
- The SFC of the cascade control loop is shown in Figure 26.

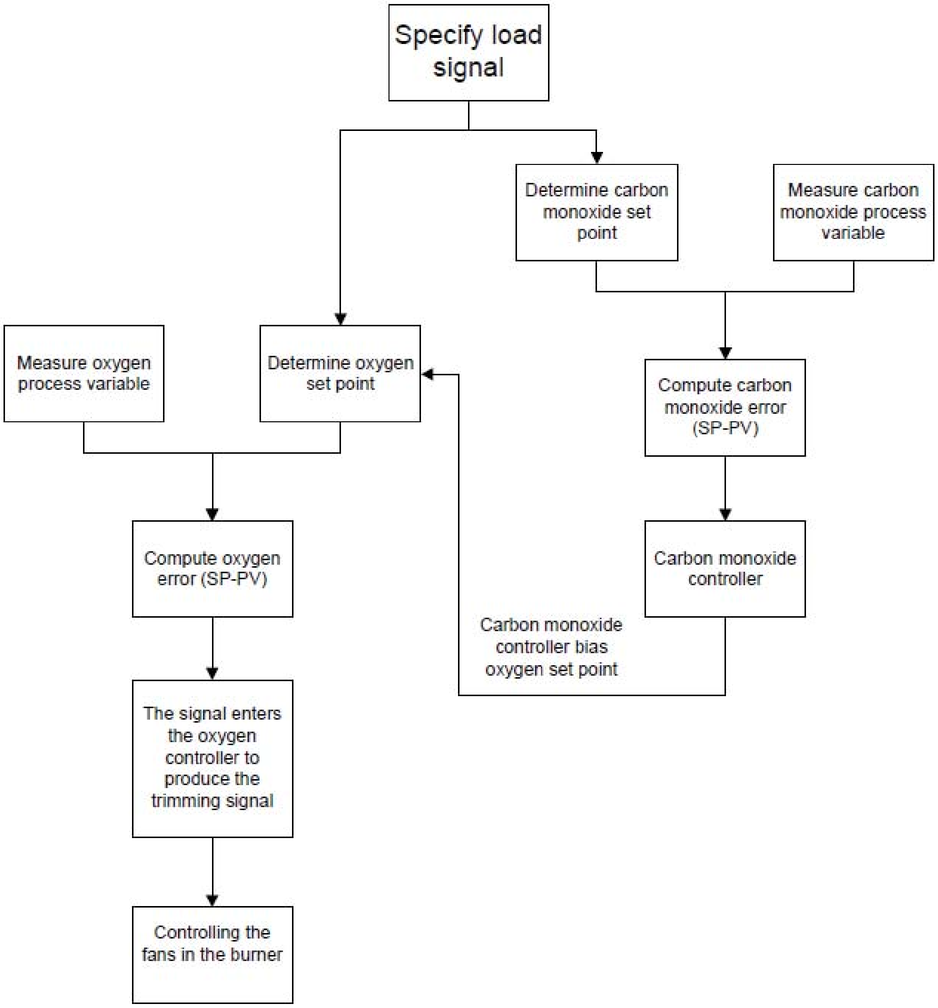


Figure 25: Carbon monoxide monitoring and oxygen trim control algorithm (Cascade control) (Dukelow, 1991)

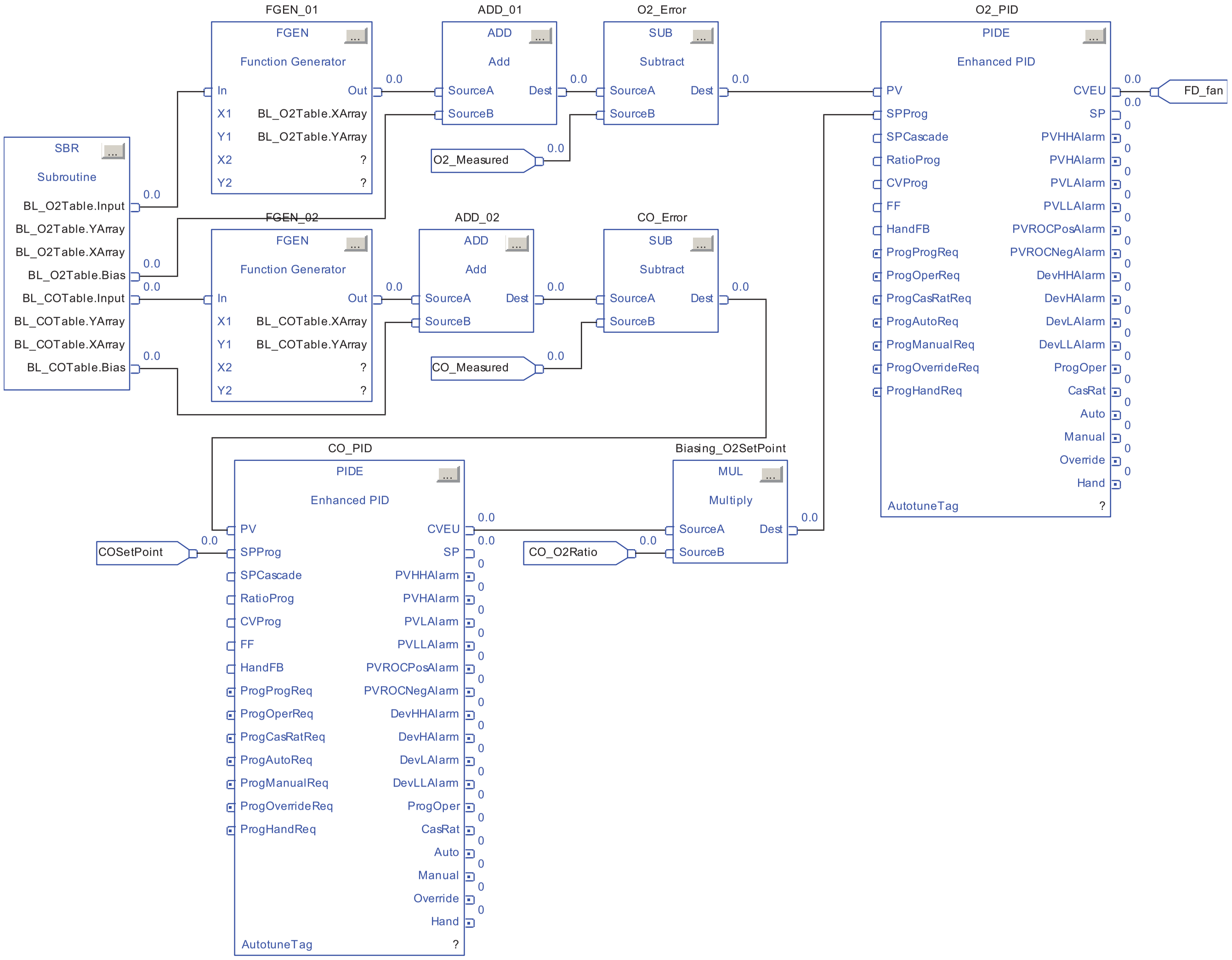


Figure 26: Carbon monoxide monitoring and oxygen trim control SFC (Cascade control)

Carbon monoxide monitoring and oxygen trim control (cascade control loop) – Structured Text

```
Program CO_O2_TrimController
var

Operating_Load: REAL;
CO_SetPoint: REAL;
O2_SetPoint:REAL;
CO_Measured: REAL;  (* Measured from the plant*)
StepChange: REAL := 7;
CO_O2_Ratio:REAL := ....; (* The ratio will be calculated based on a trend *)
O2_SetPoint_Biased: REAL;
CO_Inverted: REAL;
O2_Measured: REAL; (* Measured from the plant*)
CO_Error: REAL;
O2_Error: REAL;

end_var;

(*CO trim control biasing O2 Trim Control*)
(*Value from a look-up table based on a trend function*)
If Operating_Load_Signal:=50 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=50 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=60 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=70 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=80 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=90 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=100 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
end_if

(* CO PID controller *)
CO_PID.PV := CO_Measured;
CO_PID.SPProg := CO_SetPoint;

(*Biasing O2_Setpoint *)
O2_SetPoint_Biased:= CO_PID.CVEU * CO_O2_Ratio; (*CO_O2 ration can be determined from the trend plot that can be produced after implementing CO plus O2 trim controller*)

(*O2 PID controller *)
O2_PID.PV:= O2_Measured;
O2_PID.SPProg := O2_SetPoint_Biased;
O2_PID.CVEU := FD_fan;

Program Smothering (*Calling smothering function to check for smothering*)

end_Program
```

Trim control using single control arrangement

Working strategy of the trim control arrangement is shown in Figure 27:

- Carbon monoxide and oxygen are connected to use one controller.
- The setpoints from both carbon monoxide and oxygen are determined from the heating plant performance.
- The carbon monoxide process variable is inverted and matched to the oxygen signal.
- The lower error value between carbon monoxide and oxygen is selected.
- Another selection to be made between the selected lower error value and the oxygen error.
- The selected higher value enters the controller and manipulates the force draft fan which supplies excess air to the furnace.
- The SFC of the control loop is shown in Figure 28.

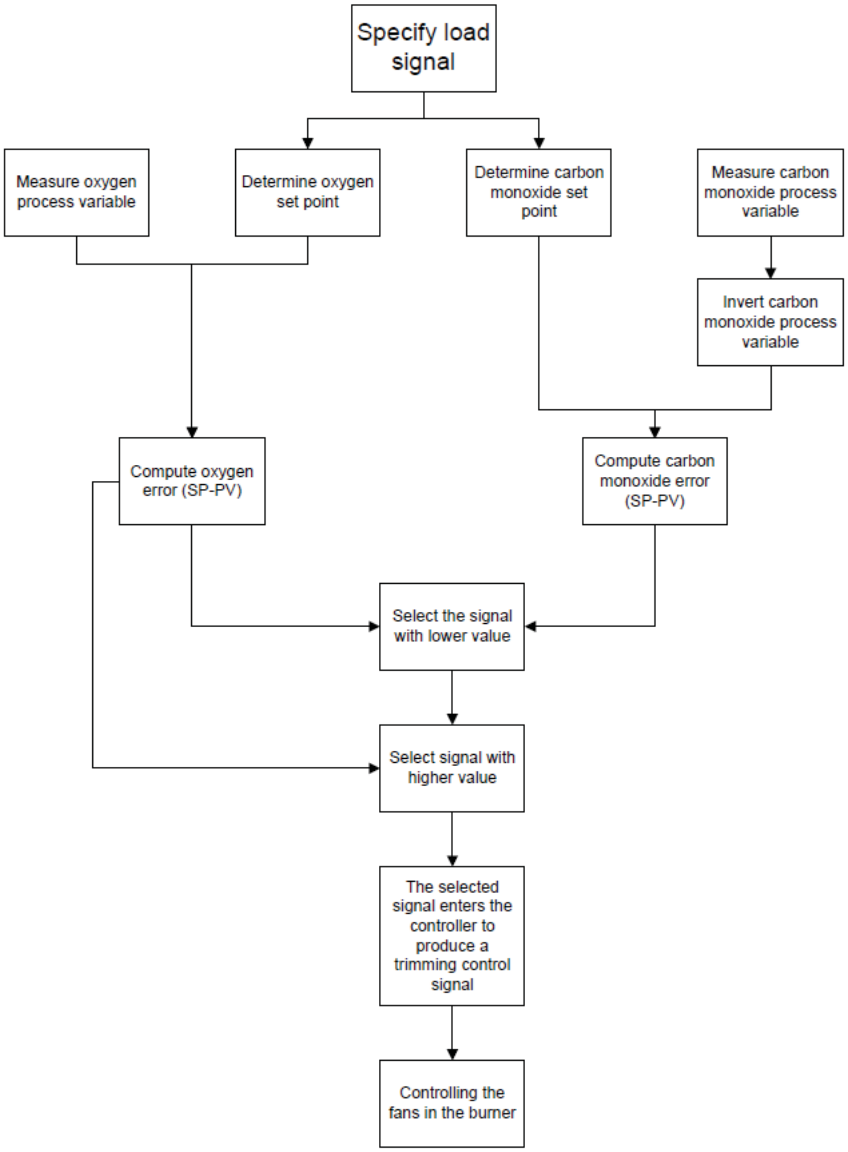


Figure 27: Carbon monoxide monitoring and oxygen trim control algorithm (Single control) (Dukelow, 1991)

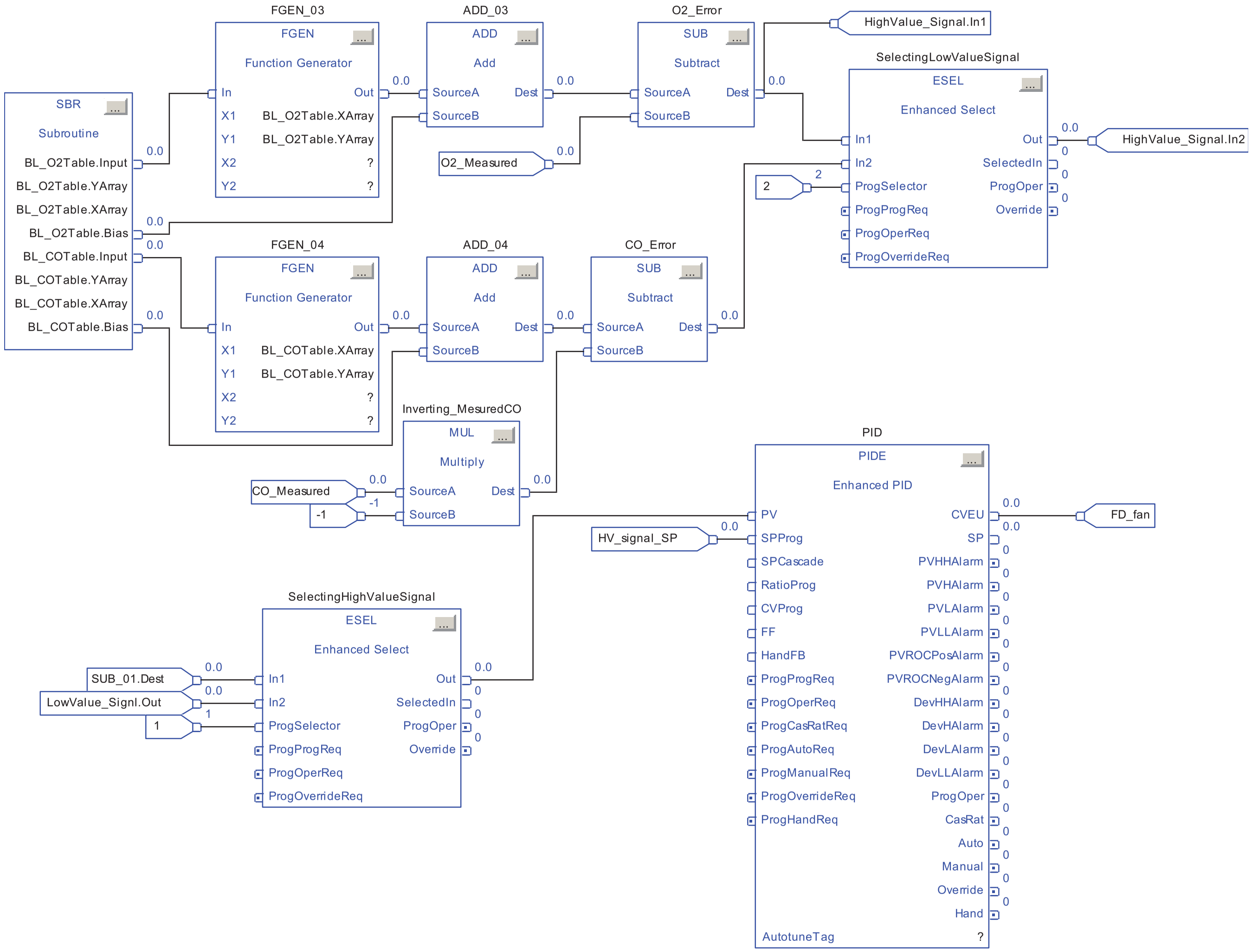


Figure 28: Carbon monoxide monitoring and oxygen trim control SFC (Single control)

Trim control using single control arrangement - Structured Text

```
Program CO_O2_TrimController
var
Operating_Load_Signal: SINT;
CO_SetPoint: REAL;
O2_SetPoint: REAL;
SetPoint: REAL;
CO_Measured: REAL; (*value measured directly from the plant*)
CO_Inverted: REAL;
O2_Measured: REAL; (*value measured directly from the plant*)
HV_Error: REAL;
previous_error: REAL;
LV_Signal: REAL;
HV_Signal: REAL;
HV_Signal_SetPoint: REAL;
end_var;

(*CO trim control biasing O2 Trim Control*)
(*Value from a look-up table based on a trend function*)
If Operating_Load_Signal:=50 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=50 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=60 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=70 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=80 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=90 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
        else_if Operating_Load_Signal:=100 then
CO_SetPoint:= ...& O2_SetPoint:=.....;
end_if

(*Calculating the errors*)
CO_Inverted:= CO_Measured * -1;
CO_Error:= CO_SetPoint - CO_Inverted;
O2_Error:= O2_SetPoint - O2_Measured;

(*Selecting the lower signal value*)
If CO_Error > O2_Error then
LV_Signal:= O2_Error;
Else_if CO_Error < O2_Error then
LV_Signal:= CO_Error;
end_if;

(*Selecting the higher signal value*)
If O2_Error> LV_Signal then
HV_Signal:= O2_Error;
Else_if O2_Error< LV_signal then
HV_Signal:= LV_Signal;
end_if;

(* PID controller *)
PID.PV:= HV_Signal;
PID.SPProg := SetPoint;
PID.CVEU := FD_fan;


Program Smothering (*Calling smothering function to check for smothering*)

end_Program
```

Smothering control system

Working strategy of the smothering control system is shown in Figure 29:

- Disable the carbon monoxide monitoring and oxygen trim controller.
- Increasing the level of oxygen in the burner to burn fuel by a step change up of the amount of the current air percentage.
- When the burner has overcome smothering, the air percentage will gradually be reduced to the setpoint value.
- The SFC of the smothering control system is shown in Figure 31.

This could be connected as shown in Figure 30.

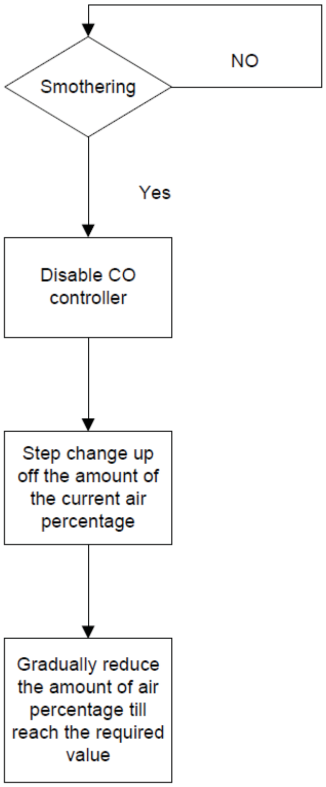


Figure 29: Smothering algorithm

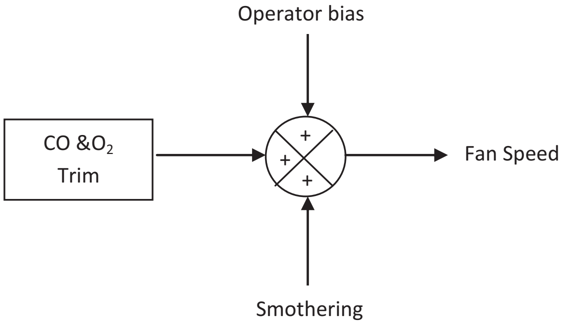


Figure 30: Connection strategy of the smothering control system

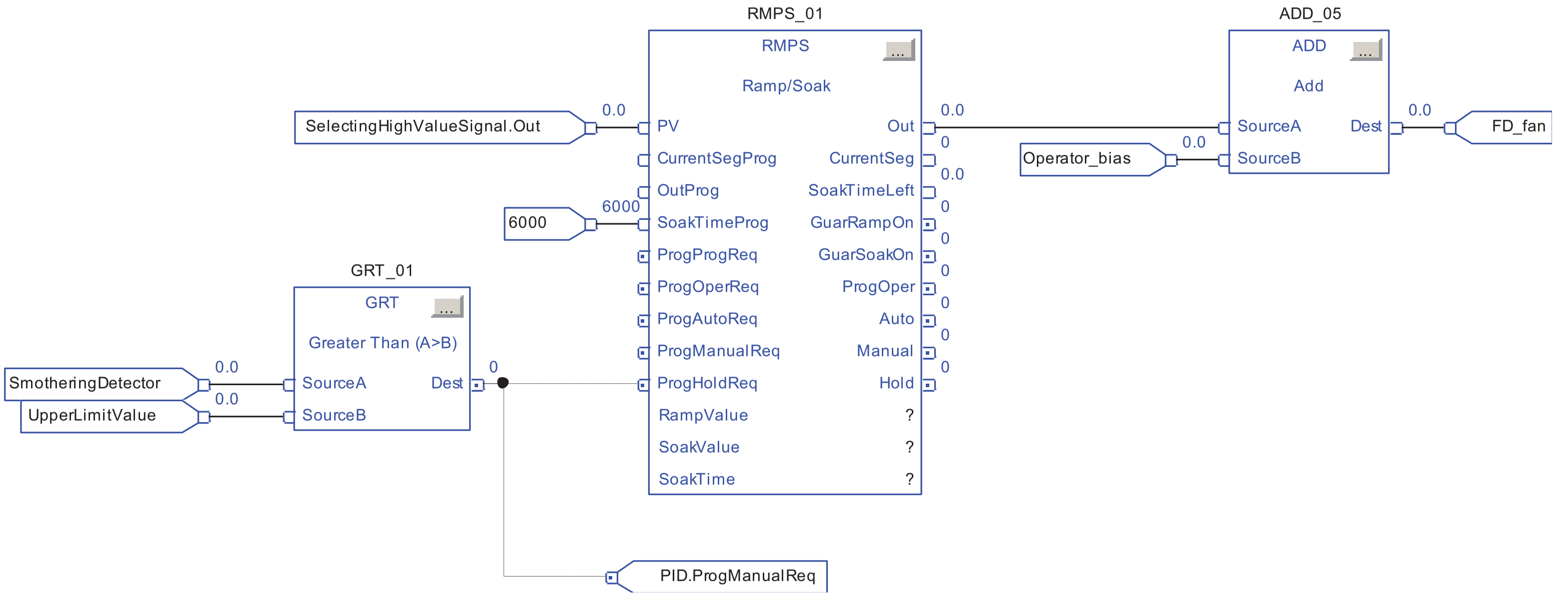


Figure 31: Smothering control system SFC

Smothering control system - Structured Text

```
(*Smothering detection*)

if Smothering_Detector_value> ....... then
(*Direct measurement of the smothering
detector from the plant*)

            PID.ProgManualReg:= 1; (*Setting the
PID controller to manual mode*)

            FD_fan_New :=  FD_fan_Current +
StepChange; (* Applying a step change up off
the amount of the current air flow into the
furnace*)

            FD_fan_Old [I]:= FD_fan_New; (*
Setting the old fan speed value with the new
value to increase the air into the furnace *)

end_if;


(* Having a delay of 10 minutes till the furnace
recover from smothering before returning the
fan speed to its original value *)

TimeDelay.Preset := 600000;

TONR_O1.Reset := reset;

TimeDelay.TimerEnable := Limit_switch1;

TONR(TONR_01)

timer_state := TONR_01.DN;


(*Reducing the inlet air gradually to the normal
required value before the step change*)

Step:= FD_fan_New /x; (* The inlet air could
be reduced gradually with a rate of x*)


For I:=1 to x by 1 DO


            FD_fan_ModifedToNormalValue[I] :=
FD_fan_Old [I]  -  Step;

    FD_fan_Current:= FD_fan_
ModifedToNormalValue [i];

            FD_fan_Old [i]:= FD_fan_
ModifedToNormalValue [i];

end_for;


PID.ProgManualReg:= 0; (*Setting the manual
mode off *)



end_program
```

APPENDIX 2: PROCESS TIME DELAY

This appendix shows the estimate of the process time delay of the oil close loop in the Hyne & Son heating plants.

The cross-correlation calculation of the process time delay was carried out between the inlet and outlet oil temperatures. It is a process delay of the oil to complete one cycle from when it leaves the combustion section and returns back again to be reheated.

The cross-correlation calculations were done using the time series tool in MatLab. Cross-correlation was performed at different period of times and days for both heating plants. Figure 32 shows an example of a cross-correlation plot from the plant, indicating a lag of 5 miuntes as the highest correlation and therefore a delay time of 5 minutes. Tables 11 and 12 show the time delays. These are not consistent in each of the heating plants. This is because the oil cycle loop period is not consistent. The heating plants produce power for wood treatment. The period of the oil cycle loop is longer when it has to pass through the parallel heat exchanger of the kiln bins, which are used to dry the wood or when it passes through the parallel heat exchanger of the reconditioning bins which are used for adding moisture into the wood.

Table 11: Heating plant 1 process time delay of the oil close loop

Heating plant 1		
Date	**Sample Period**	**Delay Time (minutes)**
21/10/2010	8:01:00 a.m. - 8:30:00 a.m.	2
27/10/2010	6:01:00 a.m. - 6:30:00 a.m.	2
5/11/2010	19:01:00 p.m. - 19:30:00 p.m.	5
12/11/2010	3:01:00 a.m. - 3:30:00 a.m.	6

Table 12: Heating plant 2 process time delay of the oil close loop

Heating plant 2		
Date	**Sample Period**	**Delay Time (minutes)**
10/10/2010	7:01:00 a.m. - 7:30:00 a.m.	2
21/10/2010	22:01:00 a.m. - 22:30:00 a.m.	3
12/11/2010	3:01:00 a.m. - 3:30:00 a.m.	3

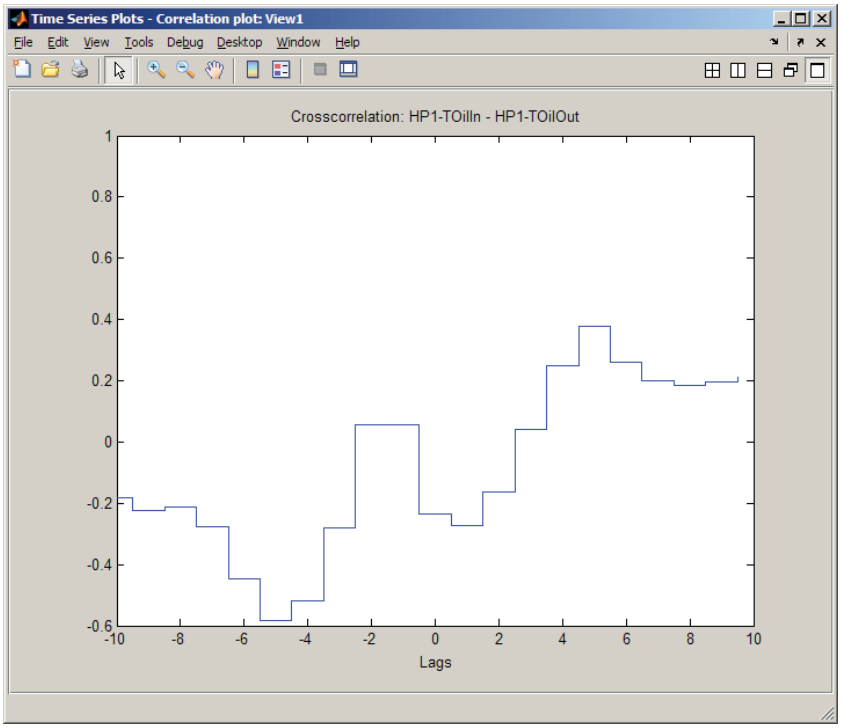


Figure 32: Heating plant 1 oil close loop process time delay cross-correlation plot

APPENDIX 3: ABB SMA 90 STACK GAS MONITORING SYSTEM FEATURES

This appendix includes the specification features of the ABB analyser units which are installed at the Hyne & Son heating plants.

Sensor Response Times 63% Span

O_2 <3.5s

COe <13s

Adjustable Span

O_2: 0-5% to 0-25%

CO_e: 0-200ppm to 0-20000ppm

Accuracy

O_2: +/-2.5% of span

CO_e: +/-20ppm

Output signals

Four analogue outputs:

AO1: Process O_2

AO2: Process CO_e

AO3: Inlet/Outlet temperature

AO4: Process combustion efficiency

Six relay alarm outputs:

DO1: Process O_2

DO2: Process CO_e

DO3: Process temperature alarm

DO4: Combustion efficiency alarm

DO5: Analyser fault alarm

DO6: Calibration in progress

Cable/Probe and Filter

Cable length from probe to electronics 54 (177ft) meters (longer lengths available).

Low temperature probe and dual filter (1649°C) 1 .57M for high particulates.

Filter blow back solenoid, and dual filter system.

Two stage Instrument air filter.

Sampling System

Patented close-couple sample system.

Measurements unaffected by CO_2, water vapour or particulates.

Product Code

SMA2.S.3.2.1

(ABB Ltd, 2010b)

APPENDIX 4: PHOTOS - ANALYSER UNIT AT THE HEATING PLANT

This appendix includes the photos of the analyser units installed at Hyne & Son heating plants.

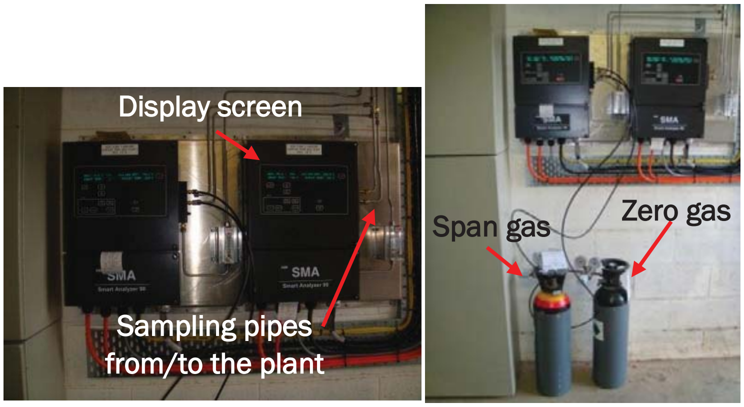


Figure 33: ABB carbon monoxide monitoring and oxygen trim control analyser units

Figure 33 shows the ABB carbon monoxide of a type SMA carbon monoxide/oxygen trim unit analyser installed in Hyne & Son heating plant 1 and heating plant 2.

Figure 34 shows a close up view of the carbon monoxide/oxygen analyser installed at the plant close to the stack. It is located after the convection coils.

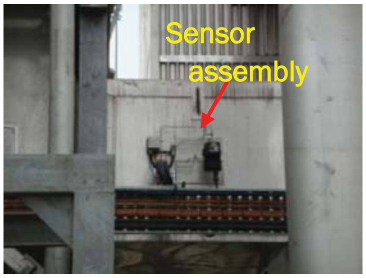


Figure 34: Close view of carbon monoxide monitoring and oxygen analyser installed at the heating plants

Figure 35: Far view of carbon monoxide/oxygen analyser Located at the plant (heating plant 1)

Figure 35 shows a far view of the carbon monoxide monitoring and oxygen sensor assembly located between the convection coils and the hopper.

APPENDIX 5: EFFICIENCY IMPROVEMENT CALCULATIONS

Appendix 5 includes the variables and calculations involved in the efficiency improvement calculations based on heat energy functions across the heating plants. Table 13 shows the nomenclature used in the calculations.

The Appendix includes three subsections:

- Appendix 5a: Hyne & Sons heating plants data
- Appendix 5b: Heat transfer oil thermal properties and flow rate
- Appendix 5c: Specific heat capacity of flue and furnace air temperatures

Table 13: Nomenclature for heat energy calculations

Variable	**Description**	**Unit**
$COSP_{HP1}$	Heating plant 1 carbon monoxide setpoint	ppm
$COSP_{HP2}$	Heating plant 2 carbon monoxide setpoint	ppm
COT_{PH1}	Heating plant 1 carbon monoxide transmitter	ppm
COT_{PH2}	Heating plant 2 carbon monoxide transmitter	ppm
Cp_{AmbHP1}	Heating plant 1 ambient temperature specific heat capacity	J/kg. °C
Cp_{AmbHP2}	Heating plant 2 ambient temperature specific heat capacity	J/kg. °C
$Cp_{FlueHP1}$	Heating plant 1 flue gas temperature specific heat capacity	J/kg. °C
$Cp_{FlueHP2}$	Heating plant 2 flue gas temperature specific heat capacity	J/kg. °C
$Cp_{FurnHP1}$	Heating plant 1 furnace air temperature specific heat capacity	J/kg. °C
$Cp_{FurnHP2}$	Heating plant 2 furnace air temperature specific heat capacity	J/kg. °C
Cp_{HEP1}	Heating plant 1 heat exchanger outlet air temperature specific heat capacity	J/kg. °C
Cp_{HEP2}	Heating plant 2 heat exchanger outlet air temperature specific heat capacity	J/kg. °C
$Cp_{OilHP1(33\%Texa+67\%Prf)}$	Heating plant 1 heat transfer oil specific heat capacity (33% Texatherm 32 + Perfecto HT12)	J/kg. °C
$Cp_{OilHP2(33\%Texa+67\%Prf)}$	Heating plant 2 heat transfer oil specific heat capacity (33% Texatherm 32 + Perfecto HT12)	J/kg. °C
$Cp_{OilInHP1Prf}$	Heating plant 1 Perfecto HT12 inlet oil specific heat capacity	J/kg. °C
$Cp_{OilInHP1Texa}$	Heating plant 1 Texatherm 32 inlet oil specific heat capacity	J/kg. °C
$Cp_{OilInHP2Prf}$	Heating plant 2 Perfecto HT12 inlet oil specific heat capacity	J/kg. °C
$Cp_{OilInHP2Texa}$	Heating plant 2 Texatherm 32 inlet oil specific heat capacity	J/kg. °C
$Cp_{OilOutHP1Prf}$	Heating plant 1 Perfecto HT12 outlet oil specific heat capacity	J/kg. °C
$Cp_{OilOutHP1Texa}$	Heating plant 1 Texatherm 32 outlet oil specific heat capacity	J/kg. °C
$Cp_{OilOutHP2Prf}$	Heating plant 2 Perfecto HT12 outlet oil specific heat capacity	J/kg. °C
$Cp_{OilOutHP2Texa}$	Heating plant 2 Texatherm 32 outlet oil specific heat capacity	J/kg. °C
E_{HP1}	Heating plant 1 efficiency improvement	%
E_{HP2}	Heating plant 2 efficiency improvement	%
F_{AirHP1}	Heating plant 1air flow rate	kg/s
$F_{AirHP1+2\%}$	Heating plant 1 air flow rate with 2% increase in excess air	kg/s
F_{AirHP2}	Heating plant 2air flow rate	kg/s
$F_{AirHP2+2\%}$	Heating plant 2 air flow rate with 2% increase in excess air	kg/s
F_{OilHP1}	Heating plant 1 oil flow rate	kg/s
$F_{OilHP1(33\%Texa+67\%Prf)}$	Heating plant 1 oil flow rate (33% Texatherm 32 + Perfecto HT12)	kg/s
F_{OilHP2}	Heating plant 2 oil flow rate	kg/s
$F_{OilHP2(33\%Texa+67\%Prf)}$	Heating plant 2 oil flow rate (33% Texatherm 32 + Perfecto HT12)	kg/s
$F_{OilInHP1Prf}$	Heating plant 1 Perfecto HT12 inlet oil flow rate	kg/s

$F_{OilInHP1Texa}$	Heating plant 1 Texatherm 32 inlet oil flow rate	kg/s
$F_{OilInHP2Prf}$	Heating plant 2 Perfecto HT12 inlet oil flow rate	kg/s
$F_{OilInHP2Texa}$	Heating plant 2 Texatherm 32 inlet oil flow rate	kg/s
$F_{OilOutHP1Prf}$	Heating plant 1 Perfecto HT12 outlet oil flow rate	kg/s
$F_{OilOutHP1Texa}$	Heating plant 1 Texatherm 32 outlet oil flow rate	kg/s
$F_{OilOutHP2Prf}$	Heating plant 2 Perfecto HT12 outlet oil flow rate	kg/s
$F_{OilOutHP2Texa}$	Heating plant 2 Texatherm 32 outlet oil flow rate	kg/s
FR_{HP1}	Heating plant 1 firing rate	%
FR_{HP2}	Heating plant 2 firing rate	%
FR_{HP2}	Heating plant 2 firing rate	%
O_2SP_{HP1}	Heating plant 1 oxygen setpoint	%
O_2SP_{HP2}	Heating plant 2 oxygen setpoint	%
O_2T_{HP1}	Heating plant 1 oxygen transmitter	%
O_2T_{HP2}	Heating plant 2 oxygen transmitter	%
$\rho_{OilHP1(33\%Texa+67\%Prf)}$	Heating plant 1 oil density (33% Texatherm 32 + Perfecto HT12)	kg/m^3
$\rho_{OilHP2(33\%Texa+67\%Prf)}$	Heating plant 2 oil density (33% Texatherm 32 + Perfecto HT12)	kg/m^3
$\rho_{OilInHP1Prf}$	Heating plant 1 Perfecto HT12 inlet oil density	kg/m^3
$\rho_{OilInHP1Texa}$	Heating plant 1 Texatherm 32 inlet oil density	kg/m^3
$\rho_{OilInHP2Prf}$	Heating plant 2 Perfecto HT12 inlet oil density	kg/m^3
$\rho_{OilInHP2Texa}$	Heating plant 2 Texatherm 32 inlet oil density	kg/m^3
$\rho_{OilOutHP1Prf}$	Heating plant 1 Perfecto HT12 outlet oil density	kg/m^3
$\rho_{OilOutHP1Texa}$	Heating plant 1 Texatherm 32 outlet oil density	kg/m^3
$\rho_{OilOutHP2Prf}$	Heating plant 2 Perfecto HT12 outlet oil density	kg/m^3
$\rho_{OilOutHP2Texa}$	Heating plant 2 Texatherm 32 outlet oil density	kg/m^3
$Q_{AirinHP1}$	Heating plant 1 air inlet power	MW
$Q_{AirinHP2}$	Heating plant 2 air inlet power	MW
$Q_{AirinNewHP1}$	Heating plant 1 air inlet power with 2% increase in excess air	MW
$Q_{AirinNewHP2}$	Heating plant 2 air inlet power with 2% increase in excess air	MW
$Q_{CombHP1}$	Heating plant 1 power generated in combustion zone	MW
$Q_{CombHP2}$	Heating plant 2 power generated in combustion zone	MW
$Q_{CombNewHP1}$	Heating plant 1 power generated in combustion zone with 2% increase in excess air	MW
$Q_{CombNewHP2}$	Heating plant 2 power generated in combustion zone with 2% increase in excess air	MW
$Q_{AirinHP1}$	Heating plant 1 air inlet power	MW
$Q_{AirinHP2}$	Heating plant 2 air inlet power	MW
Q_{HP1}	Heating plant 1 output power	MW
Q_{HP2}	Heating plant 2 output power	MW
Q_{NewHP1}	Heating plant 1 output power with 2% increase in excess air	MW
Q_{NewHP2}	Heating plant 2 output power with 2% increase in excess air	MW
$Q_{SteamHP1}$	Heating plant 1 steam power	MW
$Q_{SteamHP2}$	Heating plant 2 steam power	MW
$Q_{SteamNewHP1}$	Heating plant 1 steam power with 2% increase in excess air	MW
$Q_{SteamNewHP2}$	Heating plant 2 steam power with 2% increase in excess air	MW
T_{AmbHP1}	Heating plant 1 ambient temperature	°C
T_{AmbHP2}	Heating plant 2 ambient temperature	°C
$T_{FlueHP1}$	Heating plant 1 flue gas temperature	°C
$T_{FlueHP2}$	Heating plant 2 flue gas temperature	°C
$T_{FlueNewHP1}$	Heating plant 1 flue gas temperature with 2% increase in excess air	°C
$T_{FlueNewHP2}$	Heating plant 2 flue gas temperature with 2% increase in excess air	°C
$T_{FurnHP1}$	Heating plant 1 furnace air temperature	°C

$T_{FurnHP2}$	Heating plant 2 furnace air temperature	°C
$T_{FurnNewHP1}$	Heating plant 1 furnace air temperature with 2% increase in excess air	°C
$T_{FurnNewHP2}$	Heating plant 2 furnace air temperature with 2% increase in excess air	°C
T_{HEHP1}	Heating plant 1 heat exchanger outlet air temperature	°C
T_{HEHP2}	Heating plant 2 heat exchanger outlet air temperature	°C
$T_{HENewHP1}$	Heating plant 1 heat exchanger outlet air temperature with 2% increase in excess air	°C
$T_{HENewHP2}$	Heating plant 2 heat exchanger outlet air temperature with 2% increase in excess air	°C
T_{HHP1}	Heating plant 1 heater outlet air temperature	°C
T_{HHP2}	Heating plant 2 heater outlet air temperature	°C
$T_{OilInHP1}$	Heating plant 1 inlet oil temperature	°C
$T_{OilInHP2}$	Heating plant 2 inlet oil temperature	°C
$T_{OilInNewHP1}$	Heating plant 1 inlet oil temperature with 2% increase in excess air	°C
$T_{OilInNewHP2}$	Heating plant 2 inlet oil temperature with 2% increase in excess air	°C
$T_{OilOutHP1}$	Heating plant 1 outlet oil temperature	°C
$T_{OilOutHP2}$	Heating plant 2 outlet oil temperature	°C
$T_{OilOutNewHP1}$	Heating plant 1 outlet oil temperature with 2% increase in excess air	°C
$T_{OilOutNewHP2}$	Heating plant 2 outlet oil temperature with 2% increase in excess air	°C
UA_{HP1}	Heating plant 1 heat transfer coefficient x Area	W/°C
UA_{HP2}	Heating plant 2 heat transfer coefficient x Area	W/°C
ΔT_{HP1}	Heating plant 1 log temperature difference	°C
ΔT_{HP2}	Heating plant 2 log temperature difference	°C

APPENDIX 5a: HYNE & SONS HEATING PLANTS DATA

Appendix 5a includes tables 14 and 15 of imported variables from Hyne & Sons heating plants data log. It also includes variables calculated from the data log variables. The uncertainties of the variables were determined using the standard error method. A 95% confidence interval was calculated for the final efficiency values for both heating plants (E_{HP1} & E_{HP2}). Variables marked with a references such as (1) or (A5b), refer to the appendix or set of calculation equations which shows how it is calculated (the references are located pages 93 - 101).

Colour code:

Recorded Variable (Imported from heating plant data log)
Calculated Variable
Mean
Deviation
Standard deviation
Standard error
95% Confidence interval

Table 14: Heating plant 1 imported and calculated variables with uncertainty

	Date	Time	Recorded Variable FR_{HP1} (%)	Recorded Variable O_2SP_{HP1} (%)	Recorded Variable O_2T_{HP1} (%)
	12/11/2010	05:46:00	100	4	5.43
	12/11/2010	05:47:00	100	4	5.32
	12/11/2010	05:48:00	100	4	5.77
	12/11/2010	05:49:00	100	4	4.03
	12/11/2010	05:50:00	100	4	5.51
	12/11/2010	05:51:00	100	4	4.62
Mean (11)			100	4	5.11
SD (13)					

	Recorded Variable $COSP_{HP1}$ (ppm)	Recorded Variable COT_{PH1} (ppm)	Recorded Variable Q_{HP1} (MW)	Q_{HP1} (MW) (Deviation) (11)
	400	350.4	10.55	0.43
	400	313.6	10.62	0.51
	400	347.7	10.20	0.09
	400	358.7	9.58	-0.53
	400	376.5	9.69	-0.43
	400	365.7	10.04	-0.07
Mean (11)	400	352.1	10.11	
SD (13)				0.43
SE (14)				0.18

	Recorded Variable T_{AmbHP1} (°C)	T_{AmbHP1} (°C) (Deviation) (12)	Recorded Variable F_{OilHP1} (m^3/h)	F_{OilHP1} (m^3/h) (Deviation) (12)
	23.23	-0.07	680.69	0.73
	22.99	-0.31	681.30	1.35
	23.01	-0.30	677.67	-2.29
	23.34	0.04	682.27	2.31
	23.54	0.24	677.82	-2.13
	23.69	0.39	679.98	0.02
Mean (11)	23.30		679.95	
SD (13)		0.28		1.87
SE (14)		0.12		0.76

	Recorded Variable $T_{OilinHP1}$ (°C)	$T_{OilinHP1}$ (°C) (Deviation) (12)	Recorded Variable $T_{OilOutHP1}$ (°C)	$T_{OilOutHP1}$ (°C) (Deviation) (12)
	224.69	0.10	252.54	1.16
	224.51	-0.08	251.39	0.01
	224.90	0.31	250.62	-0.76
	224.53	-0.06	251.00	-0.39
	224.49	-0.10	251.53	0.15
	224.42	-0.17	251.22	-0.16
Mean (11)	224.59		251.38	
SD (13)		0.18		0.65
SE (14)		0.07		0.27

	Recorded Variable $T_{FlueHP1}$ (°C)	$T_{FlueHP1}$ (°C) (Deviation) (12)	Recorded Variable $T_{FurnHP1}$ (°C)	$T_{FurnHP1}$ (°C) (Deviation) (12)
	293.20	0.55	1089.77	11.81
	292.72	0.08	1080.76	2.79
	292.56	-0.08	1070.24	-7.73
	292.48	-0.16	1070.35	-7.62
	292.47	-0.17	1079.06	1.09
	292.43	-0.21	1077.63	-0.34
Mean (11)	292.64		1077.97	
SD (13)		0.29		7.30
SE (14)		0.12		2.98

	Recorded Variable T_{HEHP1} (°C)	T_{HEHP1} (°C) (Deviation) (12)	Recorded Variable T_{HHP1} (°C)	T_{HHP1} (°C) (Deviation) (12)
	82.99	0.07	252.05	0.11
	82.92	0.00	252.07	0.13
	82.96	0.04	252.12	0.17
	83.05	0.14	252.13	0.18
	82.83	-0.09	251.72	-0.23
	82.75	-0.16	251.59	-0.36
Mean (11)	82.92		251.95	
SD (13)		0.11		0.23
SE (14)		0.04		0.09

	Calculated Variable $Cp_{FurnHP1}$ (J/kg.°C) (A5c)	$Cp_{FurnHP1}$ (J/kg.°C) (Deviation) (12)	Calculated Variable $Cp_{FlueHP1}$ (J/kg.°C) (A5c)	$Cp_{FlueHP1}$ (J/kg.°C) (Deviation) (12)
	1418.38	3.85	1220.99	1.04
	1415.16	0.64	1218.42	-1.53
	1412.12	-2.41	1219.85	-0.10
	1412.14	-2.39	1220.80	0.85
	1414.82	0.30	1219.83	-0.12
	1414.53	0.01	1219.82	-0.13
Mean (11)	1414.53		1219.95	
SD (13)		2.32		0.91
SE (14)		0.95		0.37

	Calculated Variable F_{AirHP1} (kg/s) (1)	F_{AirHP1} (kg/s) (Deviation) (12)	Calculated Variable $F_{AirHP1+2\%}$ (kg/s) (2)	$F_{AirHP1+2\%}$ (kg/s) (Deviation) (12)
	-10.03	-0.26	-10.23	-0.26
	-10.23	-0.46	-10.44	-0.47
	-9.97	-0.19	-10.17	-0.20
	-9.35	0.42	-9.54	0.43
	-9.35	0.43	-9.54	0.43
	-9.71	0.06	-9.91	0.06
Mean (11)	-9.77		-9.97	
SD (13)		0.37		0.38
SE (14)		0.15		0.15

	Calculated Variable $T_{HENewHP1}$ (°C) (3)	$T_{HENewHP1}$ (°C) (Deviation) (12)	Calculated Variable $T_{FurnNewHP1}$ (°C) (4)	$T_{FurnNewHP1}$ (°C) (Deviation) (12)
	81.81	0.07	1068.86	11.57
	81.74	-0.01	1060.02	2.73
	81.78	0.04	1049.70	-7.59
	81.88	0.13	1049.82	-7.47
	81.67	-0.08	1058.36	1.07
	81.60	-0.15	1056.96	-0.32
Mean (11)	81.75		1057.29	
SD (13)		0.10		7.16
SE (14)		0.04		2.92

	Calculated Variable $T_{FlueNewHP1}$ (°C) (5)	$T_{FlueNewHP1}$ (°C) (Deviation) (12)	Calculated Variable ΔT_{HP1} (°C) (6)	ΔT_{HP1} (°C) (Deviation) (12)
	287.90	0.54	269.62	1.54
	287.43	0.07	268.86	0.78
	287.28	-0.09	267.49	-0.59
	287.21	-0.16	266.78	-1.30
	287.20	-0.17	267.78	-0.31
	287.16	-0.20	267.96	-0.12
Mean (11)	287.36		268.08	
SD (13)		0.28		1.01
SE (14)		0.11		0.41

	Calculated Variable UA_{HP1} (W/°C) (7)	UA_{HP1} (W/°C) (Deviation) (12)	Calculated Variable $p_{OilInHP1Texa}$ (kg/m^3) (A5b)	$p_{OilInHP1Texa}$ (kg/m^3) (Deviation) (12)
	39119.71	1399.72	742.71	-0.07
	39496.60	1776.61	742.85	0.06
	38137.60	417.62	742.57	-0.22
	35904.05	-1815.93	742.83	0.05
	36177.84	-1542.15	742.86	0.07
	37484.11	-235.88	742.90	0.12
Mean (11)	37719.99		742.79	
SD (13)		1484.68		0.12
SE (14)		606.12		0.05

	Calculated Variable $F_{\text{OilInHP1Texa}}$ (kg/s) (A5b)	$F_{\text{OilInHP1Texa}}$ (kg/s) (Deviation) (12)	Calculated Variable $Cp_{\text{OilInHP1Texa}}$ (J/kg.°C) (A5b)	$Cp_{\text{OilInHP1Texa}}$ (J/kg.°C) (Deviation) (12)
	140.43	0.14	2601.36	0.38
	140.58	0.30	2600.67	-0.31
	139.78	-0.51	2602.14	1.15
	140.78	0.49	2600.75	-0.24
	139.87	-0.43	2600.62	-0.37
	140.32	0.03	2600.37	-0.62
Mean (11)	140.30		2600.99	
SD (13)		0.40		0.66
SE (14)		0.16		0.27

	Calculated Variable $p_{\text{OilOutHP1Texa}}$ (kg/m^3) (A5b)	$p_{\text{OilOutHP1Texa}}$ (kg/m^3) (Deviation) (12)	Calculated Variable $F_{\text{OilOutHP1Texa}}$ (kg/s) (A5b)	$F_{\text{OilOutHP1Texa}}$ (kg/s) (Deviation) (12)
	723.22	-0.81	136.75	-0.01
	724.02	-0.01	137.02	0.27
	724.57	0.53	136.39	-0.36
	724.30	0.27	137.27	0.52
	723.93	-0.10	136.30	-0.45
	724.15	0.12	136.78	0.03
Mean (11)	724.03		136.75	
SD (13)		0.46		0.37
SE (14)		0.19		0.15

	Calculated Variable $Cp_{\text{OilOutHP1Texa}}$ (J/kg.°C) (A5b)	$Cp_{\text{OilOutHP1Texa}}$ (J/kg.°C) (Deviation) (12)	Calculated Variable $p_{\text{OilHP1TexaAvg}}$ (kg/m^3) (A5b)	$p_{\text{OilHP1TexaAvg}}$ (kg/m^3) (Deviation) (12)
	2704.41	4.29	732.97	-0.44
	2700.16	0.04	733.43	0.03
	2697.29	-2.83	733.57	0.16
	2698.69	-1.43	733.57	0.16
	2700.66	0.54	733.39	-0.02
	2699.51	-0.61	733.53	0.12
Mean (11)	2700.12		733.41	
SD (13)		2.41		0.23
SE (14)		0.99		0.09

	Calculated Variable $F_{\text{OilHP1TexaAvg}}$ (kg/s) (A5b)	$F_{\text{OilHP1TexaAvg}}$ (kg/s) (Deviation) (12)	Calculated Variable $Cp_{\text{OilHP1TexaAve}}$ (J/kg.°C) (A5b)	$Cp_{\text{OilHP1TexaAve}}$ (J/kg.°C) (Deviation) (12)
	138.59	0.07	2652.89	2.34
	138.80	0.28	2650.42	-0.14
	138.09	-0.44	2649.72	-0.84
	139.03	0.50	2649.72	-0.84
	138.09	-0.44	2650.64	0.09
	138.55	0.03	2649.94	-0.61
Mean (11)	138.52		2650.55	
SD (13)		0.38		1.20
SE (14)		0.15		0.49

	Calculated Variable **$p_{OilInHP1Prf}$** (A5b)	**$p_{OilInHP1Prf}$ (kg/m^3) (Deviation)** (12)	**Calculated Variable** **$F_{OilInHP1Prf}$ (kg/s)** (A5b)	**$F_{OilInHP1Prf}$ (kg/s) (Deviation)** (12)
	762.92	-0.06	144.25	0.14
	763.03	0.05	144.40	0.29
	762.81	-0.18	143.59	-0.52
	763.02	0.04	144.61	0.50
	763.04	0.06	143.67	-0.44
	763.08	0.10	144.13	0.02
Mean (11)	762.98		144.11	
SD (13)		0.10		0.40
SE (14)		0.04		0.17

	Calculated Variable **$Cp_{OilInHP1Prf}$ (J/kg.°C)** (A5b)	**$Cp_{OilInHP1Prf}$ (J/kg.°C) (Deviation)** (12)	**Calculated Variable** **$p_{OilOutHP1Prf}$ (kg/m^3)** (A5b)	**$p_{OilOutHP1Prf}$ (kg/m^3) (Deviation)** (12)
	2625.99	5.92	747.05	-0.66
	2735.28	115.22	747.71	-0.01
	2762.13	142.06	748.15	0.44
	2502.79	-117.28	747.93	0.22
	2494.57	-125.49	747.63	-0.08
	2599.64	-20.43	747.81	0.09
Mean (11)	2620.07		747.71	
SD (13)		112.62		0.37
SE (14)		45.98		0.15

	Calculated Variable **$F_{OilOutHP1Prf}$ (kg/s)** (A5b)	**$F_{OilOutHP1Prf}$ (kg/s) (Deviation)** (12)	**Calculated Variable** **$Cp_{OilOutHP1Prf}$ (J/kg.°C)** (A5b)	**$Cp_{OilOutHP1Prf}$ (J/kg.°C) (Deviation)** (12)
	141.25	0.03	2681.79	8.23
	141.50	0.28	2791.35	117.78
	140.83	-0.39	2816.25	142.69
	141.75	0.52	2553.28	-120.29
	140.77	-0.46	2546.00	-127.57
	141.25	0.02	2652.73	-20.83
Mean (11)	141.22		2673.57	
SD (13)		0.38		114.43
SE (14)		0.15		46.72

	Calculated Variable **$p_{OilHP1PrfAvg}$ (kg/m^3)** (A5b)	**$p_{OilHP1PrfAvg}$ (kg/m^3) (Deviation)** (12)	**Calculated Variable** **$F_{OilHP1PrfAvg}$ (kg/s)** (A5b)	**$F_{OilHP1PrfAvg}$ (kg/s) (Deviation)** (12)
	754.99	-0.36	142.75	0.09
	755.37	0.02	142.95	0.29
	755.48	0.13	142.21	-0.46
	755.48	0.13	143.18	0.51
	755.33	-0.01	142.22	-0.45
	755.44	0.09	142.69	0.02
Mean (11)	755.35		142.67	
SD (13)		0.19		0.39
SE (14)		0.08		0.16

	Calculated Variable $Cp_{OilHP1PrfAve}$ (J/kg.°C) (A5b)	$Cp_{OilHP1PrfAve}$ (J/kg.°C) (Deviation) (12)	Calculated Variable $p_{OilHP1(33\%Texa+67\%Prf)}$ (kg/m^3) (A5b)	$p_{OilHP1(33\%Texa+67\%Prf)}$ (kg/m^3) (Deviation) (12)
	2653.89	7.07	747.72	-0.39
	2763.32	116.50	748.13	0.02
	2789.19	142.37	748.25	0.14
	2528.03	-118.78	748.25	0.14
	2520.29	-126.53	748.09	-0.01
	2626.19	-20.63	748.21	0.10
Mean (11)	2646.82		748.11	
SD (13)		113.52		0.20
SE (14)		46.35		0.08

	Calculated Variable $F_{OilHP1(33\%Texa+67\%Prf)}$ (kg/s) (A5b)	$F_{OilHP1(33\%Texa+67\%Prf)}$ (kg/s) (Deviation) (12)	Calculated Variable $Cp_{OilHP1(33\%Texa+67\%Prf)}$ (J/kg.°C) (A5b)	$Cp_{OilHP1(33\%Texa+67\%Prf)}$ (J/kg.°C) (Deviation) (12)
	141.38	0.08	2653.36	5.50
	141.58	0.28	2725.87	78.0
	140.85	-0.45	2742.99	95.12
	141.81	0.51	2568.02	-79.85
	140.85	-0.45	2563.13	-84.74
	141.32	0.02	2633.84	-14.02
Mean (11)	141.30		2647.87	
SD (13)		0.39		76.05
SE (14)		0.16		31.05

	Calculated Variable $T_{OilInNewHP1}$ (°C) (8)	$T_{OilInNewHP1}$ (°C) (Deviation) (12)	Calculated Variable $T_{OilOutNewHP1}$ (°C) (8)	$T_{OilOutNewHP1}$ (°C) (Deviation) (12)
	224.03	-0.21	250.95	0.79
	224.07	-0.18	250.91	0.74
	224.85	0.61	249.95	-0.21
	224.35	0.10	249.51	-0.65
	224.10	-0.15	249.81	-0.35
	224.07	-0.17	249.85	-0.32
Mean (11)	224.25		250.16	
SD (13)		0.32		0.61
SE (14)		0.13		0.25

	Calculated Variable Q_{NewHP1} (MW) (9)	Q_{NewHP1} (MW) (Deviation) (12)	Calculated Variable E_{HP1} (%) (10)	E_{HP1} (%) (Deviation) (12)
	10.10	0.44	4.47	-0.30
	10.08	0.43	5.33	0.55
	9.70	0.04	5.21	0.43
	9.16	-0.49	4.56	-0.21
	9.28	-0.37	4.38	-0.40
	9.59	-0.06	4.70	-0.07
Mean (11)	9.65		4.78	
SD (13)		0.39		0.40
SE (14)		0.16		0.16
95% CI (15)				0.39

Table 15: Heating plant 2 imported and calculated variables with uncertainty

	Date	Time	Recorded Variable FR_{HP2} (%)	Recorded Variable O_2SP_{HP2} (%)	Recorded Variable O_2T_{HP2} (%)
	12/11/2010	00:17:30	100	6.5	5.70
	12/11/2010	00:18:30	100	6.5	5.87
	12/11/2010	00:19:30	100	6.5	5.95
	12/11/2010	00:20:30	100	6.5	5.70
	12/11/2010	00:21:31	100	6.5	5.82
	12/11/2010	00:22:30	100	6.5	6.05
Mean (11)			100	6.5	5.85
SD (13)					

	Recorded Variable $COSP_{HP2}$ (ppm)	Recorded Variable COT_{PH2} (ppm)	Recorded Variable Q_{HP2} (MW)	Q_{HP2} (MW) (Deviation) (12)
	200	221.72	13.86	-0.60
	200	218.11	14.06	-0.40
	200	225.18	13.69	-0.77
	200	244.45	14.44	-0.02
	200	241.04	15.32	0.86
	200	252.70	15.38	0.92
Mean (11)	200	233.90	14.46	
SD (13)				0.73
SE (14)				0.30

	Recorded Variable T_{AmbHP2} (°C)	T_{AmbHP2} (°C) (Deviation) (12)	Recorded Variable F_{OilHP2} (m^3/h)	F_{OilHP2} (m^3/h) (Deviation) (12)
	21.28	0.15	908.21	0.44
	21.15	-0.02	905.46	-2.31
	21.05	-0.07	906.90	-0.87
	21.05	0.07	908.85	1.08
	21.12	-0.01	908.82	1.05
	21.12	-0.01	908.38	0.61
Mean (11)	21.13		907.77	
SD (13)		0.08		1.34
SE (14)		0.03		0.54

	Recorded Variable $T_{OilinHP2}$ (°C)	$T_{OilinHP2}$ (°C) (Deviation) (12)	Recorded Variable $T_{OiloutHP2}$ (°C)	$T_{OiloutHP2}$ (°C) (Deviation) (12)
	222.80	0.22	250.77	-0.79
	222.64	0.05	250.76	-0.79
	223.16	0.57	250.78	-0.78
	222.75	0.16	251.67	0.12
	222.18	-0.41	252.64	1.08
	221.98	-0.60	252.72	1.16
Mean (11)	222.58		251.56	
SD (13)		0.43		0.94
SE (14)		0.18		0.38

	Recorded Variable $T_{FlueHP2}$ (°C)	$T_{FlueHP2}$ (°C) (Deviation) (12)	Recorded Variable $T_{FurnHP2}$ (°C)	$T_{FurnHP2}$ (°C) (Deviation) (12)
	385.51	-1.81	1059.49	-13.61
	385.73	-1.59	1061.53	-11.57
	386.26	-1.06	1066.88	-6.22
	387.31	-0.01	1078.22	5.11
	388.82	1.50	1086.99	13.89
	390.30	2.97	1085.50	12.40
Mean (11)	387.32		1073.10	
SD (13)		1.90		12.09
SE (14)		0.78		4.94

	Recorded Variable T_{HEHP2} (°C)	T_{HEHP2} (°C) (Deviation) (12)	Recorded Variable T_{HHP2} (°C)	T_{HHP2} (°C) (Deviation) (12)
	67.01	0.39	269.72	-0.64
	66.85	0.23	269.86	-0.51
	66.74	0.12	270.17	-0.20
	66.60	-0.02	270.44	0.07
	66.42	-0.20	270.73	0.36
	66.10	-0.52	271.28	0.92
Mean (11)	66.62		270.37	
SD (13)		0.32		0.58
SE (14)		0.13		0.24

	Calculated Variable $Cp_{FurnHP2}$ (J/kg.°C) (A5c)	$Cp_{FurnHP2}$ (J/kg.°C) (Deviation) (12)	Calculated Variable $Cp_{FlueHP2}$ (J/kg.°C) (A5c)	$Cp_{FlueHP2}$ (J/kg.°C) (Deviation) (12)
	1409.94	-3.68	1223.65	-0.59
	1410.35	-3.27	1223.72	-0.52
	1411.44	-2.18	1223.90	-0.34
	1414.65	1.04	1224.24	0.00
	1417.81	4.20	1224.73	0.49
	1417.51	3.90	1225.20	0.96
Mean (11)	1413.62		1224.24	
SD (13)		3.54		0.62
SE (14)		1.45		0.25

	Calculated Variable F_{AirHP2} (kg/s) (1)	F_{AirHP2} (kg/s) (Deviation) (12)	Calculated Variable $F_{AirHP2+2\%}$ (kg/s) (2)	$F_{AirHP2+2\%}$ (kg/s) (Deviation) (12)
	-15.62	0.36	-15.93	0.37
	-15.80	0.18	-16.12	0.18
	-15.27	0.71	-15.57	0.73
	-15.84	0.14	-16.16	0.14
	-16.61	-0.63	-16.94	-0.64
	-16.74	-0.76	-17.08	-0.78
Mean (11)	-15.98		-16.30	
SD (13)		0.58		0.59
SE (14)		0.24		0.24

	Calculated Variable $T_{HENewHP2}$ (°C) (3)	$T_{HENewHP2}$ (°C) (Deviation) (12)	Calculated Variable $T_{FurnNewHP2}$ (°C) (4)	$T_{FurnNewHP2}$ (°C) (Deviation) (12)
	66.11	0.38	1039.13	-13.34
	65.95	0.22	1041.13	-11.35
	65.84	0.12	1046.38	-6.10
	65.71	-0.02	1057.49	5.01
	65.53	-0.20	1066.09	13.62
	65.22	-0.51	1064.63	12.16
Mean (11)	65.73		1052.47	
SD (13)		0.32		11.85
SE (14)		0.13		4.84

	Calculated Variable $T_{FlueNewHP2}$ (°C) (5)	$T_{FlueNewHP2}$ (°C) (Deviation) (12)	Calculated Variable ΔT_{HP2} (°C) (6)	ΔT_{HP2} (°C) (Deviation) (12)
	378.37	-1.77	384.40	-5.13
	378.58	-1.56	385.28	-4.25
	379.10	-1.04	387.23	-2.30
	380.13	-0.01	390.86	1.33
	381.61	1.47	394.17	4.65
	383.06	2.91	395.22	5.69
Mean (11)	380.14		389.53	
SD (13)		1.86		4.59
SE (14)		0.76		1.87

	Calculated Variable UA_{HP2} (W/°C) (7)	UA_{HP2} (W/°C) (Deviation) (12)	Calculated Variable $p_{OilInHP2Texa}$ (kg/m^3) (A5b)	$p_{OilInHP2Texa}$ (kg/m^3) (Deviation) (12)
	36056.21	-1048.54	744.04	-0.15
	36493.09	-611.65	744.15	-0.04
	35353.60	-1751.15	743.79	-0.40
	36944.13	-160.62	744.08	-0.11
	38866.21	1761.47	744.48	0.28
	38915.23	1810.48	744.61	0.42
Mean (11)	37104.74		744.19	
SD (13)		1479.63		0.30
SE (14)		604.06		0.13

	Calculated Variable $F_{OilInHP2Texa}$ (kg/s) (A5b)	$F_{OilInHP2Texa}$ (kg/s) (Deviation) (12)	Calculated Variable $Cp_{OilInHP2Texa}$ (J/kg.°C) (A5b)	$Cp_{OilInHP2Texa}$ (J/kg.°C) (Deviation) (12)
	187.71	0.05	2594.36	0.80
	187.17	-0.49	2593.76	0.20
	187.37	-0.28	2595.68	2.12
	187.85	0.19	2594.17	0.61
	187.94	0.29	2592.06	-1.51
	187.89	0.23	2591.34	-2.22
Mean (11)	187.65		2593.56	
SD (13)		0.31		1.60
SE (14)		0.13		0.65

	Calculated Variable $p_{OilOutHP2Texa}$ (kg/m^3) (A5b)	$p_{OilOutHP2Texa}$ (kg/m^3) (Deviation) (12)	Calculated Variable $F_{OilOutHP2Texa}$ (kg/s) (A5b)	$F_{OilOutHP2Texa}$ (kg/s) (Deviation) (12)
	724.46	0.55	182.77	0.23
	724.47	0.56	182.22	-0.32
	724.45	0.54	182.50	-0.04
	723.83	-0.08	182.74	0.20
	723.15	-0.76	182.56	0.02
	723.10	-0.81	182.46	-0.08
Mean (11)	723.91		182.54	
SD (13)		0.65		0.20
SE (14)		0.27		0.08

	Calculated Variable $Cp_{OilOutHP2Texa}$ (J/kg.°C) (A5b)	$Cp_{OilOutHP2Texa}$ (J/kg.°C) (Deviation) (12)	Calculated Variable $p_{OilHP2TexaAvg}$ (kg/m^3) (A5b)	$p_{OilHP2TexaAvg}$ (kg/m^3) (Deviation) (12)
	2697.85	-2.91	734.25	0.20
	2697.82	-2.94	734.31	0.26
	2697.89	-2.87	734.12	0.07
	2701.19	0.43	733.95	-0.10
	2704.76	4.00	733.81	-0.24
	2705.05	4.29	733.86	-0.20
Mean (11)	2700.76		734.05	
SD (13)		3.46		0.21
SE (14)		1.41		0.08

	Calculated Variable $F_{OilHP2TexaAvg}$ (kg/s) (A5b)	$F_{OilHP2TexaAvg}$ (kg/s) (Deviation) (12)	Calculated Variable $Cp_{OilHP2TexaAve}$ (J/kg.°C) (A5b)	$Cp_{OilHP2TexaAve}$ (J/kg.°C) (Deviation) (12)
	185.24	0.14	2646.11	-1.06
	184.69	-0.40	2645.79	-1.37
	184.94	-0.16	2646.79	-0.37
	185.29	0.20	2647.68	0.52
	185.25	0.15	2648.41	1.25
	185.17	0.08	2648.19	1.03
Mean (11)	185.10		2647.16	
SD (13)		0.24		1.10
SE (14)		0.10		0.45

	Calculated Variable $p_{OilInHP2Prf}$ (kg/m^3) (A5b)	$p_{OilInHP2Prf}$ (kg/m^3) (Deviation) (12)	Calculated Variable $F_{OilInHP2Prf}$ (kg/s) (A5b)	$F_{OilInHP2Prf}$ (kg/s) (Deviation) (12)
	764.00	-0.12	192.74	0.06
	764.10	-0.03	192.18	-0.50
	763.80	-0.33	192.41	-0.27
	764.03	-0.09	192.89	0.21
	764.36	0.23	192.96	0.28
	764.47	0.34	192.90	0.22
Mean (11)	764.13		192.68	
SD (13)		0.25		0.31
SE (14)		0.10		0.13

	Calculated Variable $Cp_{OilInHP2Prf}$ (J/kg.°C) (A5b)	$Cp_{OilInHP2Prf}$ (J/kg.°C) (Deviation) (12)	Calculated Variable $\rho_{OilOutHP2Prf}$ (kg/m^3) (A5b)	$\rho_{OilOutHP2Prf}$ (kg/m^3) (Deviation) (12)
	2570.98	-18.51	748.06	0.45
	2601.34	11.85	748.07	0.45
	2575.55	-13.94	748.05	0.44
	2588.18	-1.31	747.55	-0.07
	2606.38	16.89	747.00	-0.62
	2594.49	5.01	746.95	-0.66
Mean (11)	2589.49		747.61	
SD (13)		14.07		0.53
SE (14)		5.74		0.22

	Calculated Variable $F_{OilOutHP2Prf}$ (kg/s) (A5b)	$F_{OilOutHP2Prf}$ (kg/s) (Deviation) (12)	Calculated Variable $Cp_{OilOutHP2Prf}$ (J/kg.°C) (A5b)	$Cp_{OilOutHP2Prf}$ (J/kg.°C) (Deviation) (12)
	188.72	0.20	2625.77	-20.93
	188.15	-0.36	2657.08	10.39
	188.45	-0.07	2629.76	-16.93
	188.72	0.21	2645.26	-1.43
	188.58	0.06	2666.96	20.27
	188.48	-0.04	2655.34	8.64
Mean (11)	188.52		2646.7	
SD (13)		0.21		16.25
SE (14)		0.09		6.63

	Calculated Variable $\rho_{OilHP2PrfAvg}$ (kg/m^3) (A5b)	$\rho_{OilHP2PrfAvg}$ (kg/m^3) (Deviation) (12)	Calculated Variable $F_{OilHP2PrfAvg}$ (kg/s) (A5b)	$F_{OilHP2PrfAvg}$ (kg/s) (Deviation) (12)
	756.03	0.16	190.73	0.13
	756.08	0.21	190.17	-0.43
	755.93	0.06	190.43	-0.17
	755.79	-0.08	190.81	0.21
	755.68	-0.19	190.77	0.17
	755.71	-0.16	190.69	0.09
Mean (11)	755.87		190.60	
SD (13)		0.17		0.25
SE (14)		0.07		0.10

	Calculated Variable $Cp_{OilHP2PrfAve}$ (J/kg.°C) (A5b)	$Cp_{OilHP2PrfAve}$ (J/kg.°C) (Deviation) (12)	Calculated Variable $\rho_{OilHP2(33\%Texa+67\%Prf)}$ (kg/m^3) (A5b)	$\rho_{OilHP2(33\%Texa+67\%Prf)}$ (kg/m^3) (Deviation) (12)
	2598.08	-19.69	748.84	0.17
	2628.92	11.14	748.90	0.23
	2602.37	-15.40	748.73	0.06
	2616.41	-1.37	748.58	-0.09
	2636.32	18.54	748.46	-0.21
	2624.56	6.78	748.50	-0.17
Mean (11)	2617.78		748.67	
SD (13)		15.11		0.18
SE (14)		6.17		0.07

	Calculated Variable $F_{OilHP2(33\%Texa+67\%Prf)}$ (kg/s) (A5b)	$F_{OilHP2(33\%Texa+67\%Prf)}$ (kg/s) (Deviation) (12)	Calculated Variable $Cp_{OilHP2(33\%Texa+67\%Prf)}$ (J/kg.°C) (A5b)	$Cp_{OilHP2(33\%Texa+67\%Prf)}$ (J/kg.°C) (Deviation) (12)
	188.92	0.14	2613.93	-13.54
	188.36	-0.42	2634.49	7.01
	188.62	-0.17	2617.03	-10.44
	188.99	0.20	2626.73	-0.75
	188.95	0.17	2640.31	12.84
	188.87	0.08	2632.36	4.89
Mean (11)	188.78		2627.47	
SD (13)		0.24		10.3
SE (14)		0.10		4.21

	Calculated Variable $T_{OilInNewHP2}$ (°C) (8)	$T_{OilInNewHP2}$ (°C) (Deviation) (12)	Calculated Variable $T_{OilOutNewHP2}$ (°C) (8)	$T_{OilOutNewHP2}$ (°C) (Deviation) (12)
	222.29	0.10	249.49	-0.93
	222.36	0.17	249.80	-0.63
	223.06	0.87	249.90	-0.52
	222.26	0.07	250.44	0.02
	221.50	-0.69	251.28	0.85
	221.66	-0.53	251.63	1.21
Mean (11)	222.19		250.42	
SD (13)		0.56		0.86
SE (14)		0.23		0.35

	Calculated Variable Q_{NewHP2} (MW) (9)	Q_{NewHP2} (MW) (Deviation) (12)	Calculated Variable E_{HP2} (%) (10)	E_{HP2} (%) (Deviation) (12)
	13.43	-0.57	3.22	-0.03
	13.61	-0.39	3.32	0.08
	13.25	-0.76	3.34	0.10
	13.99	-0.01	3.21	-0.03
	14.85	0.85	3.13	-0.11
	14.90	0.89	3.24	-0.01
Mean (11)	14.01		3.24	
SD (13)		0.72		0.08
SE (14)		0.29		0.03
95% CI (15)				0.07

A5b: Appendix 5b.

A5c: Appendix 5c.

1) Air flow rate.

$$F_{AirHP} = \frac{Q_{HP}}{\left(\frac{Cp_{FlueHP}+Cp_{FurnHP}}{2}\right)(T_{FlueHP}-T_{FurnHP})} \quad \text{(A5a. 1)}$$

e.g.: Using equation (A5a. 1) to ccalculate heating plant 1 air flow rate using equation (A5a. 1) from the first set of calculated and imported variables (variables in Table 14).

$$F_{AirHP1} = \frac{Q_{HP1}}{\left(\frac{Cp_{FlueHP1} + Cp_{FurnHP1}}{2}\right)(T_{FlueHP1} - T_{FurnHP1})}$$

$$F_{AirHP1\,(1)} = \frac{10.55\times 1{,}000{,}000}{\left(\frac{1{,}418.38+1{,}220.99}{2}\right)(293.20-1{,}089.77)} = -10.03\ kg/s$$

The negative sign indicates the direction of the air.

2) Air flow rate with 2% increase in excess air.

$$F_{AirHP+2\%} = F_{AirHP} \times 1.02 \quad \text{(A5a. 2)}$$

e.g.: Using equation (A5a. 2) to calculate heating plant 1 air flow rate with 2% increase in excess air from the first set of calculated and imported variables (variables in Table 14).

$$F_{AirHP1+2\%} = F_{AirHP1} \times 1.02$$

$$F_{AirHP1+2\%\,(1)} = F_{AirHP1} \times 1.02$$

$$F_{AirHP1+2\%\,(1)} = -10.03 \times 1.02 = -10.23\ kg/s$$

The negative sign indicates the direction of the air.

3) Heat exchanger outlet air temperature with 2% increase in excess air.

$$[Q_{AirInHP} + Q_{SteamHP}] = F_{AirHP}\left(\frac{Cp_{HEHP} + Cp_{AmbHP}}{2}\right)(T_{HEHP} - T_{AmbHP}) \qquad \text{(A5a. 3)}$$

$$[Q_{AirInNewHP} + Q_{SteamNewHP}] = F_{AirHP+2\%}\left(\frac{Cp_{HENewHP} + Cp_{AmbHP}}{2}\right)(T_{HENewHP} - T_{AmbHP}) \qquad \text{(A5a. 4)}$$

Making equations (A5a. 3) and (A5a. 4) equal to each.

$$F_{AirHP}\left(\frac{Cp_{HEHP} + \ Cp_{AmbHP}}{2}\right)(T_{HEHP} - T_{AmbHP}) = F_{AirHP+2\%}\left(\frac{Cp_{HENewHP} + \ Cp_{AmbHP}}{2}\right)(T_{HENewHP} - T_{AmbHP})$$

The specific heat capacities are assumed to be same with and without 2% increase in excess air and therefore they cancel each other.

$$F_{AirHP}(T_{HEHP} - T_{AmbHP}) = F_{AirHP+2\%}(T_{HENewHP} - T_{AmbHP})$$

Rearrange with respect to $T_{HENewHP}$.

$$T_{HENewHP} = F_{AirHP}\frac{T_{HEHP1} - T_{AmbHP}}{F_{AirHP+2\%}} + \ T_{AmbHP} \qquad \text{(A5a. 5)}$$

e.g.: Using equation (A5a. 5) to calculate heating plant 1 heat exchanger air temperature with 2% increase in excess air from the first set of calculated and imported variables (variables in Table 14).

$$T_{HENewHP1} = F_{AirHP1}\frac{T_{HEHP1} - T_{AmbHP1}}{F_{AirHP1+2\%}} + \ T_{AmbHP1}$$

$$T_{HENewHP1\,(1)} = -\,10.03 \ \times \ \frac{82.99 - 23.23}{-\,10.23} + \ 23.23 \ = 81.81\ ℃$$

$$T_{HENewHP1\,(1)} = 82\ ℃$$

4) Furnace air temperature with 2% increase in excess air.

$$Q_{CombHP} = F_{AirHP} \left(\frac{Cp_{FurnHP} + Cp_{HEHP}}{2}\right)(T_{FurnHP} - T_{HEHP}) \qquad \text{(A5a. 6)}$$

$$Q_{CombNewHP} = F_{AirHP+2\%} \left(\frac{Cp_{FurnNewHP} + Cp_{HENewHP}}{2}\right)(T_{FurnNewHP} - T_{HENewHP}) \qquad \text{(A5a. 7)}$$

Making equations (A5a. 6) and (A5a. 7) equal to each other.

$$F_{AirHP} \left(\frac{Cp_{FurnHP} + Cp_{HEHP}}{2}\right)(T_{FurnHP} - T_{HEHP}) = F_{AirHP+2\%} \left(\frac{Cp_{FurnNewHP} + Cp_{HEnewHP}}{2}\right)(T_{FurnNewHP} - T_{HENewHP})$$

The specific heat capacities are assumed to be same with and without 2% increase in excess air and therefore they cancel each other.

$$F_{AirHP}\ (T_{FurnHP} - T_{HEHP}) = F_{AirHP+2\%}(T_{FurnNewHP} - T_{HENewHP})$$

Rearrange to calculate for $T_{FurnNewHP}$.

$$T_{FurnNewHP} = F_{AirHP} \frac{T_{FurnHP} - T_{HEHP}}{F_{AirHP+2\%}} + T_{HENewHP} \qquad \text{(A5a. 8)}$$

e.g.: Using equation (A5a. 8) to calculate heating plant 1 furnace air temperature with 2% increase in excess air from the first set of calculated and imported variables (variables in Table 14).

$$T_{FurnNewHP1} = F_{AirHP1} \frac{T_{FurnHP1} - T_{HEHP1}}{F_{AirHP1+2\%}} + T_{HENewHP1}$$

$$T_{FurnNewHP1\,(1)} = -\,10.03 \times \frac{1{,}089.77 - 82.80}{-\,10.23} + 81.81 = 1{,}068.86\ ℃$$

$$T_{FurnNewHP1\,(1)} = 1{,}069\ ℃$$

5) Flue gas temperature with 2% increase in excess air.

$$Q_{HP} = F_{AirHP}\left(\frac{Cp_{FlueNewHP}+Cp_{FurnNewHP}}{2}\right)(T_{FlueHP} - T_{FurnHP}) \quad \text{(A5a. 9)}$$

$$Q_{HPNew} = F_{AirHP+2\%}\left(\frac{Cp_{FlueNewHP}+Cp_{FurnNewHP}}{2}\right)(T_{FlueNewHP} - T_{FurnNewHP}) \quad \text{(A5a. 10)}$$

Making equations (A5a. 9) and (A5a. 10) equal to each.

$$F_{AirHP}\left(\frac{Cp_{FlueHP}+Cp_{FurnHP}}{2}\right)(T_{FlueHP} - T_{FurnHP}) = F_{AirHP+2\%}\left(\frac{Cp_{FlueNewHP}+Cp_{FurnNewHP}}{2}\right)(T_{FlueNewHP} - T_{FurnNewHP})$$

The specific heat capacities are assumed to be same with and without the 2% increase in excess air and therefore they cancel each other.

$$F_{AirHP}(T_{FlueHP} - T_{FurnHP}) = F_{AirHP+2\%}(T_{FlueNewHP} - T_{FurnNewHP})$$

Rearrange to calculate for $T_{FlueNew}$.

$$T_{FlueNewHP} = F_{AirHP}\frac{T_{FlueHP}-T_{FurnHP}}{F_{AirHP+2\%}} + T_{FurnNewHP} \quad \text{(A5a. 11)}$$

e.g.: Using equation (A5a. 11) to calculate heating plant 1 flue temperature with 2% increase in excess air from the first set of calculated and imported variables (variables in Table 14).

$$T_{FlueNewHP1} = F_{AirHP1}\frac{T_{FlueHP1}-T_{FurnHP1}}{F_{AirHP1+2\%}} + T_{FurnNewHP1}$$

$$T_{FlueNewHP1\,(1)} = -10.03 \times \frac{293.20 - 1{,}089.77}{-10.23} + 1{,}068.86 = 287.90\ °C$$

$$T_{FlueNewHP1\,(1)} = 288\ °\mathrm{C}$$

6) Log mean temperature difference.

$$\Delta \mathrm{T}_{\mathrm{HP}} = \frac{(T_{FurnHP} - T_{OilInHP}) - (T_{FlueHP} - T_{OilOutHP})}{\ln \frac{(T_{FurnHP} - T_{OilInHP})}{(T_{FlueHP} - T_{OilOutHP})}} \qquad \text{(A5a. 12)}$$

e.g.: Using equation (A5a. 12) to calculate heating plant 1 log mean temperature from the first set of imported variables (variables in Table 14).

$$\Delta \mathrm{T}_{\mathrm{HP1}} = \frac{(T_{FurnHP1} - T_{OilInHP1}) - (T_{FlueHP1} - T_{OilOutHP1})}{\ln \frac{(T_{FurnHP1} - T_{OilInHP1})}{(T_{FlueHP1} - T_{OilOutHP1})}}$$

$$\Delta \mathrm{T}_{\mathrm{HP1\ (1)}} = \frac{(1{,}089.77 - 224.69) - (293.20 - 252.54)}{\ln \frac{(,1089.77 - 224.69)}{(293.20 - 252.54)}} = 269.62\ ^{\circ}\mathrm{C}$$

$$\Delta \mathrm{T}_{\mathrm{HP1\ (1)}} = 270\ ^{\circ}\mathrm{C}$$

7) Heat transfer coefficient x Area.

$$UA_{HP} = \frac{Q_{HP}}{\Delta T_{HP}} \qquad \text{(A5a. 13)}$$

e.g.: Using equation (A5a. 13) to calculate heating plant 1 heat transfer coefficient x Area from the first set of imported variables (variables in Table 14).

$$UA_{HP1} = \frac{Q_{HP1}}{\Delta T_{HP1}}$$

$$UA_{HP1\,(1)} = \frac{10.55 \times 1{,}000{,}000}{269.62} = 39{,}119.71\ W/^{\circ}C$$

$$UA_{HP1\,(1)} = 39{,}100\ W/^{\circ}C$$

8) Inlet and outlet oil temperatures with 2% increase in excess air.

$$Q_{OilNewHP} = Cp_{OilHP(33\%Texa+67\%Prf)} F_{OilHP(33\%Texa+67\%Prf)} (T_{OilOutNewHP} - T_{OilInNewHP}) \qquad \text{(A5a. 14)}$$

$$\Delta Q_{OilNewHP} = UA_{HP} \frac{(T_{FurnNewHP} - T_{OilInNewHP}) - (T_{FlueNewHP} - T_{OilOuNewtHP})}{\ln \frac{(T_{FurnNewHP} - T_{OilInNewHP})}{(T_{FlueNewHP} - T_{OilOutNewHP})}} \qquad \text{(A5a. 15)}$$

UA_{HP} is assumed to be the same with and without 2% increase in excess air and therefore they cancel each other. UA_{HP} with 2% increase in excess air cannot be calculated since the output power and inlet and outlet oil temperature with 2% increase in excess air are unknown.

There are two unknowns and two equations. Rearrange equations (A5a. 14) and (A5a. 15) to calculate for $T_{OilInlNewHP}$ and $T_{OilOutNewHP}$ using Solver tool in excel.

$$\Delta Q_{OilNewHP} = Q_{OilNewHP}$$

$$Error = \Delta Q_{OilNewHP} - Q_{OilNewHP}$$

$$\begin{aligned} &Error = \\ &\left[Cp_{OilHP(33\%Texa+67\%Prf)} F_{OilHP(33\%Texa+67\%Prf)} (T_{OilOutNewHP} - T_{OilInNewHP})\right] - \\ &\left[UA_{HP} \frac{(T_{FurnNewHP} - T_{OilInNewHP}) - (T_{FlueNewHP} - T_{OilOuNewtHP})}{\ln \frac{(T_{FurnNewHP} - T_{OilInNewHP})}{(T_{FlueNewHP} - T_{OilOutNewHP})}}\right] \end{aligned} \qquad \text{(A5a. 16)}$$

** Solver tool will solve equation (A5a. 16) by determining the appropriate values of $T_{OilInlNewHP}$ and $T_{OilOutNewHP}$.

**When appropriate values of $T_{OilInlNewHP}$ and $T_{OilOutNewHP}$ are determined, equation (A5a. 16) will equal to zero since $\Delta Q_{OilNewHP} = Q_{OilNewHP}$.

**The calculated variables for both heating plants inlet and outlet oil temperatures with 2% increase in excess air are shown in Tables 14 and 15.

9) Output power with 2% increase in excess air.

This can be calculated using equation (A5a. 14) or (A5a. 15).

e.g.: Using equation (A5a. 14) to calculate heating plant 1 inlet and outlet oil temperatures with 2% increase in excess air from the first set of calculated and imported variables (variables in Table 1).

$$Q_{OilNewHP1} = Cp_{OilHP1(33\%Texa+67\%Prf)} F_{OilHP1(33\%Texa+67\%Prf)} (T_{OilOutNewHP1} - T_{OilInNewHP1})$$

$$Q_{OilNewHP\ (1)} = \frac{2{,}653.36\ \times 141.38\ (250.95 - 224.03)}{1{,}000{,}000} = 10.10\ MW$$

$$Q_{OilNewHP\ (1)} = 10\ MW$$

10) Efficiency improvement.

Note $Q_{HP} = Q_{OilHP}$ and $Q_{OilNewHP}$ is the calculated output power with 2% increase in excess air.

Therefore the efficiency improvement from decreasing 2% in excess air can be calculated from the following equation,

$$E_{HP} = \frac{Q_{HP} - Q_{NewOilHP}}{Q_{NewOilHP}} \times 100 \qquad \text{(A5a. 17)}$$

e.g.: Using equation (A5a. 17) to calculate heating plant 1 efficiency improvement from the first set of calculated variables (variables in Table 14).

$$E_{HP1} = \frac{Q_{HP1} - Q_{NewHP1}}{Q_{NewHP1}} \times 100$$

$$\Delta Q_{HP1\ (1)} = Q_{HP1\ (1)} = 10.55\ MW$$

$$E_{HP1\ (1)} = \frac{10.55\ - 10.10}{10.10} \times 100 = 4.47\%$$

$$E_{HP1\ (1)} = 5\ \%$$

11) The average of the six data set.

$$\boldsymbol{Mean} = \frac{\boldsymbol{\Sigma}}{\boldsymbol{n}} \qquad \text{(A5a. 18)}$$

e.g.: Calculating heating plant 1 ambient temperatures mean.

$$\boldsymbol{T_{AmbHP1}} = \frac{23.23 + 22.99 + 23.01 + 23.34 + 23.54 + 23.69}{6} = 23.30\ ℃$$

12) Deviation of six data set.

$$\boldsymbol{Deviation = Actual\ value - Mean} \qquad \text{(A5a. 19)}$$

e.g.: Calculating heating plant 1 ambient temperature deviations.

Number of readings (n)	1	2	3	4	5	6
T_{AmbHP1} *Actual value (°C)*	22.23	22.99	23.01	23.34	23.54	23.69
T_{AmbHP1} *Deviation (°C)*	*-0.07*	*-0.31*	*-0.30*	*0.04*	*0.24*	*0.39*

13) Standard deviation.

$$\boldsymbol{SD} = \sqrt{\frac{\sum \boldsymbol{Deviation}^2}{\boldsymbol{n-1}}} \qquad \text{(A5a. 20)}$$

e.g.: Calculating heating plant 1 ambient temperature standard deviation.

$$\boldsymbol{T_{AmbHP1}SD} = \sqrt{\frac{-0.07^2 + -0.31^2 + -0.30^2 + 0.04^2 + 0.24^2 + 0.39^2}{6-1}} = 0.28\ ℃$$

14) Standard error.

$$\boldsymbol{SE} = \frac{\boldsymbol{SD}}{\sqrt{\boldsymbol{n}}} \qquad \text{(A5a. 21)}$$

e.g.: Calculating heating plant 1 ambient temperature standard error.

$$\boldsymbol{T_{AmbHP1}SE} = \frac{0.28}{\sqrt{6}} = 0.12\ ℃$$

15) 95% confidence interval was calculated for the final efficiency improvement value for both heating plants.

e.g.: Calculating 95% confidence interval for heating plant 1 efficiency improvement.

t value for 6 calculated variables, 95% confidence = 2.45 (Institute of Fundamental Sciences(Physics), 2005)

Heating plant 1, efficiency improvement (E_{HP1}) = 4.78 ± 0.16 %

Expressing heating plant 1, efficiency improvement (E_{HP1}) in 95% confidence:
E_{HP1} = 4.78 ± (0.16 x 2.45) %

E_{HP1} = 4.78 ± 0.39 %

APPENDIX 5b: HEAT TRANSFER OIL THERMAL PROPERTIES AND FLOW RATE

Appendix 5b includes the thermal properties of the heat transfer oil used in Hyne & Sons heating plants. The heating plants operate using two types of mineral based heat transfer oils Caltex Texatherm 32 and Castrol Perfecto HT12. Some of the thermal properties of both oils were taken from their product data sheets (Castrol, 2007; ChevronTexaco, 2003) and the rest were calculated.

Appendix 5b is divided into three sections:

- **Texatherm 32** It includes the calculations to determine the density, flow rate and specific heat capacity of heat transfer oil Texatherm 32.
- **Perfecto HT12** It includes the calculations to determine the density, flow rate and specific heat capacity of heat transfer oil Perfecto HT12.
- **Heat transfer oil (33% Texatherm 32 + 67% Perfecto HT12)** It includes the calculations for the final heat transfer oil density, flow rate and specific heat capacity based on a mixture of 33% Texatherm 32 and 67% Perfecto HT12 oils.

Texatherm 32

1. *Oil density and specific heat capacity*

The densities and specific heat capacity for Texatherm 32 were provided by the product data sheet at various temperatures as shown in Table 16.

Table 16: Oil Texatherm 32 thermal properties (ChevronTexaco, 2003)

T (°C)	p_{Texa} (kg/m^3)	Cp_{Texa} (J/kg. °C)
100	820	2150
200	760	2510
300	690	2880

The density and specific heat capacity was determined for each of the inlet and outlet oil temperatures data set. The densities and specific heat capacities shown in Table 17 were interpolated between 200°C and 300°C, from the thermal properties in Table 16, for the heating plants' inlet and outlet oil temperatures. Appendix 5a, tables 14 and 15 include the density and specific heat capacities uncertainties for all of data set temperatures.

Table 17 includes the average values with uncertainty of six data set of Texatherm 32 oil density and specific heat capacity.

Table 17: Oil Texatherm 32 density and specific heat capacity for Hyne & Sons input and output oil temperatures

HP1		**HP2**	
$P_{OilInHP1Texa}$ (kg/m^3)	$P_{OilOutHP1Texa}$ (kg/m^3)	$P_{OilInHP2Texa}$ (kg/m^3)	$P_{OilOutHP2Texa}$ (kg/m^3)
742.79 ± 0.12	724.03 ± 0.46	744.19 ± 0.30	723.91 ± 0.65
$Cp_{OilInHP1Texa}$ (J/kg. °C)	$Cp_{OilOutHP1Texa}$ (J/kg. °C)	$Cp_{OilInHP2Texa}$ (J/kg. °C)	$Cp_{OilOutHP2Texa}$ (J/kg. °C)
2600.99 ± 0.66	2700.12 ± 2.41	2593.56 ± 1.60	2700.76 ± 3.46

The uncertainties were calculated using standard error method of the six data set (see Appendix 5a).

2. *Oil flow rate*

The oil flow rate data is imported from the heating plant data log in m^3/h. The calculations are done in SI units and therefore the oil flow rate is converted to kg/s. This was done using equation (A5b. 1).

$$F_{OilHP}\left(\frac{kg}{s}\right) = \frac{F_{Oil}\left(\frac{m^3}{h}\right) \times \rho_{OilHP}}{3600} \qquad \text{(A5b. 1)}$$

e.g.: Using equation (A5b. 1) to convert heating plant 1 Texatherm 32 oil inlet flow rate from m3/h to kg/s from the first set of calculated and imported variables (variables in Appendix 5a, tables 14 and 15).

$$F_{OilInHP1Texa\ (1)}\left(\frac{kg}{s}\right) = \frac{F_{OilHP1(1)}\left(\frac{m^3}{h}\right) \times \rho_{OilInHP1Texa\ (1)}}{3600}$$

$$F_{OilInHP1Texa\ (1)} = \frac{680.69 \times 742.71}{3600} = 140.43\ kg/s$$

$$F_{OilInHP1Texa\ (1)} = 140\ kg/s$$

Tables 14 and 15, in Appendix 5a, include oil Texatherm 32 flow rates with uncertainties for all of the data set temperatures. Table 18 includes the average flow rate values with uncertainty of the six data sets.

Table 18: Oil Texatherm 32 flow rate for Hyne & Sons average inlet and outlet oil temperatures

HP1		**HP2**	
$F_{OilInHP1Texa}$ (kg/s)	**$F_{OilOutHP1Texa}$** (kg/s)	**$F_{OilInHP2Texa}$** (kg/s)	**$F_{OilOutHP2Texa}$** (kg/s)
140.29 ± 0.40	136.75 ± 0.37	187.65 ± 0.31	182.54 ± 0.20

The uncertainties were calculated using standard error method of the six data set (see Appendix 5a).

Perfecto HT12

1. *Oil density*

The Perfecto HT12 data sheet provided only a density value at 15 °C, 890 kg/m^3. Therefore, to determine the density at various temperatures for Perfecto HT12 it was assumed that the shape of the curve for the oil Perfecto H12 density/temperature relationship would be the same as that of oil Texatherm 32. This was done by plotting the data points shown in Table 16, density as a function of temperature. Then plotting the single Perfecto HT12 point on the same plot as seen in Figure 36.

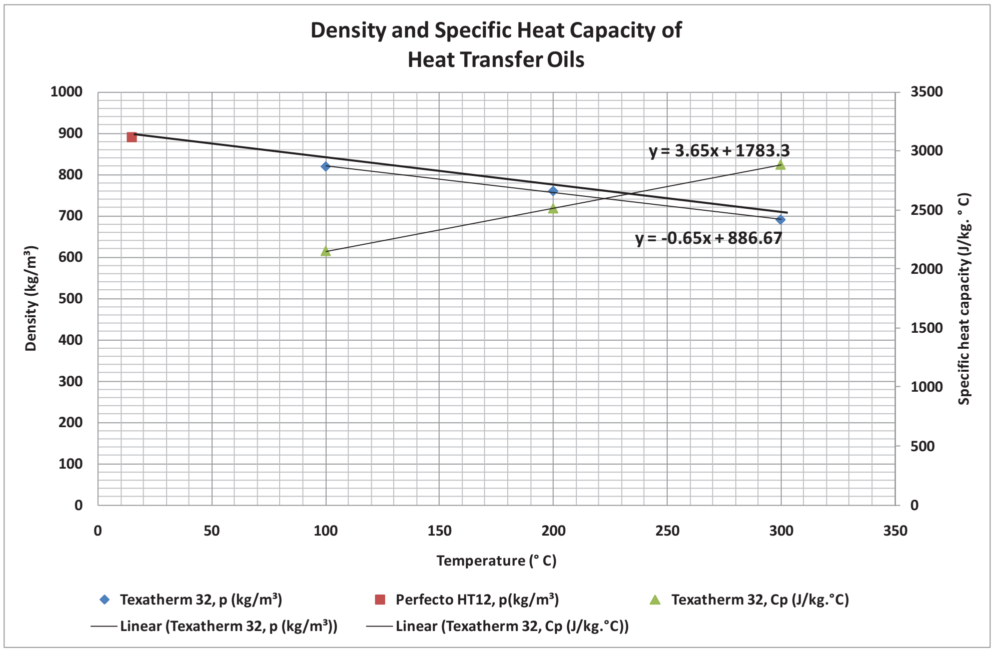


Figure 36: Heat transfer oils thermal properties

Table 19 includes the densities of oil Perfecto HT12 at different temperatures which are estimated from Figure 36.

Table 19: Densities of Oil Perfecto HT12 estimated from Figure 36

T (°C)	ρ_{Prf} (kg/m^3)
100	840
200	777
300	720

Densities and specific heat capacities of each of the heating plant's inlet and outlet oil temperatures data set were determined. The densities and specific heat capacities were interpolated between 200°C and 300°C, from the estimated thermal properties in Table 19, for heating plants' inlet and outlet oil temperatures.

Tables 14 and 15 in Appendix 5a include the densities of the inlet ant outlet oil Perfecto HT12 with uncertainties for all of the data set temperatures. Table 20 includes the average density values with uncertainty of the six data sets.

Table 20: Oil Perfecto HT12 density for Hyne & Sons inlet and outlet oil temperatures

HP1		**HP2**	
$\boldsymbol{P}_{\mathbf{OilInHP1Prf}}$ (kg/m^3)	$\boldsymbol{P}_{\mathbf{OilOutHP1Prf}}$ (kg/m^3)	$\boldsymbol{P}_{\mathbf{OilInHP2Prf}}$ (kg/m^3)	$\boldsymbol{P}_{\mathbf{OilOutHP2Prf}}$ (kg/m^3)
762.98 ± 0.10	747.71 ± 0.37	764.13 ± 0.25	747.61 ± 0.53

**** The uncertainties were calculated using standard error method of the six data set (see Appendix 5a).**

2. Oil flow rate

The oil flow rate data was imported from the heating plant data log in m^3/h. The calculations were done in SI units and therefore the oil flow rate is converted to kg/s. This was done using equation (A5b. 1). The average values with uncertainties of oil flow rate values are included in Table 21.

Table 21: Oil Perfecto HT12 flow rate for Hyne & Sons inlet and outlet oil temperatures

HP1		**HP2**	
$\mathbf{F}_{\mathbf{OilInHP1Prf}}$ (kg/s)	$\mathbf{F}_{\mathbf{OilOutHP1Prf}}$ (kg/s)	$\mathbf{F}_{\mathbf{OilInHP2Prf}}$ (kg/s)	$\mathbf{F}_{\mathbf{OilOutHP2Prf}}$ (kg/s)
144.11 ± 0.40	141.22 ± 0.38	192.68 ± 0.31	188.52 ± 0.21

The uncertainties were calculated using standard error method of the six data set (see Appendix 5a).

3. Oil specific heat capacity

The specific heat capacities of oil Perfecto HT 12 were calculated using equation 22.

$$Cp_{OilHP} = \frac{Q_{HP}}{F_{OilHP}(T_{OilOutHP} - T_{OilInHP})} \qquad \text{(A5b. 2)}$$

e.g.: Using equation (A5b. 2) to calculate heating plant 1 oil Perfecto HT12 specific heat capacity (based on the inlet oil flow rate) from the first set of calculated and imported variables (variables in, Appendix 5, a, Table 2).

$$Cp_{OilHP1Prf} = \frac{Q_{OilHP1}}{F_{OilHP1Prf1}(T_{OilOutHP1} - T_{OilInHP1})}$$

$$Cp_{OilInHP1Prf\,(1)} = \frac{10.55}{140.43(252.54 - 224.69)} = 2601.36\ \frac{J}{kg.°C}$$

$$Cp_{OilInHP1Prf\,(1)} = 2601\ \frac{J}{kg.°C}$$

Tables 14 and 15 in Appendix 5a include the specific heat capacities for oil Perfecto HT12 with uncertainties for all of the data set temperatures. Table 22 includes the average of the specific heat capacity values with uncertainty of the six data sets. Cp$_{OilInHP1Prf}$ and Cp$_{OilInHP2Prf}$ are calculated based on the inlet oil flow rates. Cp$_{OilOutHP1Prf}$ and Cp$_{OilOutHP2Prf}$ are calculated based on the outlet oil flow rates.

Table 22: Oil Perfecto HT12 specific heat capacity for Hyne & Sons inlet and outlet oil temperatures

HP1		**HP2**	
$\mathbf{Cp}_{\mathbf{OilInHP1Prf}}$ (J/kg. °C)	$\mathbf{Cp}_{\mathbf{OilOutHP1Prf}}$ (J/kg. °C)	$\mathbf{Cp}_{\mathbf{OilInHP2Prf}}$ (J/kg. °C)	$\mathbf{Cp}_{\mathbf{OilOutHP2Prf}}$ (J/kg. °C)
2620.07± 112.62	2673.57 ± 114.43	2589.49 ± 14.07	2646.70 ± 16.25

The uncertainties were calculated using standard error method of the six data set (see Appendix 5a).

Heat transfer oil (33% Texatherm 32 + 67% Perfecto HT12)

The final heat transfer oil density, flow rate and specific heat capacity were based on a mixture of 33% Texatherm 32 and 67% Perfecto HT12 oils. These values were calculated for both heating plants using equations (A5b. 3), (A5b. 4) and (A5b. 5).

$$p_{OilHP(33\%Texa+67\%Prf)} = 33\% \times \left[\left(\frac{p_{\mathrm{OilInHP1Texa}} + p_{\mathrm{OilOutHP1Texa}}}{2}\right)\right]$$

$$+67\% \times \left[\left(\frac{p_{\mathrm{OilInHP2Prf}} + p_{\mathrm{OilOutHP2Prf}}}{2}\right)\right] \qquad \text{(A5b. 3)}$$

$$F_{OilHP(33\%Texa+67\%Prf)} = 33\% \times \left[\left(\frac{F_{\mathrm{OilInHP1Texa}} + F_{\mathrm{OilOutHP1Texa}}}{2}\right)\right]$$

$$+67\% \times \left[\left(\frac{F_{\mathrm{OilInHP2Prf}} + F_{\mathrm{OilOutHP2Prf}}}{2}\right)\right] \qquad \text{(A5b. 4)}$$

$$Cp_{OilHP(33\%Texa+67\%Prf)} = 33\% \times \left[\left(\frac{Cp_{\mathrm{OilInHP1Texa}} + Cp_{\mathrm{OilOutHP1Texa}}}{2}\right)\right]$$

$$+67\% \times \left[\left(\frac{Cp_{\mathrm{OilInHP2Prf}} + Cp_{\mathrm{OilOutHP2Prf}}}{2}\right)\right] \qquad \text{(A5b. 5)}$$

e.g.: Using equations (A5b. 3), (A5b. 4) and (A5b. 5) to calculate the final oil density, flow rate and specific heat capacity (a blend of 33% oil Texatherm 32 and 67% oil perfecto HT12) from the first set of calculated and imported variables (variables in, Appendix 5a, Table 14) were calculated.

Oil density:

$$p_{OilHP1(33\%Texa+67\%Prf)} = 33\% \times \left[\left(\frac{p_{\mathrm{OilInHP1Texa\,(1)}} + p_{\mathrm{OilOutHP1Texa\,(1)}}}{2}\right)\right] + 67\% \times \left[\left(\frac{p_{\mathrm{OilInHP1Prf\,(1)}} + p_{\mathrm{OilOutHP1Prf\,(1)}}}{2}\right)\right]$$

$$p_{OilHP1(33\%Texa+67\%Prf)(1)} = 33\% \times \left[\left(\frac{742.71 + 723.22}{2}\right)\right] + 67\% \times \left[\left(\frac{762.92 + 747.05}{2}\right)\right] = 747.72\,\frac{kg}{m^3}$$

$$p_{OilHP1(33\%Texa+67\%Prf)(1)} = 748\ kg/m^3$$

Oil flow rate:

$$F_{OilHP1(33\%Texa+67\%Prf)\,(1)} = 33\% \times \left[\left(\frac{F_{\mathrm{OilInHP1Texa\,(1)}} + F_{\mathrm{OilOutHP1Texa\,(1)}}}{2}\right)\right] + 67\% \times \left[\left(\frac{F_{\mathrm{OilInHP1Prf\,(1)}} + F_{\mathrm{OilOutHP1Prf\,(1)}}}{2}\right)\right]$$

$$F_{OilHP1(33\%Texa+67\%Prf)\ (1)} = 33\% \times \left[\left(\frac{140.43 + 136.75}{2}\right)\right] + 67\% \times \left[\left(\frac{144.25 + 141.25}{2}\right)\right] = 141.38\ kg/s$$

$$F_{OilHP1(33\%Texa+67\%Prf)(1)} = 141\ kg/s$$

Oil specific heat capacity:

$$Cp_{OilHP1(33\%Texa+67\%Prf)\,(1)} = 33\% \times \left[\left(\frac{Cp_{\mathrm{OilInHP1Texa\,(1)}} + Cp_{\mathrm{OilOutHP1Texa\,(1)}}}{2}\right)\right] + 67\% \times \left[\left(\frac{Cp_{\mathrm{OilInHP1Prf\,(1)}} + Cp_{\mathrm{OilOutHP1Prf\,(1)}}}{2}\right)\right]$$

$$Cp_{OilHP1(33\%Texa+67\%Prf)(1)} = 33\% \times \left[\left(\frac{2601.36 + 2704.41}{2}\right)\right] + 67\% \times \left[\left(\frac{2625.99 + 2681.79}{2}\right)\right] = 2653.36\ \frac{J}{kg.°C}$$

$$Cp_{OilHP1(33\%Texa+67\%Prf)(1)} = 2653\ \frac{J}{kg.°C}$$

Tables 14 and 15 in Appendix 5a include the final heat transfer oil density, flow rate and specific heat capacity with uncertainties for all of the data sets. Table 23 includes the average values with uncertainty of the six data sets.

Table 23: Heat transfer oil density, specific heat capacity and flow rate for Hyne & Sons inlet and outlet oil temperatures (33% Texatherm 32 + 67% Perfecto HT12)

HP1	$\frac{p_{\mathrm{OilInHP1Texa}} + p_{\mathrm{OilOutHP1Texa}}}{2}$	733.48 ± 0.23 kg/m^3	$p_{\mathrm{OilHP1(33\%Texa+67\%Prf)}}$	748.11 ± 0.21 kg/m^3
	$\frac{p_{\mathrm{OilInHP1Prf}} + p_{\mathrm{OilOutHP1Prf}}}{2}$	755.35 ± 0.19 kg/m^3		
	$\frac{F_{\mathrm{OilInHP1Texa}} + F_{\mathrm{OilOutHP1Texa}}}{2}$	138.52 ± 0.38 kg/s	$F_{\mathrm{OilHP1(33\%Texa+67\%Prf)}}$	141.30 ± 0.39 kg/s
	$\frac{F_{\mathrm{OilInHP1Prf}} + F_{\mathrm{OilOutHP1Prf}}}{2}$	142.67 ± 0.39 kg/s		
	$\frac{Cp_{\mathrm{OilInHP1Texa}} + Cp_{\mathrm{OilOutHP1Texa}}}{2}$	2650.55 ± 1.20 J/kg.°C	$Cp_{\mathrm{OilHP1(33\%Texa+67\%Prf)}}$	2647.87 ± 76.05 J/kg.°C
	$\frac{Cp_{\mathrm{OilInHP1Prf}} + Cp_{\mathrm{OilOutHP1Prf}}}{2}$	2646.82 ± 113.52 J/kg.°C		
HP2	$\frac{p_{\mathrm{OilInHP2Texa}} + p_{\mathrm{OilOutHP2Texa}}}{2}$	734.05 ± 0.21 kg/m^3	$p_{\mathrm{OilHP2(33\%Texa+67\%Prf)}}$	748.67 ± 0.18 kg/m^3
	$\frac{p_{\mathrm{OilInHP2Prf}} + p_{\mathrm{OilOutHP2Prf}}}{2}$	755.87 ± 0.17 kg/m^3		
	$\frac{F_{\mathrm{OilInHP2Texa}} + F_{\mathrm{OilOutHP2Texa}}}{2}$	185.18 ± 0.24 kg/s	$F_{\mathrm{OilHP2(33\%Texa+67\%Prf)}}$	188.78 ± 0.24 kg/s
	$\frac{F_{\mathrm{OilInHP2Prf}} + F_{\mathrm{OilOutHP2Prf}}}{2}$	190.60 ± 0.25 kg/s		
	$\frac{Cp_{\mathrm{OilInHP2Texa}} + Cp_{\mathrm{OilOutHP2Texa}}}{2}$	2647.16 ± 1.10 J/kg.°C	$Cp_{\mathrm{OilHP2(33\%Texa+67\%Prf)}}$	2627.47 ± 10.30 J/kg.°C
	$\frac{Cp_{\mathrm{OilInHP2Prf}} + Cp_{\mathrm{OilOutHP2Prf}}}{2}$	2618.09 ± 15.13 J/kg.°C		

The uncertainties were calculated using standard error method of the six data set (see Appendix 5a).

APPENDIX 5c: SPECIFIC HEAT CAPACITY OF FLUE AND FURNACE AIR TEMPERATURES

The specific heat capacities for the flue gas (Cp_{FlueHP}) and furnace air (Cp_{FurnHP}) temperatures were calculated based on the percentages of the composition elements included. These percentages were provided by RCR energy Systems and depend on the type of the burning fuel. The composition produced from burning biomass fuel at Hyne & Son heating plants consists of nitrogen (N_2), carbon dioxide (CO_2), carbon monoxide (CO), sulphur oxide (SO_2) and vapour (H_2O).

The specific heat capacities of the composition elements in the flue gas and furnace air temperatures were determined for the six data set using a nomograph and standard thermal property tables. The percentage of each element was then multiplied by its specific heat capacity. The sum of the total specific heat capacities of the gas compositions was presented as a final specific heat capacity. The specific heat capacities of flue gas and furnace air temperatures for both heating plants are included in tables 24 and 25.

Specific heat capacitates for flue gas composition elements

The specific heat capacities of the following composition elements N_2, O_2, CO, CO_2 and H_2O for the flue gas temperature were determined using the interpolation method from the standard thermal property tables (Perry, et al., 1997; Turns & Kraige, 2007); while SO_2 was determined from a nomograph (Perry & Chilton, 1973). No standard thermal property table that the author can get hold to, at required flue gas temperatures, for SO_2.

Specific heat capacitates for furnace air composition elements

Furnace air specific heat capacities of the composition elements N_2, O_2, CO and H_2O for the flue gas temperature were determined using the interpolation method from the standard thermal property tables (Perry, et al., 1997; Turns & Kraige, 2007); while CO_2 and SO_2 were determined from a nomograph (Perry & Chilton, 1973). No standard thermal property tables that the author can get hold to, at required furnace air temperatures, for CO_2 and SO_2.

Table 24: The specific heat capacity of the flue gas temperature

		Heating plant 1											
Flue gas composition elements	**Elements composition %**	**293.20 °C**		**292.72 °C**		**292.56 °C**		**292.48 °C**		**292.47 °C**		**292.43 °C**	
		***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**
N_2	**70.00%**	1068.30	747.81	1068.21	747.74	1068.17	747.72	1068.13	747.69	1068.16	747.71	1068.15	747.70
CO_2	**11.00%**	1068.81	117.57	1055.20	116.07	1068.43	117.53	1068.38	117.52	1068.37	117.52	1068.35	117.52
CO	**0.03%**	1079.27	0.27	1079.17	0.27	1079.14	0.27	1079.13	0.27	1079.12	0.27	1079.12	0.27
O_2	**5.00%**	990.58	50.52	990.44	49.52	990.40	49.52	990.38	50.51	990.37	49.52	990.36	49.52
SO_2	**0.02%**	753.12	0.15	753.12	0.15	753.12	0.15	753.12	0.15	753.12	0.15	753.12	0.15
H_2O	**14.00%**	2176.23	304.67	2176.18	304.66	2176.16	304.66	2176.15	304.66	2176.15	304.66	2176.15	304.66
Total	100%		**1220.99**		**1218.42**		**1219.85**		**1220.80**		**1219.83**		**1219.82**

		Heating plant 2											
Flue gas composition elements	**Elements composition %**	**385.51 °C**		**385.73 °C**		**386.26 °C**		**387.31 °C**		**388.82 °C**		**390.30°C**	
		***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp* (J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**
N_2	**70.00%**	1088.59	762.01	1088.64	762.05	1088.76	762.14	1089.01	762.30	1089.35	762.55	1089.69	762.78
CO_2	**11.00%**	1107.33	121.81	1107.44	121.82	1107.71	121.85	1108.21	121.90	1108.89	121.98	1109.55	122.05
CO	**0.03%**	1100.02	0.28	1100.07	0.28	1100.20	0.28	1100.45	0.28	1100.81	0.28	1101.16	0.28
O_2	**5.00%**	1017.01	50.85	1017.07	50.85	1017.23	50.86	1017.53	50.88	1017.97	50.90	1018.40	50.92
SO_2	**0.02%**	774.04	0.15	774.04	0.15	774.04	0.15	774.04	0.15	774.04	0.15	774.04	0.15
H_2O	**14.00%**	2061.06	288.55	2061.22	288.57	2061.59	288.62	2062.32	288.73	2063.38	288.87	2064.41	289.02
Total	100%		**1223.65**		**1223.72**		**1223.90**		**1224.24**		**1224.73**		**1225.20**

The uncertainties of specific heat capacities are calculated using standard error method of the six data set (see Appendix 5a).

Table 25: The specific heat capacity of furnace air temperature

Heating plant 1													
Furnace air composition elements	**Elements composition %**	**1089.77**		**1080.76**		**1070.24**		**1070.35**		**1079.06**		**1077.63**	
		Cp (**J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp*** **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp*** **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp*** **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp*** **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp*** **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**
N_2	**70.00%**	1227.47	859.23	1226.27	858.39	1224.87	857.41	1224.88	857.42	1226.04	858.23	1225.85	858.10
CO_2	**11.00%**	1317.96	144.98	1305.40	143.59	1297.04	142.67	1297.04	142.67	1305.40	143.59	1305.40	143.59
CO	**0.03%**	1240.55	0.31	1217.54	0.30	1238.21	0.31	1238.22	0.31	1239.26	0.31	1239.09	0.31
O_2	**5.00%**	1127.66	56.38	1126.85	56.34	1125.90	56.30	1125.91	56.30	1126.70	56.33	1126.57	56.33
SO_2	**0.02%**	870.27	0.17	861.90	0.17	857.71	0.17	857.71	0.17	861.90	0.17	861.90	0.17
H_2O	**14.00%**	2552.19	357.31	2545.43	356.36	2537.54	355.26	2537.62	355.27	2544.15	356.18	2543.08	356.03
Total	**100%**		**1418.38**		**1415.16**		**1412.12**		**1412.14**		**1414.82**		**1414.53**

Heating plant 2													
Furnace air composition elements	**Elements composition %**	**1059.49**		**1061.53**		**1066.88**		**1078.22**		**1086.99**		**1085.50**	
		Cp **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp*** **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp*** **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp*** **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp*** **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**	***Cp*** **(J/kg.°C)**	**EC % x *Cp* (J/kg.°C)**
N_2	**70.00%**	1223.44	856.41	1223.71	856.60	1224.42	857.10	1225.93	858.15	1227.10	858.97	1226.90	858.83
CO_2	**11.00%**	1297.04	142.67	1297.04	142.67	1297.04	142.67	1305.40	143.59	1317.96	144.98	1317.96	144.98
CO	**0.03%**	1236.92	0.31	1237.16	0.31	1237.80	0.31	1239.16	0.31	1240.22	0.31	1240.04	0.31
O_2	**5.00%**	1124.94	56.25	1125.12	56.26	1125.60	56.28	1126.62	56.33	1127.41	56.37	1127.28	56.36
SO_2	**0.02%**	853.54	0.17	853.54	0.17	857.71	0.17	861.90	0.17	870.27	0.17	870.27	0.17
H_2O	**14.00%**	2529.48	354.13	2531.01	354.34	2535.02	354.90	2543.52	356.09	2550.11	357.01	2548.99	356.86
Total	**100%**		**1409.94**		**1410.35**		**1411.44**		**1414.65**		**1417.81**		**1417.51**

The uncertainties of specific heat capacities are calculated using standard error method of the six data set (see Appendix 5a).

APPENDIX 6: PAYBACK SAVINGS AND PERIOD CALCULATIONS

This appendix includes the equations and calculations for determining payback savings and internal rate of return analysis for the 37MW Fonterra Edendale boiler and small sized boilers. To determine the payback savings and internal rate of return it was necessary to calculate the difference in thermal efficiency improvement between 7% and 5% excess air. The thermal efficiency is calculated based on the British Standards For Assessing Thermal Performance Of Heating plants For Steam, Hot Water And High Temperature Fluids – Part 1 (British Standards Institution, 1987).

The appendix includes three subsections:

- Appendix 6a: Heat losses and thermal efficiency calculations based on the British Standard institution (BS 845-1:11987)
- Appendix 6b: Payback savings and period calculations
- Appendix 6c: Internal rate of return cash flow calculations

APPENDIX 6a: HEAT LOSSES AND THERMAL EFFICIENCY CALCULATIONS BASED ON THE BRITISH STANDARD INSTITUTION (BS 845-1:11987)

This appendix includes heat losses and thermal efficiency calculations for the 37MW Fonterra Edendale boiler. The calculations are based on the British Standard Institution (BS 845-1:1 1987).

Table 26 includes measured and constant variables for a 37MW coal fired boiler at Fonterra, Edendale. Table 27 shows the losses and thermal efficiency calculations when operating the 37MW Fonterra Edendale boiler at 7% and 5% excess air.

Table 26: Measured and constant variables for a coal fired boiler at Fonterra, Edendale (RCR Energy Systems Limited, 2009)

Fixed variables (from fuel sample analysis)	**Symbol**	**Values**	**Unit**
Moisture content of fuel as fired, %wgt	mH_2O	40.75	%
Hydrogen content of fuel as fired, %wgt	H	3.06	%
Gross calorific value of fuel	Q_{gr}	16382	kJ/kg
Mass of solid fuel fired	M_f	1	kg
Carbon content for coal as fired, %wgt	C	40.85	%
Fixed variables (from ash samples)			
Quantity of grate ash collected	M_1	0.000456	kg
Quantity of fly ash collected	M_2	0.036	kg
Carbon content of grate ash, %wgt	a_1	2.34	%
Carbon content of fly ash, %wgt	a_2	45.74	%
Quantity of fuel burnt		1	kg
Live Variables			
Ambient temperature	t_a	27	°C
Heating plant exit temperature	t_3	206	°C
Heating plant excess oxygen, %mol	VO_2	7 & 5	%
Carbon monoxide	CO	200	ppm
Volume of carbon monoxide	VCO	0.02	%
Constant			
Coal constant. typical value of k_1 for coal is 63 in accordance with British standard 845-1:1987	k_1	63	-
Typical stoichiometric volume value of CO_2, V/CO_2 (percent dry basis) for coal	$\frac{V}{CO_2}$	18.4	-

$$V_{CO_2} = \left(1 - \frac{V_{O_2}}{21}\right) \frac{V}{CO_2} \quad \text{(A6a. 1)}$$

$$k_{gr,} = \frac{255\,C}{Q_{gr}} \quad \text{(A6a. 2)}$$

Losses equations

$$L_{1gr} = \frac{K(t_3 - t_a)[1 - 0.01(L_4 + L_5)}{V_{CO_2}} \quad \text{(A6a. 3)}$$

$$L_{2gr} = \frac{[(mH_2O \ + 9H)(2488 - 4.2t_a + 2.1t}{Q_{gr}} + 0.001 \quad \text{(A6a. 4)}$$

$$L_{3gr} = \frac{K_1.V_{CO}[1 - 0.01(L_4 + L_5)]}{(V_{CO_2} + V_{CO})} \quad \text{(A6a. 5)}$$

$$L_{4gr} = \frac{33820.M_1.a_1}{M_f.Q_{gr}} \quad \text{(A6a. 6)}$$

$$L_{5gr} = \frac{33820.M_2.a_2}{M_f.Q_{gr}} \quad \text{(A6a. 7)}$$

$$L_{6gr} = \frac{6.7\,.A_1(t_k - t_1)}{Q_{agr}} + \frac{53A_2Q_{agr}}{A\,Q_{R\,gr}\,(l_2 + \ 1.3)} \quad \text{(A6a. 8)}$$

$$L_{tgr} = L_1 + L_2 + L_3 + L_4 + L_5 + L_6 \qquad \text{(A6a. 9)}$$

Thermal efficiency equation

$$E_{gr} = 100 - L_{tgr} \qquad \text{(A6a. 10)}$$

Table 27: Thermal efficiency comparison of a coal fired boiler at Fonterra, Edendale (RCR Energy Systems Limited, 2009)

	7% Excess Air	**5% Excess Air**
V_{CO_2}	$\left(1 - \frac{7}{21}\right) \times 18.4 = 12.3\ \%$	$\left(1 - \frac{5}{21}\right) \times 18.4 = 14.0\ \%$
k_{gr}	$\frac{255 \times 40.85}{16382} = 0.6$	$\frac{255 \times 40.85}{16382} = 0.6$
L_{1gr}	$\frac{0.6(206 - 27)[1 - 0.01(0.002 + 3.399)}{12.3} = 9.0\%$	$\frac{0.6(206 - 27)[1 - 0.01(0.002 + 3.399)}{14.0} = 7.9\%$
L_{2gr}	$\frac{[(40.75 + 27.54)(2488 - 113.4 + 432.6)}{16382} + 0.001 = 11.7\%$	$\frac{[(40.75 + 27.54)(2488 - 113.4 + 432.6)}{16382} + 0.001 = 11.7\%$
L_{3gr}	$\frac{63 \times 0.02 \times [1 - 0.01(0.002 + 3.399)]}{(0.02 + 12.3)} = 0.1\%$	$\frac{63 \times 0.02 \times [1 - 0.01(0.002 + 3.399)]}{(0.02 + 14.02)} = 0.1\%$
L_{4gr}	$\frac{33820 \times 0.000456 \times 2.34}{1 \times 16382} = 0.002\%$	$\frac{33820 \times 0.000456 \times 2.34}{1 \times 16382} = 0.002\%$
L_{5gr}	$\frac{33820 \times 0.036 \times 45.7}{1 \times 16382} = 3.4\%$	$\frac{33820 \times 0.036 \times 45.7}{1 \times 16382} = 3.4\%$
L_{6gr}	0.3% ***Note L_{6gr} was not calculated it was selected from BS845-1:1987, Appendix C, Table 3.**	0.3% ***Note L_{6gr} was not calculated it was selected from BS845-1:1987, Appendix C, Table 3.**
L_{tgr}	$9.0 + 11.7 + 0.010 + 0.002 + 3.4 + 0.2 = 24.5\%$	$7.9 + 11.7 + 0.09 + 0.002 + 3.4 + 0.2 = 23.4\%$
E_{gr}	$100 - 24.5 = 75.5\%$	$100 - 23.4 = 76.6\%$

APPENDIX 6b: PAYBACK SAVINGS AND PERIOD CALCULATIONS

This appendix includes payback savings and period calculations from the coal fuel cost of the 37MW Fonterra Edendale boiler and small size boilers. The payback savings are based on the difference in thermal efficiencies between operating a boiler at 7% and 5% excess air which were calculated in Table 27, Appendix 6a.

Table 28: Fuel cost payback savings for a 37MW Fonterra Edendale

	Units	Fonterra Edendale	10MW Boiler	20MW Boiler
Difference in efficiency improvement	%	1.14	1.14	1.14
Boiler size	watts	37,000,00	10,000,000	20,000,000
Calorific value (coal)	J/kg	16,382,000	16,382,000	16,382,000
Fuel consumed / hour (coal)	kg/hr	8,130.88	2,197.53	4,395.07
Fuel cost/ kg (coal)	NZ$/kg	0.12	0.12	0.12
Fuel cost / hour (coal)	NZ$/hr	975.71	263.70	527.41
Savings / hour	NZ$/ hr	11.12	3.01	6.01
Average boiler output	%	100	100	100
Monthly savings	**NZ $**	**8,120.15**	**2,194.63**	**4,389.27**
Annual savings	**NZ $**	**97,441.75**	**26,335.56**	**52,671.24**

Equations used for calculating payback savings from the fuel cost

$$\mathit{Difference\ in\ efficiency\ improvment} = E_{gr,7\%} - E_{gr,5\%} \tag{A6b. 1}$$

$$\frac{\mathit{Fuel\ consumed}}{\mathit{Hour}} = 3600 \times \frac{\mathit{Boiler\ size}}{\mathit{Calorific\ value}} \tag{A6b. 2}$$

$$\frac{\mathit{Fuel\ cost}}{\mathit{hour}} = \frac{\mathit{Fuel\ cost}}{\mathit{kg}} \times \frac{\mathit{Coal\ consumed}}{\mathit{hour}} \tag{A6b. 3}$$

$$\frac{\mathit{Savings}}{\mathit{hour}} = \left(\mathit{Difference\ in\ efficiency\ improvement} \times \frac{\mathit{Fuel\ cost}}{\mathit{hour}}\right) \times 100 \tag{A6b. 4}$$

$$\mathit{Monthly\ savings} = \frac{\mathit{Savings}}{\mathit{Hour}} \times 24 \times \left(\frac{365}{12}\right) \tag{A6b. 5}$$

$$\mathit{Annual\ savings} = \mathit{Monthly\ savings} \times 12 \tag{A6b. 6}$$

APPENDIX 6c: INTERNAL RATE OF RETURN CASH FLOW CALCULATIONS

This appendix includes tables 29, 30 and 31 of the internal rate of return analysis over a period of two years of coal fuel cost savings if excess air for combustion is reduced by 2%. The fuel cost savings were calculated in Appendix 6b. The cost of implementing the trim control can be calculated from the following figures:

- The trim control transmitter: NZ$30,000
- Installation: NZ$5,000
- Software: NZ$5,000
- Calibration per a year: NZ$1,500

The net cash flow from implementing the trim control is NZ$ 40,000 and an annual cost of NZ$ 1, 500 for calibration.

Table 29: Internal rate of return of coal fuel cost savings for 37MW Fonterra Edendale boiler if excess air for combustion is reduced by 2%

Period (Year)	**0**	**1**	**2**
Savings NZ$	$0.00	$97,441.75	$97,441.75
Costs NZ$	$40,000.00	$1,500.00	$1,500.00
***Net NZ$**	$40,000.00	$95,941.75	$95,941.75
****IRR**	**216%**		

***Net NZ$ = Savings NZ$ - Costs NZ$**

****IRR: was calculated using IRR function in Microsoft excel.**

Table 30: Internal rate of return of coal fuel cost savings for 10MW boiler if excess air for combustion is reduced by 2%

Period (Year)	**0**	**1**	**2**
Savings NZ$	$0.00	$26,335.61	$26,335.61
Costs NZ$	$40,000.00	$1,500.00	$1,500.00
***Net NZ$**	$40,000.00	$24,835.61	$24,835.61
****IRR**	**16%**		

***Net NZ$ = Savings NZ$ - Costs NZ$**

****IRR: was calculated using IRR function in Microsoft excel.**

Table 31: Internal rate of return of coal fuel cost savings for 20MW boiler if excess air for combustion is reduced by 2%

Period (Year)	**0**	**1**	**2**
Savings NZ$	$0.00	$52,671.21	$52,671.21
Costs NZ$	$40,000.00	$1,500.00	$1,500.00
***Net NZ$**	$40,000.00	$51,171.21	$51,171.21
****IRR**	**94%**		

***Net NZ$ = Savings NZ$ - Costs NZ$**

****IRR: was calculated using IRR function in Microsoft excel.**

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