Emerson Process Management

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# Combustion Process Control

# Technical Review

# Summary

This report considers the control of combustion in industrial energy boiler applications and specifically the significant economic and other benefits of good control. The report first introduces the various aspects of the combustion control problem. It describes traditional control schemes and also explains how sophisticated control methods can improve efficiency and performance, with significant benefits when applied to the use of waste fuels and multi-fuel boilers.

In Sections 1 and 2 the main concepts and efficiency considerations in combustion control, with respect to fuel types and emissions are discussed. There are increasing costs of fuel and stricter government regulations regarding emissions (CO2, SOx, NOx etc) and energy efficiency. There is therefore a need for advanced technologies to control and optimise operation within these strict regulations and constraints. This is what model based predictive control can uniquely provide, through dynamically maintaining an optimal air/fuel supply.

The use of alternate cost-effective fuels like waste gases, biomass, municipal waste and the shift towards multi-fuel boilers is highlighted, as fuel is the greatest overall cost factor. It is argued that a thorough analysis of the asset together with the use of advanced control and automation can yield significant sustainable energy savings and financial returns. Moreover good control can increase efficiency by dynamically maintaining an optimal air/fuel supply.

Section 3 looks at the traditional approach to combustion control which tends to rely on having fuels with stable calorific value (natural gas, oil, etc) and with essentially fixed air fuel ratio. Some basic approaches for dynamic combustion control to increase combustion efficiency and stability are discussed.

In Section 4 the report considers an example of a leading combustion control system, namely SmartProcess Boiler that is commercially available from Emerson and for which access to technical information was provided. It is an advanced control application which integrates with existing lower level controls to fully automate combustion. Online calorific analysis of the energy content of any fuel (or fuels in the multi-fuel boiler case) is obtained continuously and compared against heat demand requirements and other constraints (e.g. cost, quality and supply of fuel, emissions and process faults). Optimal set-points for the control of air and fuel are then determined. The combination of automation, lower excess air from combustion, decrease of emissions and increase of the use of alternate fuels is shown to yield proven benefits of up to $1.2M in a single large scale multi-fuel boiler.

# Contents

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# 1. Introduction

Driven by major economic and environmental restrictions, the field of energy generation for industrial processes is about to face significant changes over the next 10 years. The decrease of resources and rising costs in fossil fuel based energy along with strict initiatives against emissions of greenhouse gases (EU 20/20/20 legislation) necessitates changes in the operation of large industrial units. As a result strategies that promote the utilisation of cleaner, cost effective alternatives like biomass or waste based fuels are becoming more attractive. A particular area where this is applicable is the optimisation of the overall energy generation cycle in large multi-fuel boilers.

The benefits that can be achieved by improving control in these applications are often significant. Currently many control loops in the industry run in manual operation (more than 30% in some cases), controllers are sub-optimally tuned and equipment is often problematic. The shift to more efficient configurations (e.g. multi-fuel biomass and gas based boilers) is not therefore a trivial task.

This report focuses on a very important component in boiler operation, which is the control of combustion. As explained in the following sections combustion control consists of a series of interacting loops responsible for defining the correct combustible ratios to deliver the right amount of air and fuel whilst responding to the varying heat demand requirements of the boiler. The use of multi-fuel boilers adds extra complexity.

For fuel/air supply control a straightforward approach would be to breakdown the process and treat each subsystem separately. This would require addressing interactions between them separately in terms of control loop disturbance rejection and also in relation to safety. The individual controllers in this case are mostly simple Proportional-Integral-Derivative (PID), often in combination with feedforward control. The optimisation of fuel consumption and combustion efficiency (with respect to load and economic factors) traditionally relies on manual intervention, particularly if there are changing set-points and fuel types.

Advanced control methods can cope with interactions and the changes in set-points, system parameters and disturbances. For example, the SmartProcess Boiler advanced combustion control by Emerson uses an optimisation approach which can take advantage of an existing setup. It monitors energy release and heat demand requirements online and generates the most efficient boiler operation for safety, fuel savings and emissions reduction. It is therefore an intermediate step bridging the supervisory level, in which optimal air/fuel quantities are computed online, with the final control elements that deliver air and fuel supply.

# 2. Combustion in Industrial Boiler Systems

The mechanism of combustion is summarised in Figure 1. Fuel and oxygen are combined in the appropriate ratios. From resulting exothermic reaction, heat is produced which is then used to increase the temperature for various applications that range from power generation to other non-electric utility industrial processes (e.g. steam production, product heating etc.). The by-products of combustion are solids (ash for solid fuel boilers) and gases like nitrogen ($N_2$), carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$), and sulphur oxides ($SO_x$).

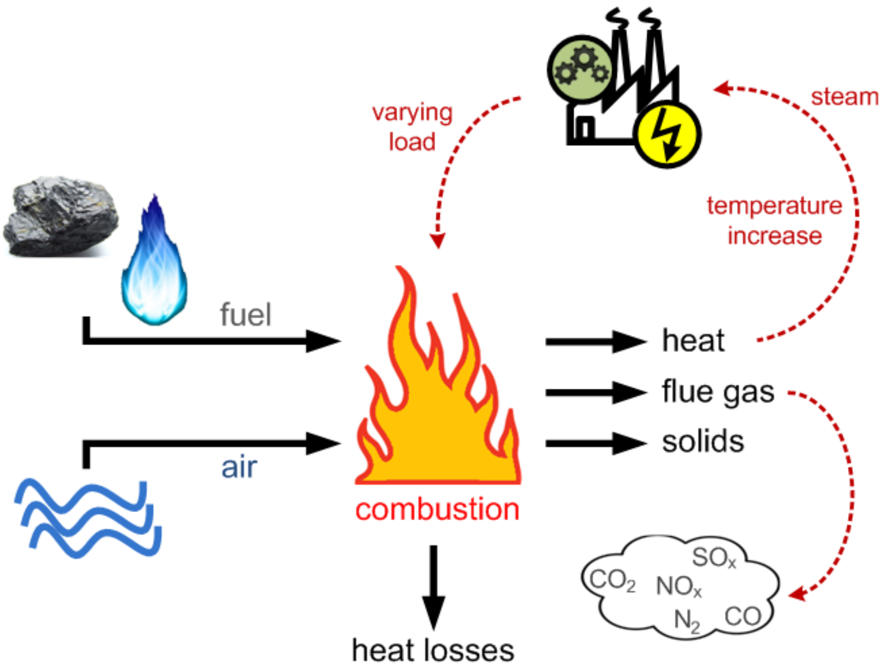


**Figure 1: Heat generation through combustion**

In this study, combustion is considered independent of the type of process the generated energy is used for (i.e. steam/electricity for boilers and heated product for fired heaters), and simply considered as a varying heat demand (load) as seen in Figure 1.

Combustion is a vital area in boiler control and highly coupled to the overall system efficiency and process economics. It is common to find many control loops running in manual operation, automated loops that are poorly configured and degraded equipment for various reasons (e.g. inadequate maintenance, faulty sensors etc.)[1]. A typical breakdown of factors responsible for abnormal situations is shown in Figure 2. Assuming that issues regarding equipment condition and suitability have been taken care of, there remain a significant proportion of problems that can be avoided through improved and advanced control. Several ways to achieve this are discussed in the following section[2].

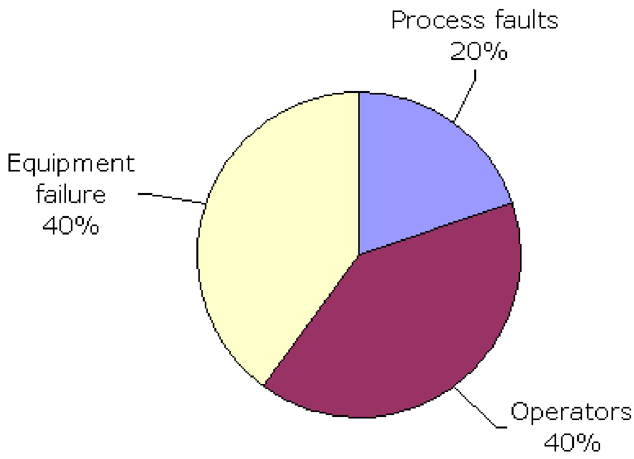


**Figure 2: Potential causes of abnormal situations in a plant[3] by %.**

## 2.1 Control Objectives in Industrial Combustion

As with all energy generating processes the principle task of combustion control is to match the energy generated to the energy consumed whilst maximising efficiency. Furthermore emissions and operation costs should be kept as small as possible. Once in service the only possible way to achieve improvements is by improving fuel usage, load and operational stability which can be accomplished through better control. The key economic considerations are efficiency, emissions and fuel type trade-offs as covered in the next sections.

### 2.1.1 Efficiency Considerations

Efficiency in a boiler system refers to the steam generator input-output heat ratio as shown in Equation 1 and usually varies between 60% and 90%.

$$Efficiency\ \eta_{boiler},\quad = \frac{Heat_{output\ to\ process}}{Heat_{input\ from\ fuel}} \times 100 \qquad \textbf{(1)}$$

There are two methods of calculating boiler efficiency the *direct* and the *indirect*. For a steam raising boiler for example the direct method relies on fuel, steam flow, boiler temperature and pressure measurements to calculate the ratio as defined in Equation 2. $Q_s$ is the steam flow in kg/hr, $Q_f$ is the fuel flow in kg/hr, $h_s$ is the enthalpy of saturated steam in kCal/kg of steam, $h_f$ is the enthalpy of feed water in kCal/kg of water and $CV_g$ is the gross calorific value of the fuel in kCal/kg of fuel.

$$Efficiency\ \eta_{boiler},\quad = \frac{Q_s \times (h_s - h_f)}{Q_f \times CV_g} \times 100 \qquad \textbf{(2)}$$

In what is referred to as the *indirect method* (Equation 3), analysis is carried out in fuel and stack gas to perform a per-unit-basis calculation of all heat losses which are then subtracted from the heating value of the fuel and the percentage against the latter is obtained.

$$Efficiency\,\eta_{boiler}, \quad = \frac{Heat_{input\ with\ fuel} - \sum Heat_{losses}}{Heat_{input\ with\ fuel}} \times 100\,, \qquad \textbf{(3)}$$

More details on the indirect computation of boiler efficiency can be found in various sources[3, 4, 5].

There are various factors that contribute in the overall efficiency of industrial boilers. This study only considers those which can be improved through advanced combustion control strategies as listed below.

**Thermal Losses;** the main thermal losses during combustion that account for efficiency degradation are listed below[3]:

- *Dry Flue Gas Loss:* heat carried out of the stack with the combustion air and products.
- *Moisture Loss:* loss due to evaporation of moisture in fuel (for Biomass) and the moisture produced from combustion of the hydrogen in the fuel.
- *Unburned Carbon Loss:* loss due to carbon that is not combusted and ends up in the refuse (ash).
- *Moisture in the Combustion Air Loss:* loss due to heating up water vapour produced from the combustion chemical reaction contained in the combustion air.
- *Radiation Loss:* heat lost from the external furnace walls to the surrounding air and other surfaces.

A summary of these losses in significance order for a conventional boiler can be seen in Figure 3[6].

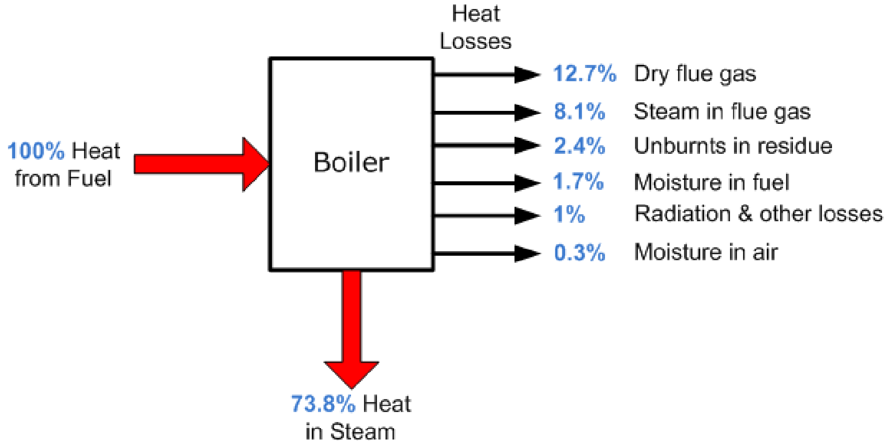


**Figure 3: Typical Industrial Boiler losses[6]**

**Excess air:** The regulation of excess air inside the furnace is of great importance for efficiency. This is defined as the additional air supplied to the burner beyond the amount that theoretically ensures complete combustion. It is within the safety features of boilers to operate at some level of excess of air. This guards against incomplete combustion due to equipment faults, $O_2$ measurement loss, fast variations in load demand etc. Air leakages into various parts of the furnace[5] (e.g. at the seals between the burner or stoker and the furnace) also contribute to the excess.

Figure 4 shows how efficiency in a typical fully loaded large boiler degrades with respect to excess air and fuel type[5]. It is calculated that 5% loss in efficiency due to only a small increase of 2% in excess air results in an increase of the yearly operating cost of about $50K in a 45,000 kg/hr boiler, converted into present rates[3].

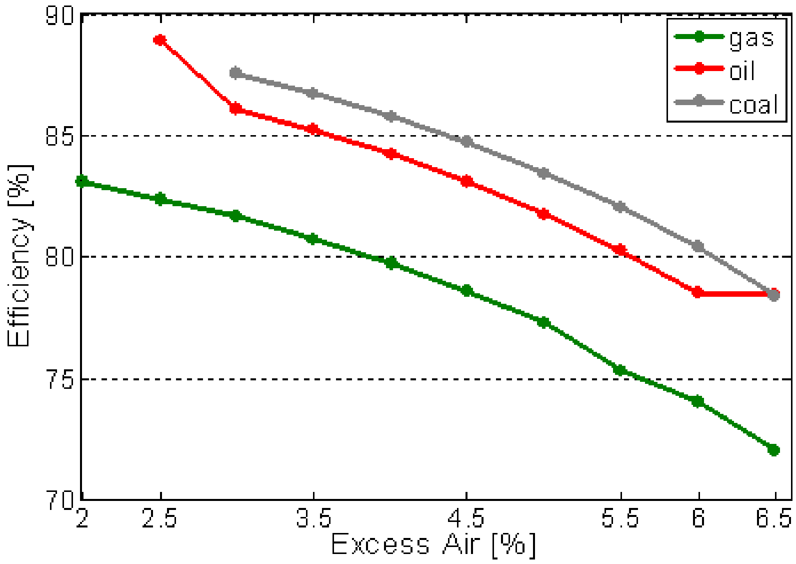


**Figure 4: Boiler efficiency vs. excess air in large boilers[5]**

Figure 5 indicates the optimal air-fuel ratio range to achieve a reasonable performance[3].

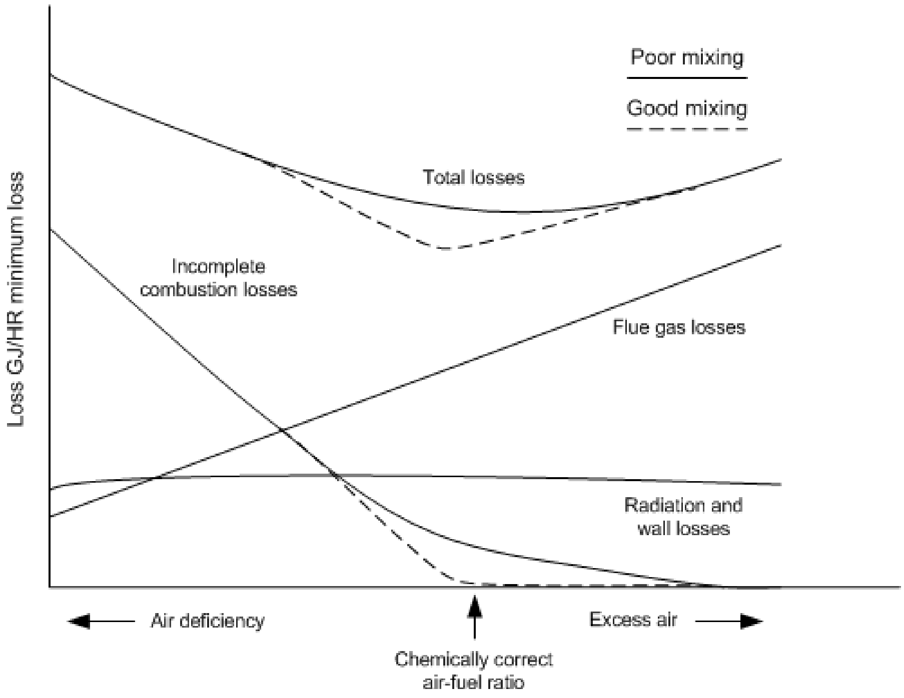


**Figure 5: Operational trade-offs vs. excess air levels[5]**

### 2.1.2 Combustion Emissions

In industrialised countries specific standards are implemented for the hazardous by-products of combustion which includes carbon monoxide and particulates, as well as greenhouse gases such as $CO_2$ and for $SO_2$ and $NO_X$. Industrial facilities that fail to comply with certain directives[7, 8] against these air pollutants are at risk of austere incurring penalties[9]. A recent study showed that Enel's European thermal power plants generated overall costs due to emissions of up to €169 billion in 2009[10]. On the other hand, methods that address this problem are often very expensive and technically challenging within short timescales which can force companies to compromise their competitiveness[11, 12].

Emissions in large industrial plants depend mainly upon the primary fuel type and boiler capacity, also upon the reliability and performance of controls. Poor implementation can lead to poor combustion which is not only inefficient but also a serious cause of harmful emissions. Advanced control can help provide proper conditions and improve emissions regulation within the acceptable limits, increasing savings and reducing damage to the environment.

### 2.1.3 Fuel Type Trade-offs

Typical fuel types for combustion are fossil based hydrocarbons like oil and gas which can either be used individually or in combination with selection based on availability and pricing[9]. In industrialised countries more than 50% of the industrial boilers use natural gas as the primary fuel. However, industrial boilers that primarily operated on fossil fuels are now often designed to use combinations of fossil, biomass and waste based fuels (by-products of site processes) to reduce costs. For a full load steam system, with a typical 86%-94% boiler utilisation, fuel costs are by far the main contributor in the total life cycle cost[9] with a typical overall breakdown as shown in Figure 6.

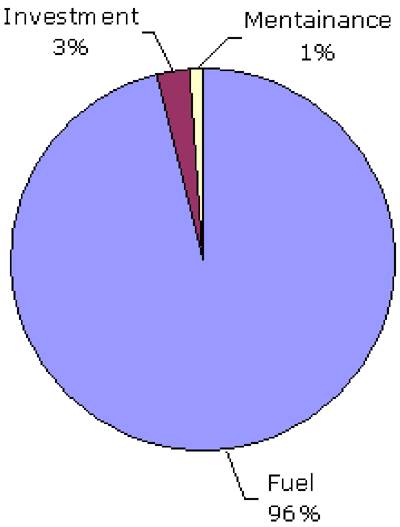


**Figure 6: Full load steam system costs breakdown[9]**

With respect to cost, alternatives like biomass and waste based type fuels appear to be a very attractive option and therefore are likely to be encountered more frequently in industrial multi-fuel boilers in the future. Further, biomass and waste gas fuels tend to be less affected by global economic instabilities, and can also have reliable availability from local resources. Studies show that while Gas supply costs rise by up to 15%, fuel like the wood chip and pellet maintain a rise of 3% annually[13]. Figure 7 shows typical variations in fuel costs[15].

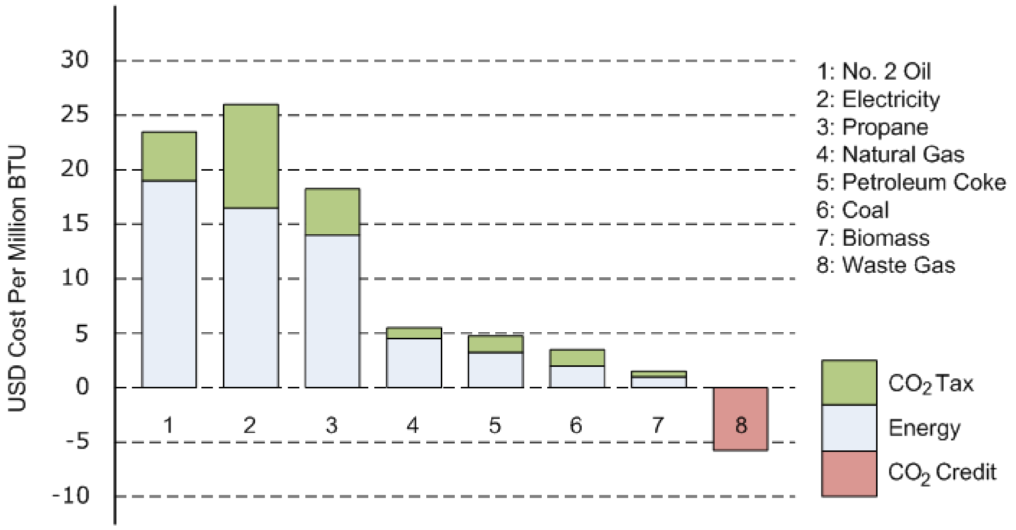


**Figure 7: Fuel Cost Including $CO_2$**

Despite the low $CO_2$ emissions, biomass fuels show higher emissions for other pollutants like CO, $NO_2$ and various other polyaromatic hydrocarbons especially when combustion is incomplete[14]. Another issue related to the use of biomass is the difficulty in physically handling/supplying the fuels due to their variable properties. Woodchip, for example, has a maximum fuel content of 35% and its size has to be made consistent for proper deployment.

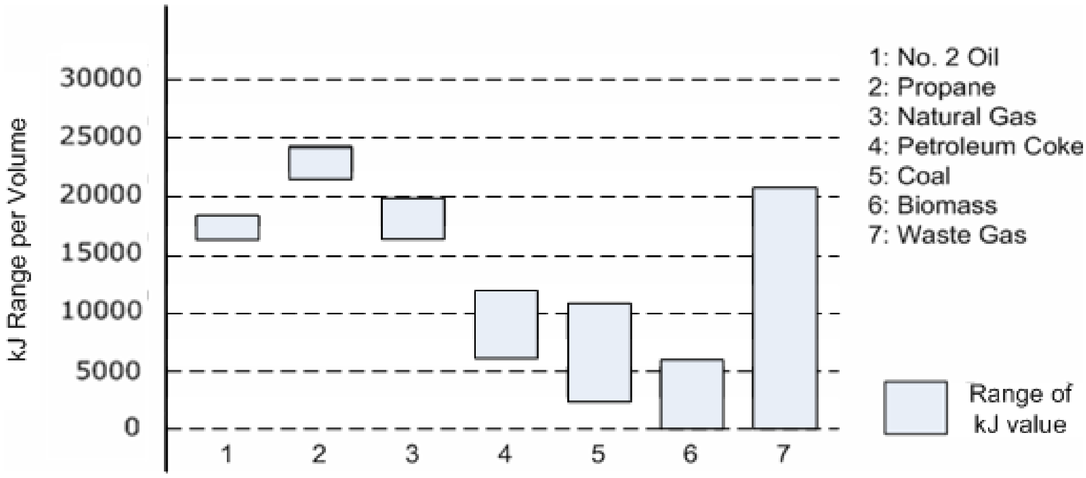


**Figure 8: Fuel calorific content variations[15]**

To allow utilisation of low cost biomass-based fuels while preserving system reliability in multi-fuel boilers, control strategies need to compensate properly for fuel calorific content variability. This manifests itself as a load disturbance in the combustion process and can reduce system efficiency. Even a stable and consistent fuel like natural gas can vary in calorific value per volume by ± 10% over time[15] and coal has a natural variability of ± 10% which can also differ further to the type and blends of coal[16]. Calorific variations with respect to fuel type are shown in Figure 8.

Last but not least is the high moisture content in biomass fuel which removes a significant amount of heat from the process when burning and so impacts the overall efficiency of combustion as compared with other fuels. Wood and biomass have moisture content often greater than 40%, resulting in a good annual average efficiency with these fuels of about 60%[16]. Even when using natural gas the resulting $H_2O$ content is high as a result of the chemical reaction in the combustion process. The effect on combustion efficiency (heat loss) must therefore be considered. However this is predictable and generally not as variable as in biomass or solid fuels.

# 3. Combustion Control Strategies

In any steam generation process, the load demand (header steam pressure or flow for a boiler or fluid temperature for a fired heater) must be met by the control system. It is a critical task as constant header pressure regulation is highly coupled with the overall stability of plant-wide operation. Driven by the process, this load can exhibit predictable and unpredictable variations. A good control system can ensure the generating assets, efficiently respond to these demands while optimising for minimal emissions and overall costs[3], especially when mixed fuel or simultaneous multi-fuel firing is considered.

## 3.1 Control Loops in Industrial Combustion

This section provides an overview of the main combustion control loops. In boiler applications a primary control loop will handle steam pressure deviations by adjusting fuel and air flow commands which drive the final control elements (valve controllers etc.). Proportional-Integral-Derivative (PID) controllers are traditionally used, often enhanced with feedforward to improve responsiveness. The principle objectives of these controls are:

1. To supply the correct amount of fuel as demanded by the process.
2. To maintain proper combustion zone conditions (air/fuel ratio) to support complete and safe combustion.
3. To attain highest possible efficiency.

There are important issues related to attaining these objectives in multi-fuel boilers, including:

- the varying calorific value of fuels and its impact on efficiency and emissions
- the discontinuity in fuel supply
- the unreliability or lack of measurements
- the guarantee of stability relative to the specific combination of fuels

The individual control loops traditionally used in combustion are explained in the following sections[3].

### 3.1.1 Load Control - Steam Pressure

The steam header pressure controller is termed the Boiler Master (or Plant Master in the multi-boiler case) and it outputs a firing demand. This demand corresponds to a change in air/fuel firing rate and it will naturally trigger the response of combustion controls.

In the intermediate level that computes fuel and air feed commands to regulate steam pressure variations, general schemes irrespective of the type of boiler can be employed[17] as seen in Figure 9 which will now be discussed in more detail.

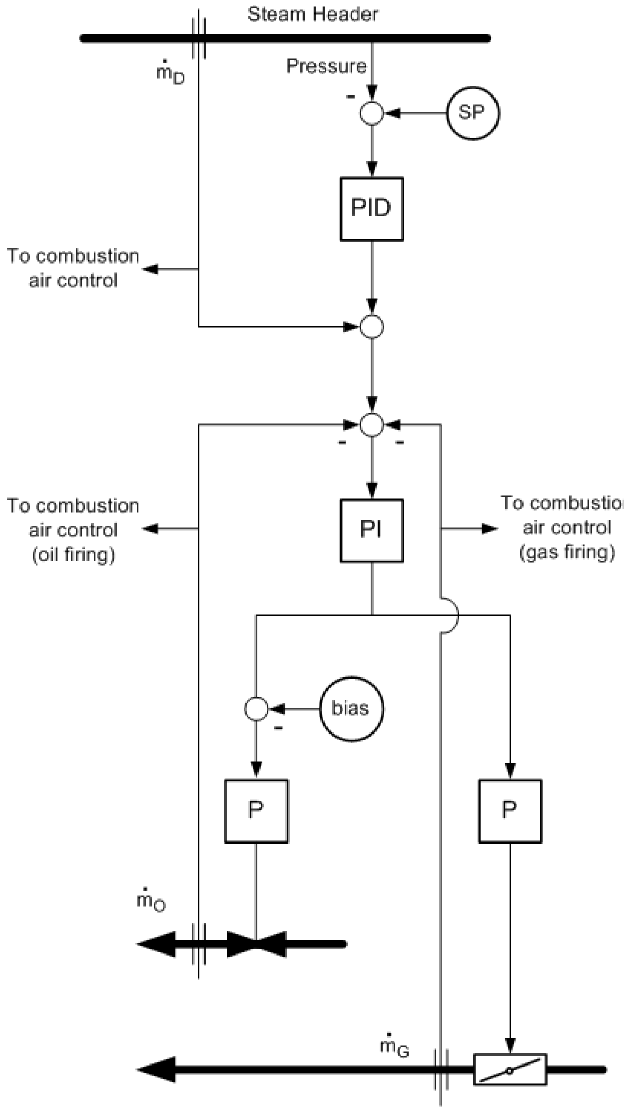


**Figure 9: Typical control scheme for firing natural gas and oil[17]**

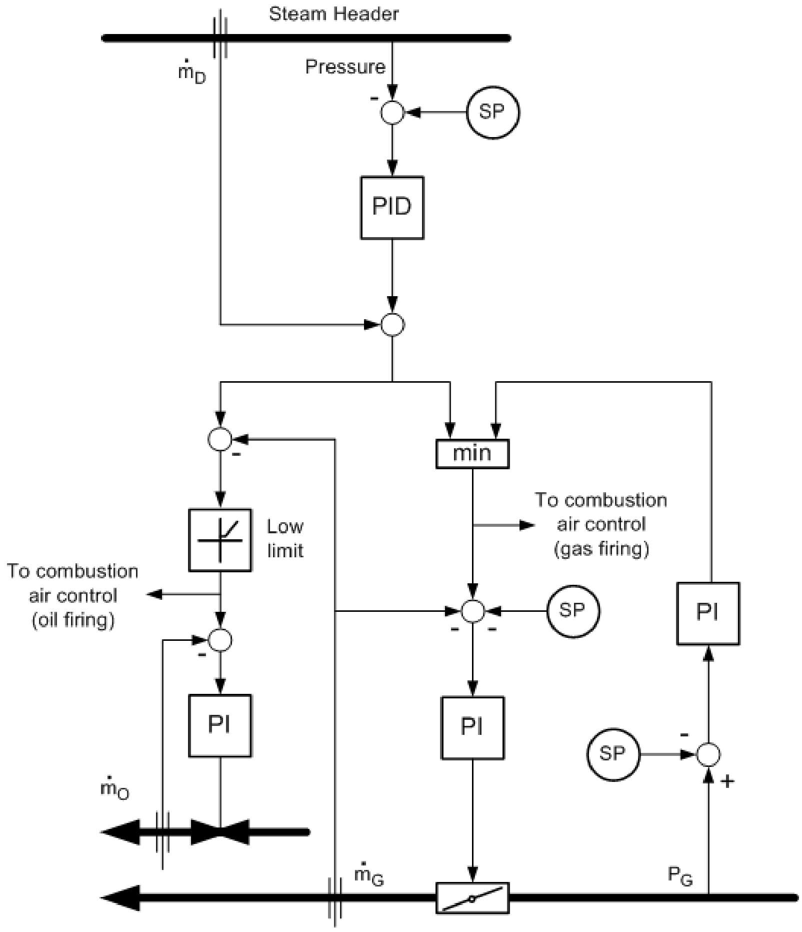


**Figure 10: Method for fuel burning prioritazation[17]**

Thermal energy that is released in the burning process is the main manipulated variable (MV). This energy is produced by the fuel flow and the matching combustion air flow[17]. In the first case (Figure 9), the master steam pressure controller is augmented with steam flow ( $\dot{m}_D$ ) feedforward compensation and provides the demand signal for the cascaded total fuel controller. This output then provides the driving signal for the fuels (oil and natural gas) control valves. Fuel flow signals like $\dot{m}_O$ are used to calculate the desired air flow into the combustion.

In this configuration both fuels are burned in a fixed ratio but given appropriate adjustments the ratio/order of burning can be defined differently. A common method is the sequential burning of the fuels i.e. for low loads only gas is burned and expensive oil is used only when gas is not available. A way to achieve that is by adding a negative bias to the oil flow controller as shown in the diagram (Figure 9). This negative signal keeps the oil control valve shut or just barely open until the fuel flow controller output signal rises above the negative bias.

Another approach is to replace the master fuel controller with separate controllers for each fuel. The advantage of this is that all disturbances on one side (e.g. oil burner out of service etc.) would be corrected by that firing loop alone and would have no effect on the other side.

In other schemes, as implemented in the SmartProcess Boiler for example, fuel burning is prioritised with respect to cost. A typical example would be the case where waste gases, such as blast furnace gas, are given priority to burn as much as is available instead of being flared to atmosphere. The main problem is the available amount of waste fuel may vary considerably which in turn necessitates smooth transitions between fuel controllers in order to avoid disturbances in steam production.

A possible solution to this problem can be seen in Figure 10. Starting with the assumption that no fuel gas is available, steam pressure control is derived by oil fuel only. Here a low limit is provided to guarantee a minimum oil flow in all circumstances. This is very important as an extinction of the oil flame while there is surplus of fuel gas must be prevented at all costs. Upon the start of the gas flow, gas pressure $P_G$ rises and the fuel gas pressure controller (note this is direct acting where error=PV-SP) acts via a minimum selector on the gas flow controller. The other signal to the selector comes from the steam pressure controller and corresponds to boiler load (upon start-up it needs to be greater than the signal coming from the gas pressure controller which starts from zero). Thus the gas pressure controller keeps increasing the set-point of the gas flow controller as long as the gas flow into the furnace is below that available, and the oil flow is gradually reduced in proportion to the increasing gas flow.

### 3.1.2 Load Control - Steam Flow & Feedforward

Steam flow can also be used to represent load in boiler control. This is common where multiple boilers supply steam to a header. Load in this case can be the total steam output from all boilers. Alternatively, steam flow control sets one of the boilers to output a constant steam flow while other boilers handle the steam pressure control namely in *base load control.*

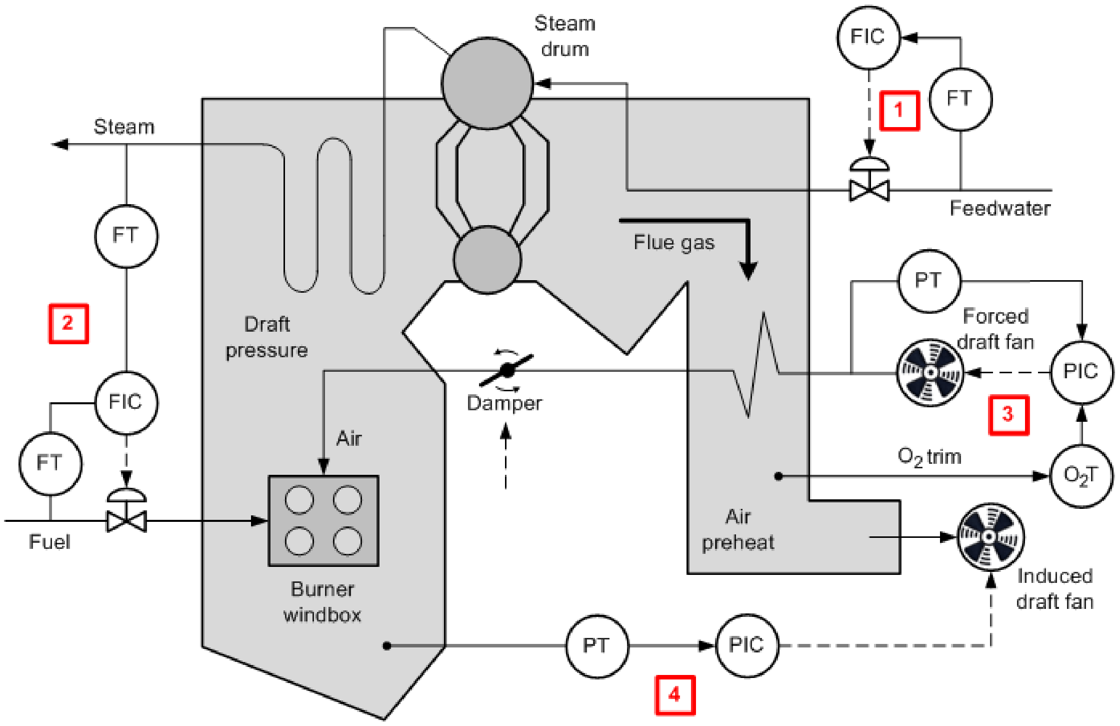


**Figure 11: Generic basic boiler controls on balanced draft type configuration[3]**

In Figure 11 a basic structure for boiler controls on steam flow load is presented. Feedforward on steam flow is used for compensation of faster load variations (Figure 10, box 2). Often if the boiler is fired with more than one fuel then one of the fuels is set at a constant firing rate while the second is controlled to compensate for load fluctuations. Feedforward can also mitigate the inherent dead times in boiler response. Steam flow measurements should be avoided for this purpose as they do not necessarily correspond to actual demand. For example an increase in steam flow caused by increased firing should not be interpreted as a load increase as this would create a positive feedback loop that could potentially destabilise the boiler.

### 3.1.3 Air Flow Control

The air flow control loops (Figure 11, box 3, 4) are responsible for supplying and maintaining the appropriate excess air to allow efficient combustion and also maintain a pressure inside the furnace that is negative of ambient to avoid leakage and ensure safety. This task can be categorised as follows[17]:

1. **Natural draft:** excess air is naturally drawn into the furnace via the draft created by the stack and controlled by dampers. The downside of natural draft being combustion performance is affected by outside air conditions and flue gases temperature variations, which are disturbances on the combustion process and result in high excess air (low efficiency).

2. **Forced draft:** excess air is forced into the furnace through air ducts with the use of a centrifugal forced draft fan (FD). Air flow is regulated by a damper, or a variable speed drive on the fan (which does not have the hysteresis and nonlinearity of the damper). This also saves electrical power for the FD Fan. As seen in Figure 10, the draft can be preheated before entering the furnace to increase the overall efficiency of the boiler.

3. **Induced draft:** flue gas can be drawn out of the furnace and up to the stack using an induced draft fan (ID). Usually ID fans are used when the height of the stack is inadequate to meet the draft requirements. Negative pressure inside the furnace ensures air supply to the burners from atmosphere.

4. **Balanced draft:** excess air in the combustion chamber is achieved by regulating both the forced and induced drafts via combinations of fans. This is often encountered in large boilers where flue gases can travel long distances through many boiler passes.

### 3.1.4 Air/Fuel Ratio Control

**Active $O_2$ control:** Active control of the Air/Fuel ratio can be achieved with direct $O_2$ trimming, where an excess $O_2$ sensor in the flue gas automatically determines the adjustment to the air flow to maintain a target excess $O_2$. If for example one burner fails the $O_2$ measurement will detect a deviation from set-point and the $O_2$ controller will attempt to correct the error. This however can affect and compromise the operation of the rest of the burners. To successfully employ $O_2$ control good measurements, that accurately represent the entire area of combustion under all load ranges, are required. Due to the flue gas stratification and air leakage, this remains a difficult problem to solve[17].

**Characteristic curves:** A standard way to determine the correct air/fuel relationship is by empirically obtaining standard air flow characteristics for various boiler load levels[3]. Such an example is shown in Figure 12.

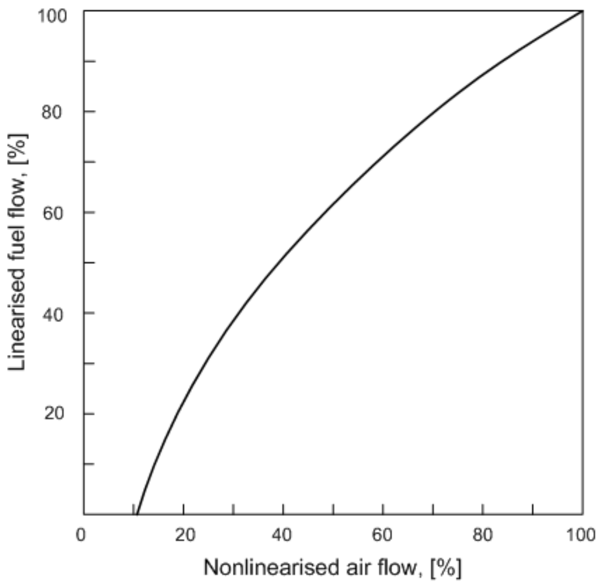


**Figure 12: Air / fuel ratio characteristic curve example[3]**

This approach is often used as a solution to inaccurate air flow measurements at less than 25% of the maximum boiler load. In many cases the oxygen trim of air/fuel ratio is turned off within this operating region. The downside of this method being to maintain safety, excess oxygen levels are often higher than optimal to avoid incomplete combustion. Moreover, they are only defined for specific ambient conditions and fuel type, therefore they become sub-optimal when these parameters vary.

**Cross limiting:** A key point to remember is that fuel demand should not exceed the corresponding combustion air for complete combustion. Air/fuel cross-limiting ensures there is no chance of a “fuel-rich” mixture arising from changes to the firing rate (up or down). Specifically, cross-limiting addresses the problem, when the firing demand is increasing there is a tendency for the fuel flow to rise before the air flow, simply because it has a naturally faster responding actuator. A cross-limiting scheme has the fuel flow demand lagging the actual air flow in this situation and vice versa for falling firing rates. Figure 13 shows air and fuel feed responses during a load change in a system with cross-limiting[18].

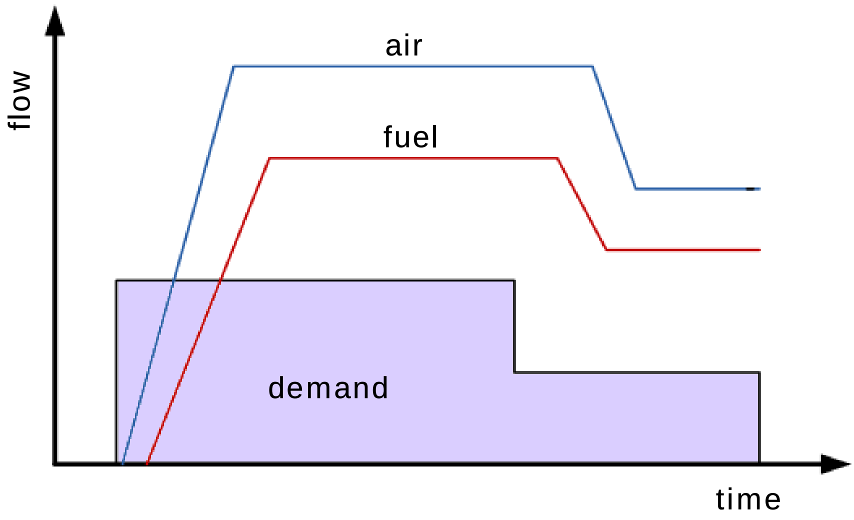


**Figure 13: Cross-limiting effect during load changes**

# 4. SmartProcess Boiler Control

Emerson's SmartProcess Boiler control was reviewed with information made available by the company. It is an innovative approach for multi-fuel boiler control that fully automates the combustion and safety requirements described in the previous section by incorporating on-line fuel calorific value analysis. It does not require significant restructuring or replacement of existing equipment and it can be installed on top of existing low level regulatory control loops, provided necessary measurements from the process are available. Also, final control elements need to be prime working order and any significant problem that hinders their operability should be resolved beforehand.

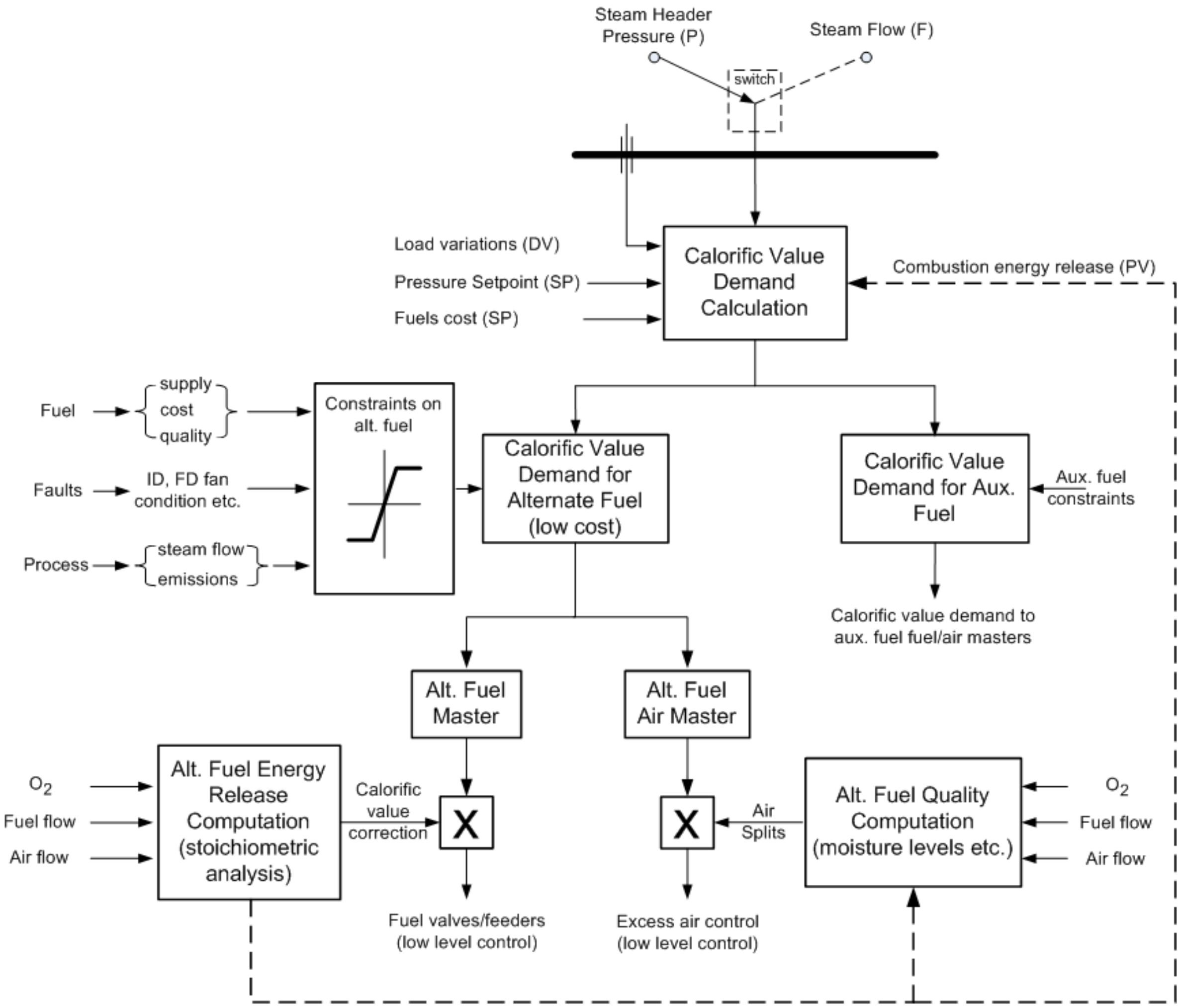


**Figure 14: SmartProcess Boiler optimisation strategy**

Figure 14 illustrates where SmartProcess Boiler optimisation fits in the overall configuration of boiler pressure control for multi-fuel boilers with low cost alternate fuel (e.g. waste fuel, biomass etc.) and auxiliary firing to backup when needed. Notice the analogy with structures in Figure 9, 10 which highlights the underlying simplicity of the SmartProcess Boiler concept.

## 4.1 Energy Optimisation Methodology

As shown in the diagram SmartProcess Boiler co-ordinates individual control logic for automatic air and fuel distribution into the combustion under the overall objective of “Energy” control. Variables like air-fuel flow, oxygen levels and process output are used in the online computations of fuel constraints and stoichiometric analysis algorithm, with everything translated into energy release (Calorific value) variations and limits. For example header master pressure demand is also translated into a demand in GJ. This approach naturally accommodates fuels with different calorific content as each fuel is normalised on an energy release basis and the system is aware of relevant variations (switching between fuels) before applying the air-fuel commands. Even for cases where flue gas analysis was carried out to evaluate excess air levels in combustion for control purposes, the stoichiometric algorithm offers a more robust tool preventing direct measurement variations due to varying fuels composition. SmartProcess Boiler operation can be summarised as follows:

***Stage 1 (fuel selection):*** Steam pressure (or flow depending on the control mode selected) of the Boiler Header Master is converted to an energy demand in GJ (load disturbance). This demand is then compared against the current heat release in the combustion chamber and pre-specified setpoint to generate the control error (GJ). A decision is made, based on fuel cost/availability (in the multi-fuel case), regarding the most cost efficient fuel that should be used in response to the demand. A bias towards alternate fuels like Biomass or waste gasses is hence naturally achieved. In effect SmartProcess Boiler always optimises base load to be handled by the alternative fuel (60-70%) while auxiliary fuel is only used when necessary; when least cost fuel is limited or unavailable, fuel pressure goes below bias etc. Finally this decision signal drives the equivalent fuel master, for which there is a dedicated master for every available fuel.

***Stage 2 (air/fuel ratio definition):*** The air/fuel ratio for burning fuels that have been prioritised by Stage 1 is determined by considering various factors such as current fuel supply rate and quality, steam flow, emissions restrictions and operational status (e.g. any fault in the excess air regulation control elements - ID, FD fans etc.). The air and fuel flow commands are then handed over to separate masters for each. Note that because air demand is based on GJ and not air/fuel characteristic curves, lower excess air can be achieved while guaranteeing sufficient oxygen levels across the entire load range.

***Stage 3 (disturbance regulation):*** Is where measurements of oxygen and air/fuel flow are used within the stoichiometric combustion analysis. This is an on-line calculation which acts as a feedforward term to provide direct compensation for energy release deviations due to variations in the combustion (e.g. fuel moisture content variations, air leaks, fan trips etc.). Fuel corrections are then handled by the fuel master and air corrections through air splits adding to the flow coming out of the air master. The energy release PV in GJ is also computed and fed back to the 1st stage controller. It is also used in the air flow corrections feedforward term calculations.

## 4.2 Control Approach

The underlying control strategy in the SmartProcess Boiler application utilises Model Predictive Control (MPC). This is a very successful advanced control technique used in applications spanning chemical to aerospace industries. It has the ability to optimally control a multivariable process when subject to constraints. Figure 15 is the same scheme as in Figure 14 but showing what the MPC controller encompasses. The operator has the option to choose between header steam pressure or steam flow control depending on the operation more. Smooth switching is provided between the two modes.

A model of the process is used to provide future predictions on the *main steam flow* and *fuel set-point*, based on least cost, with respect to constraints. The constraints can include the flue gas $O_2$ and CO levels, the ID fan status, the steam header pressure and the boiler drum level. Minimisation of the cost function gives the optimal fuel demands which are then passed to the individual fuel and air masters. The use of energy-based control provides automatic online corrections for changes in fuel moisture content, availability of fuel and other factors that might affect the consistency of combustion sufficiently quickly.

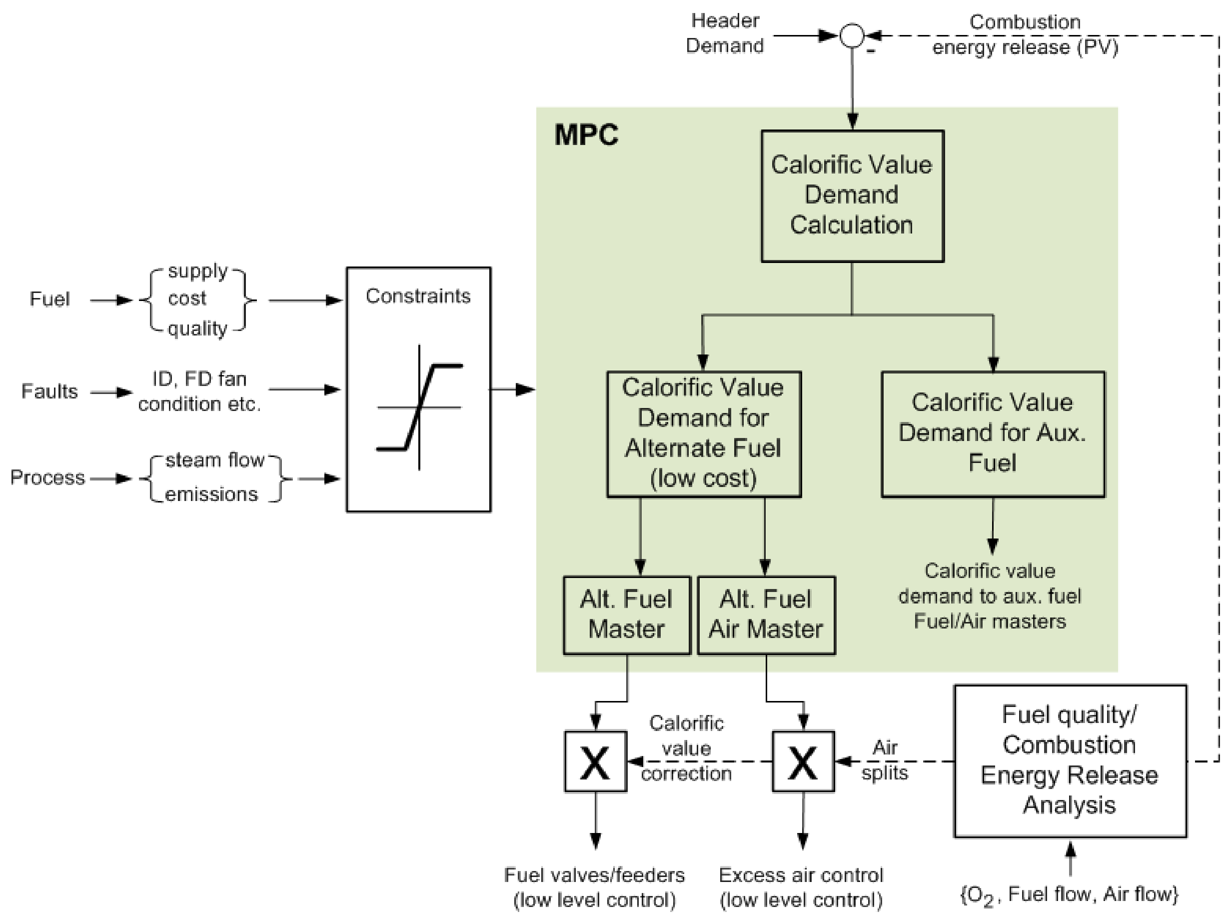


**Figure 15: SmartProcess Boiler strategy rearranged in a feedback control formulation**

### 4.2.1 **Fuel Prioritisation**

Fuel and air demands are computed after the fuel optimisation stage. Consider the case where natural gas is the most expensive fuel. Its use is controlled by the available amount of calculated air that remains after considering the burning of low cost fuels. Should this amount exceed a certain value (e.g. due to limited supply of waste gas or biomass fuel which leads to an increase in excess air), only then is that path enabled and natural gas can contribute to the combustion. The same arrangement applies to all fuels and an air leading fuel relationship is established.

### 4.2.2 Excess Oxygen and Air Flow Control

The total air demand is then determined from the target excess air and the individual air/fuel to fuel demand ratios as seen in Equation 4, for a three fuel scenario (i.e. natural gas, waste fuel and fuel oil).

$$Air\ Demand_{total} = \left(\sum_{n=1}^{3} Fuel_{demand} \times \frac{Air}{Fuel}\right) \times Excess\ Air_{demand}\,, \qquad n = \{nat.\ gas,\ waste\ fuel,\ oil\} \qquad \textbf{(4)}$$

Two feedback controllers in cascade are used to regulate the air flow into the combustion chamber as seen in Figure 16. A header steam demand measurement is translated into a demand in excess oxygen which is the set-point for the corresponding controller. A trim is used to provide a measurement on the current levels of oxygen and compared against the set-point, gives the error that drives the PI controller. In turn the excess oxygen controller provides the set-point for the inner final air flow controller.

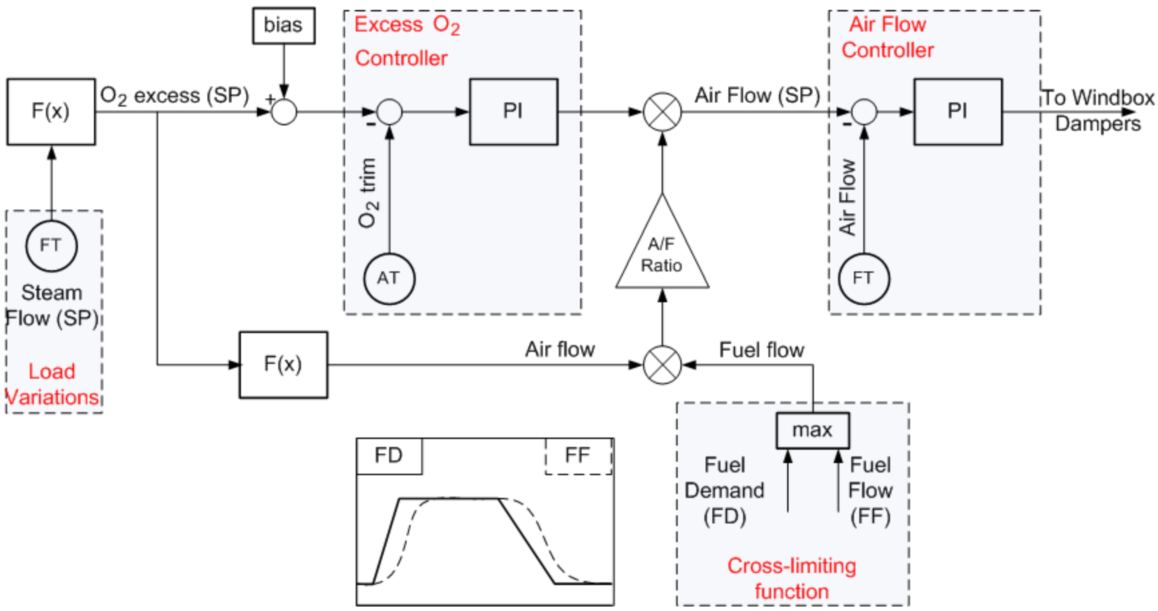


**Figure 16: SmartProcess Boiler Air flow control and cross-limiting**

The air flow set-point is adjusted via feedforward action with respect to load variations which the excess $O_2$ feedback loop maybe too slow to follow (it is common for oxygen measurements to be relatively slow, resulting in a slow overall feedback response. Another adjustment comes from the relation between fuel flow and fuel demand. Considering the time lag between a fuel demand and the actual resulting fuel flow the higher of the two is selected to create an air leading fuel relationship ensuring that there is always sufficient air for combustion (cross-limiting) during transient operations. This mechanism mostly applies to gas or liquid fuels, for solid fuels the air and fuel relationship is managed using calculations to provide a more flexible and robust strategy.

### 4.2.3 Calorific Value Compensation

As mentioned earlier, alternative fuels like waste gases or biomass exhibit inconsistency in the energy released upon burning. Variations in pressure and temperature caused by this effect may compromise stability of operation. Conventional methods to tackle this issue would see this drop in energy output in temperature and pressure measurements. The feedback control loops then would react to compensate for these variations by adjusting the fuel supply accordingly. This approach means that the time before the system actually responds to this disturbance can be substantial.

A key feature of SmartProcess Boiler utilises the total airflow and excess air measurements into a simple equation (Equation 5) parameterised with respect to one particular fuel. This equation is then used to calculate the air that is consumed in combustion and consequently obtain a more accurate estimate of the energy release. Factors in the equation are converted from % percentages to a multiplier relative to 1.0.

$$Consumed\ Air\ Ratio = \frac{Actual\ Airflow_{total}}{Target\ Air\ Demand_{total}} \times \frac{Target\ Excess\ Air_{fuel\ type}}{Actual\ Excess\ Air}, \qquad \textbf{(5)}$$

For example, a consumed air value of 0.95 would mean that the boiler has experienced a 5% reduction in heat input. This information is then applied as a trim control to the relative fuel to automatically compensate for the drop, so that the heat release in the boiler remains more consistent for any given load.

# 5. Conclusions about SmartProcess Boiler

The advantages from using the SmartProcess Boiler application are evident in different aspects of a combustion process. From an implementation point of view, it is a technology that integrates well with pre-installed equipment with few requirements, mostly concerning the operability and configuration of lower regulatory control loops and access to necessary instrumentation (sensors etc.).

The main feature is fuel delivery optimisation with the use of true Energy control. With only three measurements (air flow, fuel flow and excess oxygen on the boiler outlet), a stoichiometric algorithm calculates the energy release from combustion and this is then fed back to a model predictive controller which rapidly compensates for load variations. In addition constrained optimisation (available through the predictive action) prioritises available fuels ensuring the low cost ones are used at up to 60-70%, whereas the use of auxiliary fuel is restricted to situations when the alternative fuels are limited. As presented in Figure 6 fuel for a full load steam boiler can rise up to 96% of through life costs when compared against all other costs like maintenance and capital investment.

A typical paper industry boiler of capacity 105GJ/hr can have an annual natural gas consumption of $316x10^3$ GJ. Assuming a taxed price of \$5 per 1GJ of natural gas from Figure 7, an annual fuel cost of \$1.5M is obtained[9]. A reduction of 70% in natural gas and the use of biomass instead to meet the same calorific demand could give a total fuel cost of \$0.6M (\$0.4M of natural gas - 30% and \$0.2M of biomass - 70%), corresponding to an annual profit of \$900K. Obviously these numbers will vary depending on the exact application, boiler size and fuel costs. There would be an even higher gain if the specific fossil fuel was related to high $CO_2$ taxation. In a similar process site in North Carolina an equivalent reduction of 70% in fossil fuel use was achieved by installing the SmartProcess Boiler application. That along with improvements in efficiency and steam variability resulted in \$1.2M of annual savings.

By avoiding air/fuel characteristic curves and the fidelity of measurements through the use of an energy release algorithm, lower excess $O_2$ levels are achievable. Figure 4 shows that for large scale boilers even a 2% decrease in excess $O_2$ can bring substantial economic savings.

The quality and supply of fuels is monitored online and output energy deviations due to moisture content and/or supply variations are directly compensated. This effectively reduces variability of steam generation and allows process set-points to move closer to certain limits where maximum efficiency is achieved. An example of this can be found in Johnman ET al[19] for a boiler final steam temperature control loop. Due to high variability of the process, steam temperature is set below the maximum achievable value. That study estimated that by reducing variability through improved control, the steam temperature set-point could be increased by 6 °C giving a total annual benefit of approximately \$1M from improved process efficiency.

Advanced control has much to offer in this application area and potential benefits are easy to determine, however transforming and upgrading existing control systems can involve considerable effort and require both expertise and experience. Further minor changes to existing classical controls are unlikely to lead to meaningful improvements and hence a commercial product that is easy to apply in many different situations is valuable.

From the review completed the SmartProcess Boiler application has significant benefit and integrates well with the plant and can be extended with other optimisation packages like the SmartProcess Header, SmartProcess Energy and the Delta V Burner Management Systems

(BMS) (not examined in this report). It is based upon proven predictive control and can ultimately deliver maximum efficiency and coordinate combustion of up to 7 boilers on any combination of fuels and availability.

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