Proceedings of the 12th International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT 2025)
July 15, 2025 - July 17, 2025 | Imperial College London Conference, London, United Kingdom
Paper No. 213
DOI: 10.11159/ffhmt25.213

A Method for Calibrating a Thermo-Fluid Model of a Hybrid Biomass Boiler Using Low Fidelity Plant Data

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Abstract **-** Numerical thermo-fluid models of whole boiler systems can be robust tools for optimising boiler designs in terms of steady-state efficiency as well as inform optimum control strategies to increase transient flexibility. The benefits of such models only bear fruit if they can be validated against real life operational measurement data. In practice, it is not always possible to obtain a full set of data describing the system with no redundancies. Additionally, uncertainties in measurements creep in leading to low fidelity data that may be inconsistent or contradictory. This paper introduces a weight based ranking methodology applied to the various errors between model predicted conditions and site measurement data for a unique 4 ton/hr hybrid fire-tube-water-tube boiler. A key aspect of the proposed method applies the ranking system to the errors of 5 measured temperatures against the model predicted temperatures for a parametric study that varies an effective radiation scaling factor (C-factor). Verification on the heat transfer rates between simple analytical models, numerical Flownex models and the Maximum Continuous Rating (MCR) data for the individual heat exchangers provided confidence in the implemented thermodynamics in the individual Flownex heat exchanger models. This formed a strong starting point for calibration of the integrated whole boiler Flownex model via the proposed error ranking methodology. The calibrated model can serve as a reliable tool for performance analysis and transient control studies.

Keywords**:** Heat transfer, fire-tube boiler, water-tube boiler, calibration, analytical, transient, Flownex

1. Introduction

Numerical simulation models of biomass boilers are important for performance and control optimisation to aid operational flexibilities which may arise such as steam demand changes and fuel quality variability. The present work shows a systematic approach to calibrate a numerical Flownex model of a hybrid boiler using low fidelity plant data. Flownex [1] is a one-dimensional thermofluid network solver software known for its accuracy and computational efficiency.

Operational measurement data is crucial for power plant and process performance monitoring [2]. Measurement uncertainties due to device type, measurement techniques, and equipment degradation prevent perfect validation between measured data and numerical models. The authors of [3] emphasise the sentiment that all measurements are incorrect and that conservation laws can therefore not be satisfied. The authors of [4] explain that measurement redundancy used to minimise measurement errors is applied as part of a data reconciliation methodology.

Many authors follow the fundamental methodologies described in the Association of German Engineers guidelines – VDI 2048 [5]&[6]. These guidelines involve a statistical methodology for data reconciliation by manipulating the measurement redundancy and process data constraints. The methodology applies the least squares optimisation to minimise the sum of the squared deviations between measured and predicted values. Reference [3] applies the statistical methodology through and equation-based solver (VALI III) to reconcile data for measurements of a Nuclear Power Plant. [3] reports a 2% deviation between the measured and reconciled feedwater flowrate with a reconciled reactor power up to 30MWth lower than the power based purely on the measurement data.

As described by [2] when the number of measured values is larger than the number of unknown parameters, then there is a redundancy. The redundancy coupled with inevitable measurement errors results in calibration conflicts since the erroneous data cannot satisfy the fundamental mass, momentum, and energy equations [2].

In the present work, a rigorous model development and verification of each heat exchanger model, followed by fine tuning of the integrated model through parametric studies was only able to ensure agreement with the site measurement data to a certain point. After successful calibration of the feedwater mass flow, Air-Fuel-Ratio (AFR), and fuel flow requirement in the present work, the last step is to calibrate the furnace radiation contribution via an effective view factor (C-factor). The redundancy leading to the calibration conflicts in the present work presents itself as 5 measured temperatures whose values are targeted through the fine tuning of a single parameter – the so-called C-factor.

To combat the redundancy the present work proposes an error weighted calibration methodology to assign subjective confidence rankings to the 5 redundant temperature measurements. The rankings are assigned with insights from the manufacturer regarding the practical limitations of certain measurements. The ranking system allows one to normalise 5 model-vs-measurement errors to a single weighted error as a function of a single model parameter (C-factor).

The aim of this paper is to present a methodology to calibrate a whole boiler process model using low-fidelity data. The implementation of this methodology can provide a level of confidence to process modellers who face the challenges of low fidelity data, such that the resultant calibrated model can be confidently used as the starting point for further off-design condition and transient studies.

2. Plant of Interest

A 4 ton/hr hybrid unit was commissioned at a distillery in the Caribbean with architecture that includes an air heater and economiser, as well as a water-cooled furnace followed by a fire-tube evaporator as illustrated in Fig 1. The process flow diagram (PFD) in Fig 2 illustrates the relevant fluid stream paths. The biomass fuel is fed into the furnace via a port in the lower front wall where it falls onto the vibrating grate. The ambient air supply is split into two streams with the bulk being sent to the air heater to be heated (HA0-HA1), while the smaller portion of the supply air is sent directly into a plenum below the grate to cool it. The split ratio ("SR" in Fig 2) is the ratio of cooling air (CA) to the total combustion air (COMBA).

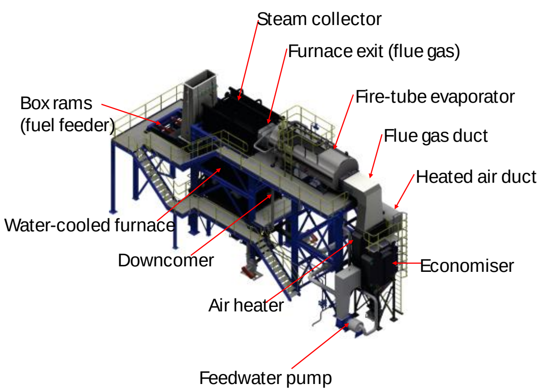

Fig. 1: 3D CAD model of the 4 ton/hr hybrid boiler

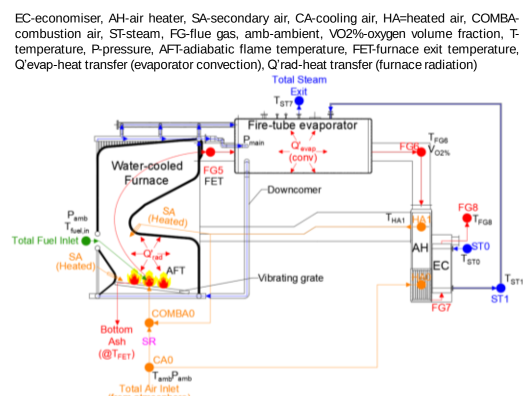

Fig. 2: Process flow diagram of the hybrid boiler of interest

After combustion of the air-fuel mixture, the product species are assumed to be at the adiabatic flame temperature which [7] defines as the "maximum theoretically possible temperature of the flue gas mixture (flame ball) at the outlet of the combustion zone." Radiant heat is transferred to heat up the water inside the waterwalls while the remaining hot flue gasses rise to the furnace exit at node FG5 in Fig 2. Heat is recovered from the flue gas downstream of the evaporator (FG6-FG8) where it is used to heat the air in the air heater (HA0-HA1) and preheat the feedwater in the economiser (ST0-ST1). The hot flue gas enables natural convective heat transfer from the firetube walls to the surrounding water in the evaporator shell. The combined convective and radiative heat transfer from the evaporator and furnace respectively causes a phase change from liquid to vapour inside of the evaporator such that saturated steam at node ST7 can be extracted for factory use.

3. Heat Exchanger Model Development and Verification

The MCR data available from the manufacturer included temperatures, pressures and mass flowrates for the fuel, air, steam, and flue gas streams at key points in the boiler system except for a Furnace Exit Temperature (FET at node FG5 in Fig 2). Unfortunately, the ultimate fuel analysis used to generate the MCR data is unknown. Since the FET is unknown, a direct comparison between the furnace and evaporator models with the MCR data is not possible.

Three types of models have been developed for the heat exchangers. The first type is the Analytical-air model (A-a) implemented in Mathcad where flue gas properties were assumed to be that of air for simplicity. The second type is the Numeric-air model (N-a) implemented in Flownex using the same air approximation. The third type is the Numeric-flue gas (N-fg) model implemented in Flownex to use the real flue gas properties by specifying the mass weighted compositions of a custom “flue gas” fluid developed in-house by the Applied Thermofluid Process Modelling Research Unit (ATProM). Good agreement between the Analytical-air and Numeric-air models verifies the correct implementation of the thermodynamic principles, while good agreement between the Numeric-flue gas and MCR-flue gas data validates the numeric model.

3.1. Economiser & Air Heater Model Development and Verification

The economiser is an inline finned-tube heat exchanger. with “H” type fins. The water splits into 6 tube rows from the inlet header as it makes 14 passes before collecting at the outlet header. The flue gas heats the water by making a single pass between the finned-tubes. The air heater is a multi-pass tubular heat exchanger with a staggered tube arrangement which sees the combustion air being heated through its three-pass flow between the tubes. The flue gas is the tube side fluid in the air heater and makes only a single pass. Both these heat exchangers were modelled using Flownex’s finned-tube heat exchanger component where only a single finned-tube component is employed for the economiser, as shown in Fig 3, while three are connected in series in the air heater model as illustrated in Fig 4 to account for the 3 air side passes.

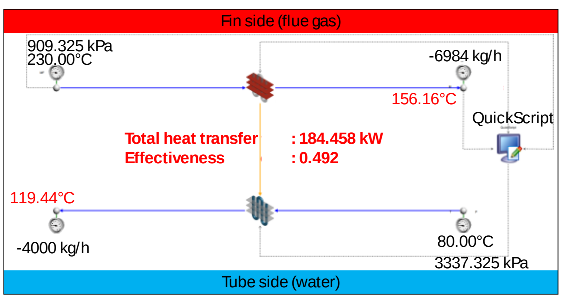

Fig. 3: Economiser Flownex model (single finned-tube heat exchanger and QuickScript component)

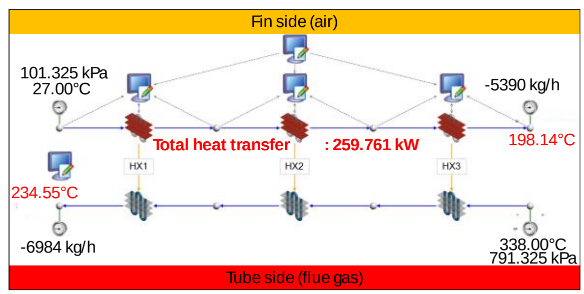

Fig. 4: Air heater Flownex model (3 x finned-tube heat exchangers in series and QuickScript components)

The QuickScript components illustrated in Figures 3 and 4 take in various geometric factors such as tube arrangement and nodal fluid properties such that convective heat transfer coefficients can be calculated and transferred to the fin side component inputs. Flownex’s built-in Gnielinski correlation is used to model the tube side convection while the QuickScripts (coded in C# by the user) employ Nusselt Number correlations for banks of finned-tubes from the VDI heat Atlas [8]. The QuickScript calculations follow the same heat transfer theory and correlations as implemented in the Analytical-air model.

Table 1 and 2 show a pairwise comparison of the Analytical-air model, Numeric-air model, Numeric-flue gas model and MCR data in terms of heat transfer rates for the economiser and air heater respectively. Green represents errors less than 5%, orange – between 5 and 10% and red – above 10%. In general, the results are within 10% accurate, with the biggest errors observed when comparing the flue gas models with air models. This error is to be expected, as the high moisture content of biomass flue gas causes a significant change in fluid properties as compared to pure air.

Table 1: Economiser heat transfer %error pairwise comparison

	A-a	N-a	N-fg	MCR-fg
A-a		-2.32%	-8.82%	-5.35%
N-a	2.37%		-6.65	-3.10%
N-fg	9.67%	7.13%		3.81%
MCR-fg	5.65%	3.20%	-3.67%	
Key: A-Analytical, a-air, N-Numeric, fg-flue gas				

Table 2: Air heater heat transfer %error pairwise comparison

	A-a	N-a	N-fg	MCR-fg
A-a		-0.30%	-9.33%	-8.70%
N-a	0.30%		-9.06%	-8.42%
N-fg	10.29%	9.97%		0.70%
MCR-fg	9.52%	9.20%	-0.70%	
Key: A-Analytical, a-air, N-Numeric, fg-flue gas				

3.2. Firetube Evaporator Model Development

The evaporator is a horizontal cylindrical shell with an arrangement of 116 firetubes through which the flue gas makes a single pass thereby heating up the surrounding saturated water via natural convection. The natural convective heat transfer is driven by a temperature difference between the outer tube wall and the surrounding fluid and has been calculated inside of the QuickScript using the Churchill and Chu correlation [9] before being transferred to the composite heat transfer component (CHP) linking the firetubes to the Two-Phase Tank as illustrated in Fig 3.

The Two-Phase Tank models the saturated water volume accurately and an enforced quality boundary condition ensures the correct design operational water-level. Other boundary conditions include a mass source of 4 ton/hr (i.e. MCR load) on the steam extraction, feedwater inlet temperature and pressure, flue gas inlet temperature and pressure as well as a flue gas mass source at the MCR condition. The temperature boundary condition enforced on the flue gas inlet has been taken to be that which was solved for in the Analytical-air model since no MCR FET data point was available. A convection heat transfer component coupled with a solid node was used to capture the steel thermal inertia of the evaporator shell as well as the solid steel staybars (structural supports) which is important for accurate transient analyses.

The pairwise comparison on the heat transfer rates is shown in table 3. Again, the difference between air and flue gas models are to be expected, while the good agreement between the two air models confirms a valid coding implementation of the heat transfer correlations in the Flownex QuickScripts.

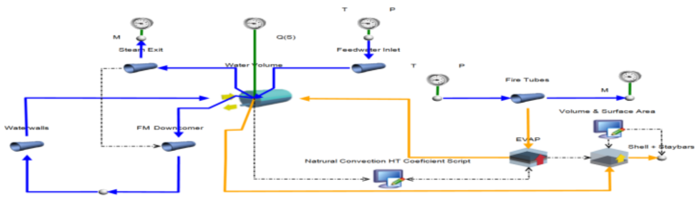

Fig. 3: Firetube evaporator model (Two-Phase Tank, Composite Heat Transfer, Convection, QuickScript and Pipe components)

Table 3: Evaporator heat transfer %error pairwise comparison

	A-a	N-a	N-fg	MCR-fg
A-a		0.30%	-18.90%	/
N-a	-0.30%		-19.14%	/
N-fg	23.31%	23.67%		/
MCR-fg	/	/	/	
Key: A-Analytical, a-air, N-Numeric, fg-flue gas				

3.2. Water-Cooled Furnace Model Development

The standalone furnace model consists of the combustion side and radiation side as illustrated in Fig 4. This model has been adapted from an existing and validated model developed by ATProM. The combustion side centres around an excel workbook component, which handles all combustion calculations based on user-specified fuel and air mass flow rates and compositions. Key outputs from the excel workbook includes the calculated calorific value, combustion heat and flue gas composition, among others. These results are transferred to the appropriate flow elements through data transfer links as illustrated by the dashed lines in Fig 4.

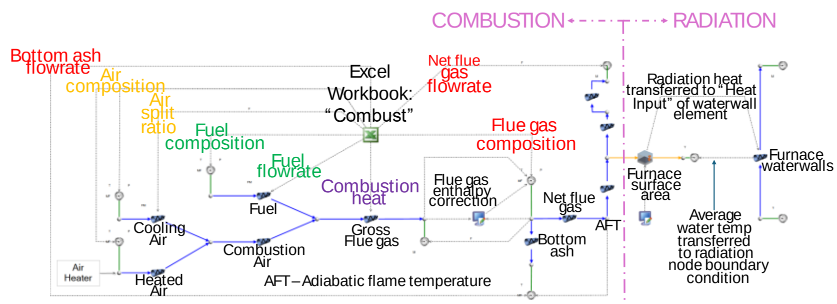

Fig. 4: Furnace Flownex model (Combustion Excel Workbook, Fluid Radiation, QuickScript and Flow Resistance components)

The radiation is modelled using Flownex's Fluid Radiation component which models radiative heat transfer between a solid surface (furnace wall) and a participating medium (flue gas). The direct radiation equation governing the net radiant heat transfer is shown in equation 1 below. This formulation accounts for the wall temperature (T_W), wall emissivity (ε_W) as well as the emissivity (ε_f) and absorptivity (α_f) of the gas particle suspension of the fluid (flue gas). σ is the Stephan Boltzmann constant and A is the projected area of the furnace walls which was calculated from the pipe lengths of the four waterwalls and furnace roof using the manufacturing drawings. C is a scaling factor which acts as an effective radiation view factor which may also account for complex radiation phenomena such as backscatter.

$$\dot{Q}_{\mathrm{rad,net}} = C\,\frac{\sigma A \varepsilon_W}{\left[1-(1-\varepsilon_W)\cdot(1-\alpha_f)\right]}\cdot\left[\varepsilon_f T_f^4 - \alpha_f T_W^4\right] \tag{1}$$

Although [7] presents details involved in the calculation of the gas-particle suspension emissivity and absorptivity via the standard, low, and high particle models, these methods rely heavily on empirical values which can be a function of parameters such as the particle size. Plant data of these fine details are not available and fall outside the research scope.

Instead of explicitly calculating the emissivity and absorptivity of the flue gas, the implementation of the direct method via the Fluid Radiation component in Flownex was set-up with a fixed fluid emissivity of 0.6 representing a typical low-ash content fuel with the absorptivity calculated as the emissivity-vs-absorptivity ratio to the power of a user-defined exponent. Most important for the calibration methodology as the subject of this paper is the inclusion of the effective view factor ("C" in equation 1). Accurate characterization of view factors is a complex task which is typically done through 3D Computational Fluid Dynamics (CFD) modelling of furnaces and is a function of the complex furnace geometries and flame characteristics. It is however a value that should remain relatively constant if assumed that the flame geometry remains reasonably constant.

The present work therefore adopts a calibration procedure whereby the fluid radiation component is set with fixed conservative values (e.g. wall emissivity, $\varepsilon_W = 1$) such that the C-factor can be tuned parametrically to target site measurement data. The calibration essentially gets reduced to tuning a single parameter.

4. Site Data and Calibration Methodology

The site measurement data was obtained from a 70% (2.8 ton/hr) load test conducted in 2021. The fuel being fired in this case was bagasse and measurements were logged every 10 minutes. The only flowrate data available was that of the feedwater. A turbine flow meter measured a water volume after each 10-minute interval. This allowed a value of 0.000789 m^3/s to be calculated as the average volume flowrate over the hour test period, which translates to the 2.8 ton/hr flow rate.

The ambient pressure was atmospheric (101.325 kPa) with a fuel inlet temperature of 32°C. The rest of the data available from the test is summarised in table 4 and included measurements of the main steam pressure, temperatures of fluid streams at key locations, as well as an oxygen volume fraction measured at the flue gas exit of the evaporator. The arithmetic mean was used for the calibration. Single starred (*) parameters in table 4 indicate data that was directly implemented as boundary conditions to the Flownex model. Double stars (**) indicate parameters used in the preliminary calibration steps, while the remaining unstarred fluid temperatures became the targeted conditions which should result from a successful calibration of the C-factor as will be detailed in section 4.4.

Table 4: Site test measurement data at 70% load case (2.8 ton/hr)

	Node (Fig 2)	Measurement	Unit	Min	Mean	Max	Std Dev	CAL
Water	P_{main}	Main steam pressure	kPa-abs	2951.3	2992.8	3011.3	21.157	**
	ST0	Economiser inlet temperature	°C	46.0	52.6	58.0	4.276	*
	ST1	Economiser exit temperature	°C	82.0	89.7	95.0	4.424	
Air	HA0	Air heater inlet temperature	°C	34.0	35.1	36.0	0.900	*
	HA1	Air heater exit temperature	°C	194.0	198.4	210.0	5.350	
Flue gas	$V_{O2\%}$	O_2 volume fraction	%	4.8	5.7	6.7	0.735	**
	FG5/FET	Furnace exit temperature	°C	524.0	557.4	587.0	24.220	
	FG6	Evaporator exit temperature	°C	270.0	273.0	276.0	2.160	
	FG8	Economiser exit temperature	°C	130.0	132.3	136.0	2.059	

4.1. Feedwater Mass Flow and Feedwater Pump Exit Pressure Calibration

This step begins with guessing an inlet feedwater pressure to the economiser and applying this guess along with the feedwater inlet temperature as per table 4 to the boundary condition in the economiser model. The initial water mass flowrate that is enforced as the steam extraction boundary condition in the evaporator model is taken as the product of the average volume flowrate as per the site data (0.000789 m^3/s) and an expected subcooled water density. After solving the model, the Flownex computed pressure in the two-phase tank is checked against the expected main steam pressure as per table 4. If the pressures differ, then a new pressure is guessed successively until convergence at the measured mean.

4.2. Air-Fuel-Ratio (AFR) Calibration Through Oxygen Volume Fraction Target

The fuel and air mass flowrates are set to 0.3047 kg/s and 1.155 kg/s with the crude assumption being that the fuel and air are also at 70% MCR. To calibrate the Air-Fuel-Ratio (AFR) the fuel mass flow is fixed, while the air flow is varied after each steady state run of the model, being updated based on the O_2 volume fraction calculated by the combustion excel workbook. The calibrated AFR was found to be 0.241, ensuring an O_2 volume fraction of 5.66%.

4.3. Fuel Mass Flow Calibration Through Whole Boiler Energy Balance

With the momentum (pressure) balance satisfied after calibrating the feedwater inlet pressure, one needs to check that the energy balance of the whole boiler network is satisfied. The bulk of the energy input comes from the combustion heat, ultimately driven by the fuel flowrate since the AFR has already been calibrated. If too much or too little heat exists in the system for the specified steam extraction, the solver will indicate this energy imbalance. Satisfying the energy balance now results from tuning the fuel flowrate to nullify the energy imbalance in the system. The calibrated fuel flow was 0.185 kg/s.

4.4. Furnace Radiation Calibration Through C-Factor Parametric Studies

The calibration up until this point has been implemented based on simplifying assumptions due to lack of a complete data set from the site measurements. The main assumptions which the user still has freedom to vary are as follows:

1. Cooling air ratio (assumed to be 10% as per MCR)
2. Fluid emissivity (assumed to be 0.6 based on similar furnace models for grate firing of low ash solid fuels)
3. Fluid emissivity vs. absorptivity exponent (assumed to be 1.5 as per Flownex documentation example [10]).
4. Radiation view factor – C (set at 0.15, i.e. lower extreme)

The steam flowrate as calculated using the mean volumetric water flowrate has been used. The economiser inlet temperature and air inlet temperature from table 4 have been taken as fact in their application as boundary conditions in the model. The main steam pressure and oxygen volume fraction were also taken as fact and were calibrated with single values – feedwater inlet pressure and AFR respectively. There are now 5 remaining temperature data points at nodes ST1, HA1, FG5, FG6, and FG8 as per table 4. The task is to use a single model parameter (i.e. C-factor) to calibrate the 5 remaining temperatures. Ideally there should exist a single C-factor for which the model temperatures should agree with the arithmetic mean temperatures at nodes ST1, HA1, FG5, FG6, and FG8 in table 4.

Initially it was postulated that assumptions 1-3 are valid which means that the C-factor can now be increased parametrically after each steady state solve while logging all the model temperatures at the 5 nodes. The C-factor was varied in increments of 0.05 up to a value of 3, with the results illustrated in Fig 5.

The solid lines in the figure are the 5 targeted temperatures as per table 4. The dots are the Flownex model predicted temperatures at the various C-factors with data callouts illustrated at the points where there is agreement between the model predictions and the site measurements. It is clear from Fig 5 that the flue gas temperatures are calibrated at high C-factors (2.25 and 2.9) compared to the heated feedwater (0.35) and air (0.45). To converge the 5 differing C-factors, parametric studies were run to vary the cooling air split ratio to increase the heated air calibrated C-factor. The large flue gas calibrated C-factors of 2.25 for FET and 2.90 for the evaporator exit in Fig 5 also indicate that there may be more heat uptake in the waterwalls than is accounted for by pure radiation. This was addressed by including localised convection effects around the pronounced rear wall nose (see Fig 2) as well as varying the flue gas absorptivity. The best calibration results after these adjustments are shown in Fig 6.

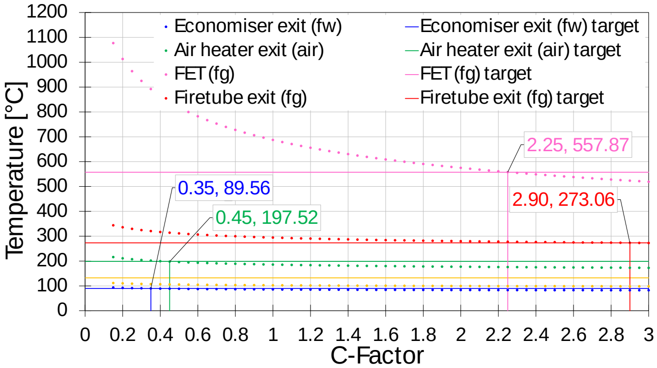

Fig. 5: C-factor calibration at 10% cooling air, radiation with fluid emissivity=0.6 & absorptivity=1.0, and zero convection

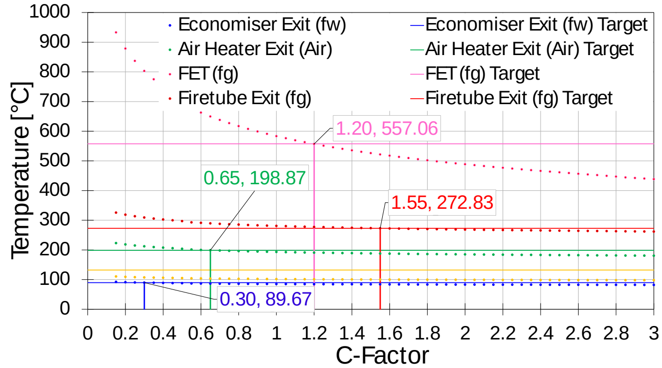

Fig. 6: C-factor calibration at 25% cooling air, radiation with fluid emissivity=0.6 & absorptivity=0.6, convection (25 W/m^2K)

Although the addition of furnace convection, an increase in cooling air, and a reduction in flue gas absorptivity did pull the 5 C-factors closer to one another as illustrated in Fig 6, one expects that there should still be a singular C-factor which would satisfy the calibration with all 5 targeted temperatures. The task is now to consider the low fidelity nature of the measured site data and come up with a ranking system to weight the confidence one should expect in each of the 5 measurement points such that a best-fit C-factor can be found.

5. Error Weighting Methodology

Since there is confidence in the accuracy of the individual heat exchanger models as shown by the verification with MCR data and the fact that the ATProM combustion model employed through the excel workbook has been proven valid and generic for any fuel composition, the shortfall in determining a single C-factor during calibration is likely due to measurement uncertainties and inconsistencies in the available site test data. This is where the inherent measurement uncertainties have led to redundancies in the calibration. In the absence of specific details around the measurement devices and techniques used to collect the site test data one can still develop a qualitative ranking system to give weights to the confidence one can expect in each of the 5 measurements.

5.1. Measurement Uncertainty

The recorded measurements from site could have up to a +- 5K error depending on the measurement technique and apparatus used. Secondly, 10 minutes is a rather course interval where notable fluctuations can be observed between successive measurements. This can be seen in table 4 where the FET had a 63K temperature difference between the minimum and maximum temperature recorded within the 1-hour testing period.

5.2. Reconciling the %Errors to a Single Weighted %Error

Qualitative insights obtained from the boiler designer and manufacturer were incorporated into a pairwise comparison matrix as shown in table 5 used to rank the confidence one can expect in the accuracy of the five measurements of interest. Notable qualifications from the boiler designer and manufacturer included details of the complexity of accurate FET measurements needing to be taken at multiple locations at the furnace exit plane such that a mass weighted average can be calculated. This along with the 63K temperature difference between the maximum and minimum recorded FET resulted in a relatively low confidence in the FET measurement data. On the other hand, the flue gas temperature at the evaporator exit scores higher since it is a closely monitored temperature which is critical for safety interlocks in the boiler control system.

The values in table 5 were completed by assigning a fraction of unity between each pairwise comparison. For example, the evaporator flue gas exit (FG6) vs. the FET (FG5) is 0.9 vs 0.1 due to the reasons explained above. Summing the column values for each row provides a rank for each of the 5 measurements which is then normalised to a weighted percentage.

Table 5: Pairwise comparison for confidence rankings of site measurements

	ST1	HA1	FG5	FG6	FG8	Rowa total (rank)	Weighting	Motivation
ST1	-	0.60	0.90	0.50	0.95	2.95	29.50%	Thermocouple measurement for subcooled water.
HA1	0.40	-	0.85	0.40	0.90	2.55	25.50%	Complex flow field - single measurement unreliable
FG5	0.10	0.15	-	0.10	0.60	0.95	9.50%	Single point measurement with suction pyrometer in duct connecting furnace to evaporator
FG6	0.50	0.60	0.90	-	0.95	2.95	29.50%	PT100 for control and safety interlocks (critical)
FG8	0.05	0.10	0.4	0.05	-	0.60	6.00%	Single point measurement (non-critical)

The weighted error is now simply calculated as the summation of the product of each measurement error with its corresponding weighting as per equation 2.

$$Weighted\ error = \sum_{i=0}^{n} (error_i * weighting_i) \qquad (2)$$

The error inside the brackets of equation 2 represents the absolute error between the model predicted temperature and its corresponding site measurement target based on the Kelvin temperature scale. With the calculation of a single weighted error for each C-factor, all the data illustrated in Fig 6 is reconciled to a single line graph as shown in Fig 7.

The best-fit C-factor is 1.2 at a weighted error of 1.537%, i.e. the turning point of the graph in Fig 7. Fig 8 shows that almost all 5 temperatures at the calibration point (C=1.2) fall within the standard deviation of the site measurements.

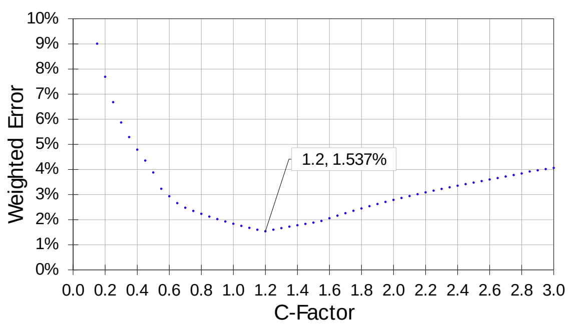

Fig. 7: Final calibration results – normalised weighted error vs. C-Factor

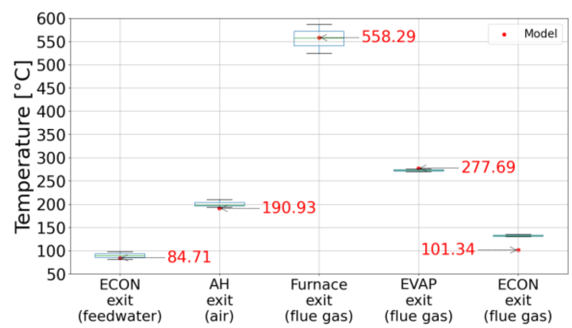

Fig. 8: Box & Whisker Plot illustrating model temperatures at a C-factor of 1.2 compared to site measurement data

5. Application of the Calibrated Model

The weighted error methodology led to the best calibration one could achieve with the low fidelity data that was available. The calibrated model can now be used as the starting point to initialise the model for a host of different studies which could include investigations into off-design steady-operation as well as controllable transient studies.

A simple control system was implemented in the Flownex model consisting of two simple PID control loops. The first loop controls the boiler pressure with feedback to the fuel flowrate, while the second controls the boiler water-level with feedback to the feedwater mass flowrate. Fig 9 illustrates the boiler pressure response to changes in steam demand and Fig 10 illustrates the boiler water level response for a separate transient study which varied the fuel quality through a fuel moisture input profile.

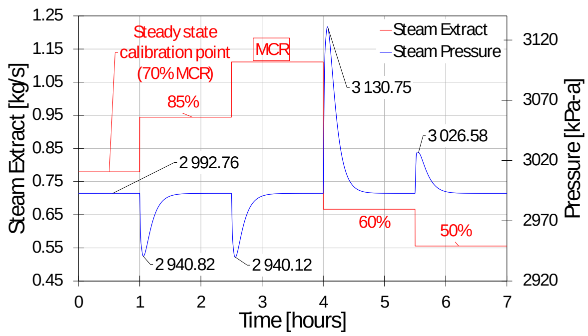

Fig. 9: Boiler steam pressure response to steam demand profile

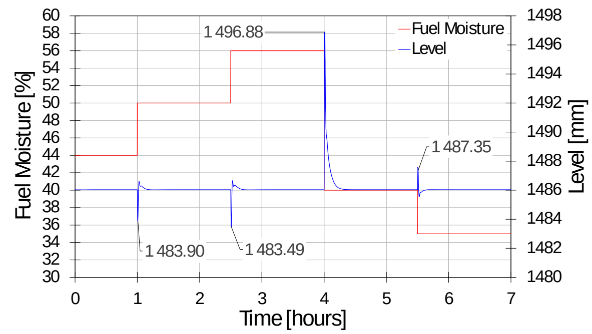

Fig. 10: Boiler level response to fuel moisture profile

These types of transient studies are highly valuable for boiler designers since they can be used to optimise boiler control systems to improve flexible operations. This research can act as a benchmark such that the controllable transient response in the numerical model can be validated by imposing step changes in steam demand and fuel moisture content during a real-life transient test.

6. Conclusion

Good practice in using accurate heat transfer theory and correlations were demonstrated through a verification between 3 types of models with available MCR data. The calibration methodology using the arithmetic mean site measurements was successful in calibrating the feedwater pressure, AFR and fuel flow through 1 to 1 parameter tuning. The challenge of calibrating the C-factor to obtain agreement with 5 temperatures measurements was first addressed via parametrically varying furnace convection, flue gas absorptivity and cooling air ratios which did see the calibration converging to a narrower band of C-factors. Reconciling the remaining C-factor was achieved with the introduction of a weighted error methodology to assign subjective rankings to the fidelity of each measurement, ultimately normalising the C-factor calibration to a single weighted error. The results at the best-fit C-factor saw the 5 measurements falling reasonably well within the standard deviation of the site measurements.

This paper successfully demonstrated a methodology to reconcile errors due to low fidelity data to output a calibrated model which can serve as the starting point for future studies to investigate off-design points and transient characteristics.

Acknowledgements

A special thanks to the engineers at John Thompson Boilers for providing relevant workshop drawings, MCR data and site test data. This information was instrumental in the present research. Appreciation also given to ATProM for modelling support and merSETA for funding support.

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