ASME International

The American Society of Mechanical Engineers
Three Park Avenue
New York, NY 10016-5990

Reprinted From
Proceedings of the
2007 ASME Power Conference
San Antonio, Texas, July 17-19, 2007
POWER2007-22009

Revised Dec. 15, 2011

MONITORING AND IMPROVING COAL-FIRED POWER PLANTS USING THE INPUT/LOSS METHOD - PART V

Fred D. Lang, P.E.
Exergetic Systems, Inc.
San Rafael, California 94901
Lang@ExergeticSystems.com

ABSTRACT

This paper presents generic methods for verifying on-line monitoring systems associated with coal-fired power plants. It is applicable to any on-line system. The methods fundamentally recognize that if coal-fired units are to be understood, that system stoichiometrics must be understood in real-time, this implies that fuel chemistry must be understood in real-time. No accurate boiler efficiency can be determined without fuel chemistry, heating value and boundary conditions. From such fundamentals, four specific techniques are described, all based on an understanding (or not) of real-time system stoichiometrics. The specific techniques include: 1) comparing a computed ambient relative humidity which satisfies system stoichiometrics, to a directly measured value; 2) comparing a computed water/steam soot blowing flow which satisfies system stoichiometrics, to a directly measured value; 3) comparing computed Energy or Flow Compensators (based on computed boiler efficiency, heating value, etc.), to the unit's DCS values; and 4) comparing a computed fuel flow rate, based on boiler efficiency, to the plant's indication of fuel flow. Although developed using the Input/Loss Method, the presented methods can be applied to any on-line monitoring system such that verification of computed results can be had in real-time. If results agree with measured values, within defined error bands, the system is said to be understood and verified; from this, heat rate improvement will follow.

This work has demonstrated that use of ambient relative humidity is a viable verification tool. Given its influence on system stoichiometrics, use of relative humidity immediately suggests that effluent (Stack) flow can be verified against an independently measured parameter which has nothing to do with coal-fired combustion *per se*. Whether an understanding of coal-fired combustion is believed to be in-hand, or not, use of relative humidity (and, indeed, soot blowing flow) provides the means for verifying the actual and absolute carbon and sulfur emission mass flow rates. Such knowledge should prove useful given emission taxes or an imposed cap and trade system. Of the four methods examined, success was not universal; notably any use of plant indicated fuel flow (as would be expected) must be employed with caution.

Although applicable to any system, the Input/Loss Method was used for development of these methods. Input/Loss is a unique process which allows for complete understanding of a coal-fired power plant through explicit determinations of fuel chemistry including fuel water and mineral matter, fuel heating (calorific) value, As-Fired fuel flow, effluent flow, boiler efficiency and system heat rate. Input consists of routine plant data and any parameter which effects stoichiometrics, typically: effluent CO_2, O_2 and, generally, effluent H_2O.

The base technology of the Input/Loss Method has been documented in companion ASME papers, Parts I thru IV, which addressed topics of base formulations, benchmarking fuel chemistry calculations, high accuracy boiler efficiency methods and correcting instrumentation errors in those terms affecting system stoichiometric (e.g., CEMS and other data). PAPER75_Rev6.WPD

NOMENCLATURE

Stoichiometric Terms

a = Moles of combustion O_2 input to the system.
$a\beta$ = O_2 entering with air leakage; moles/base.
A_{Act} = Concentration of O_2 in dry ambient air local to the system; NASA standard is 0.20948.
b_A = Moisture entering with combustion air.
$b_A\beta$ = Moisture entering with air leakage; moles/base.
b_Z = Water/steam in-leakage; moles/base.
d_{Act} = Total effluent CO_2 at boundary; moles/base.

g = Effluent oxygen without air leakage; moles/base.
G_{Act} = Total effluent O_2 at boundary; moles/base.
j = Effluent water without air leakage; moles/base.
J_{Act} =Total effluent water at boundary; moles/base.
N_k = Molecular weight of compound k.
R_{Act} = Ratio of moles of dry gas before entering the Air Pre-Heater to gas leaving, termed the Leakage Factor; molar ratio.
x = As-fired fuel moles per the base of 100 moles of dry gas product; moles/base.
α_k = As-Fired (wet-base) fuel constituent k/Fuel-Mole
β = Air Pre-Heater Dilution Factor (ratio of air leakage to true combustion air); molar ratio
= $100(R_{Act} - 1.0) /[a\, R_{Act} (1.0 + \varphi_{Act})]$
Λ_i = Choice Operating Parameter (i).
φ_{Act} = Ratio of non-oxygen gases (N_2 and Ar) to O_2 in combustion air $(1.0 - A_{Act})/A_{Act}$; molar ratio.

Quantities Related to System Terms

HBC ≡ Firing Correction, accounting for sensible heats from calorimetric conditions to the actual As-Fired; ΔBtu/lbm_{AF}.
HHVP = As-Fired higher heating value, corrected for constant pressure from HHV_{AF}; Btu/lb_{AF}
HR = System heat rate; Btu/kWh.
H_{Amb} = Relative humidity of ambient air; fraction.
m_{AF} = Fuel mass flow rate, lbm/hr.
$P_{Dry\text{-}Bulb}$ = Pressure of ambient air, psiA.
$\sum Q_{WF}$ = Working fluid useful energy flow; Btu/hr.
$T_{Dry\text{-}Bulb}$ = Temperature of ambient air, ^oF.
W_{output} = Gross power generated; kWe.
η_B = Boiler efficiency; unitless.
ω_{Air} =Ambient sp. humidity, lb-H_2O/lb-Dry-Air.
= $f\,(P_{Amb}, T_{Dry\text{-}Bulb}, {}_{Hamb})$.

Subscripts and Abbreviations

Act = An actual value (and typically measured).
AF = As-Fired fuel (wet with mineral matter).
Amb = Ambient conditions at boundary of system.

INTRODUCTION

On-line monitoring systems used in power plants have suffered for years from poor reputations ... justified or not. Surely, one cause for a poor reputation in coal-fired units, and generally quite justified, is their lack of knowledge as to As-Fired fuel chemistry, fuel heating value and fuel flow. Fuel chemistry (ultimate analysis) and heating value are required inputs to any accurate boiler efficiency calculation [Lang, 2000, 2006]. As seen in Eqs.(1) or (2) describing unit heat rate, one requires at least either boiler efficiency or fuel flow and heating value, in addition to power and useful working fluid energy flow, to determine an absolute value of unit thermal efficiency (heat rate, *HR*). A coal-fired plant may use a relative indication of heat rate by relying on total fuel energy flow [m_{AF} (HHVP + HBC)]; e.g., using fuel energy flow based on a scalable value from DCS control logic. This would allow determination of a relative boiler efficiency back-calculated from Eq.(2). However, it is obvious given increased use of "spot" coal, and/or coal with variable moisture content, that the operator has no indication of whether higher fuel consumption is due to lower actual boiler efficiency, or higher turbine cycle losses, or changes in fuel quality, etc. The few coal-fired plants known to the author which rely on such relative indication have either not improved their heat rates or, at a minimum, have no means to demonstrate such proof.

$$HR = m_{AF}\,(HHVP + HBC)\,/W_{output} \qquad (1)$$
$$= \sum Q_{WF}\,/(\eta_B\, W_{output}) \qquad (2)$$

The Input/Loss Method addresses these fundamental issues by computing As-Fired fuel chemistry, As-Fuel heating value and fuel flow based on emission concentrations, i.e., CEMS data. Its governing equation combines Eqs.(1) & (2) to back-calculate fuel flow (m_{AF}). Indeed, it is argued that the resulting Eq.(3) should be the governing equation for any monitoring system. Eq.(3) forces measurement of the single reason we burn fuels, to develop a useful energy flow ($\sum Q_{WF}$); it also requires the computation of boiler efficiency independent of fuel flow (using the heat loss method), and requires the determination of heating value terms (HHVP and HBC). All of these terms are critically important if the system is to be accurately monitored.

$$m_{AF} = \sum Q_{WF}\,/\,(\eta_B\ (HHVP + HBC) \qquad (3)$$

Of course, with m_{AF} and heating value, determining unit heat rate becomes obvious. As important, note that Stack flow may then be computed with complete consistency since system stoichiometrics must be known.

The Input/Loss Method is believed unique relative to traditional systems in that it integrates emission measurements with thermal performance [patents, 1994-2011]. Benchmark comparisons were made successfully to over 1200 lab-produced ultimate analyses [Lang, 1999]. However, when on-line - and until implementation of this work - the Method's alleged absolute accuracy clearly had not been cleanly demonstrated. In the past, on-line results have been compared to a number of plant parameters: indicated fuel flow, indicated Stack flow, operator's best judgement of heating value, fuel grab samples, and so-forth. Although these were considered sanity checks, as always needed, none were compelling.

NEW APPROACH

Impetus for establishing verification techniques originated when testing in 2003-2004 at the Boardman Coal Plant. A portion of this testing involved emulating heat exchanger tube leaks by matching steam flow used for soot blowing [Lang, Rodgers & Mayer, 2004b]. By zeroing the metered soot blowing flow, the Input/Loss' Tube Failure Model was then called on to compute a "tube leak" which satisfied system stoichiometrics. The computed "tube leak" was then compared to the metered soot blowing flow. When these quantities matched it clearly indicated that system stoichiometrics, and fuel chemistry upon which they were based, and system mass balances (both combustion gases and working fluid) were all well understood; Eq.(3) was considered resolved.

As an aside, it is important to note that the formulation for fuel flow, Eq.(3), does not allow for cancellation of errors. A Powder River Basin (PRB) heating value which is erroneously high by 2%, will cause boiler efficiency to compute high by typically 0.4% using the same fuel chemistry. All other parameters being held constant, fuel flow will compute 2.4% high. Such affects are also true of the $\sum Q_{WF}$ term; they are non-offsetting.

Although the author can find no engineering reason why matching soot blowing flow is not a viable verification procedure, it is, after all, based on an in-plant measurement. A computed soot blowing flow is clearly dependent on understanding (or not) system stoichiometrics, it is also dependent on the computed As-Fired fuel flow and thus on working fluid energy flow, $\sum Q_{WF}$, boiler efficiency and heating value.

However, what is needed for verification is a parameter which would have sensitivity to system stoichiometrics, but also, from a political view-point, a parameter which can be measured outside the power plant environs; a parameter not associated with the combustion process. This parameter is ambient relative humidity. Although it affects combustion by affecting system stoichiometrics, it can be measured quite independently from plant instrumentation and without understanding coal-fired combustion. If a monitoring system ignores the measured ambient air psychrometrics, but back-calculates a humidity required for balancing stoichiometrics, and then successfully compares the computed to the measured, verification is assured.

In addition to ambient relative humidity and soot blowing flow, it appeared not unreasonable to also look to the unit's control system for verification. Controlling a power plant is a "relative" proposition. For example, in a Boiler-Follow-Turbine control mode, fuel feed is set incrementally higher or lower as affecting drum pressure such that demand power is met; absolute fuel flow, high accuracy boiler efficiency, etc. have no import. The measure of this control stems from the Boiler Master, a unit of the DCS, as its compensated output. Although there would appear no standard nomenclature, two Boiler Master parameters are considered: an Energy Compensator (in North America termed the "Btu Compensator"); and a Flow Compensator. At first blush, this is a bad idea for an on-line system purporting absolute accuracy. However, there is no other direct handle on the "throttle" of the machine than the Boiler Master. Thus the equivalent of these compensated parameters, produced by the on-line system has been investigated. Although not ideal, problems exist, these computed compensators have shown promise for a certain applications.

Further still, the use of the plant's indicated fuel flow for verification purposes was also considered. Years ago this author believed that "coal flow measurements have such poor accuracy that they can be used only as relative indicators." However, for a few Input/Loss installations a remarkable matching of computed versus measured fuel flows was observed. Techniques were then developed to alter fuel water such that the computed and measured agreed. The problem was that verification could only truly be established through detailed performance testing, concluding with a back-calculated fuel flow. Although in several installations forcing agreement (even with bias) seemed reasonable, the lack of direct verification has resulted in all but one installation dropping this method.

SYSTEM STOICHIOMETRICS

No matter the technique employed, ambient relative humidity, soot blowing flow, DCS Compensators or fuel flow, the on-line system computing such parameters must develop accurate fuel chemistry. This then leads to system stoichiometrics. To accent the importance of system stoichiometrics, consider that the simple mass balance of TABLE 1 contains several key terms which occur throughout: the combustion air term, "a"; the ratio of non-oxygen to ambient oxygen, φ_{Act}; moisture in combustion air, b_A; and the system air leakage described by the defined Dilution Factor, β.

TABLE 1:
Mass Balance Based on System Stoichiometrics

Fuel Flow, Eq.(3)	$= \sum Q_{WF}/[\eta_B\,(HHVP + HBC)]$
Combustion Dry Air	$= m_{AF}\,(1+\beta)\,(a+a\,\varphi_{Act})N_{Air}/(xN_{AF})$
Comb. Air Moisture	$= m_{AF}\,(1+\beta)\,b_A\,N_{H2O}\,/(xN_{AF}\,)$
Water In-Leakage	$= m_{AF}\,b_Z\,N_{H2O}\,/(xN_{AF}\,)$
	$\sum$ INLET MASS FLOWS
Boundary Dry Gas	$= m_{AF}\,100\,N_{Dry\text{-}Gas}\,/(R_{Act}\,xN_{AF}\,)$
Dry Air Leakage	$= m_{AF}\,\beta\,(a + a\,\varphi_{Act})\,N_{Air}\,/(xN_{AF})$
Boundary Moisture from Fuel, Combustion, Air and In-Leakage	$= m_{AF}\,J_{Act}\,N_{H2O}\,/(xN_{AF})$
Bottom and Fly Ash	$= m_{AF}\,\alpha_{10}\,N_{Ash}\,/N_{AF}$
	$\sum$ OUTLET MASS FLOWS

TABLE 1demonstrates that if inlet and outlet mass flows are to agree, that at least the following stoichiometric terms must be computed correctly: a, φ_{Act}, b_A and β. Note the importance of understanding both air and water in-leakage affects. System air leakage is principally described by the Leakage Factor, R_{Act}, which in-turn leads to β. The water/steam in-leakage term, b_Z, as a special case, is of obvious import when matching soot blowing flow.

To fully explain, allow the presentation of a typical combustion equation. Although the details are not required, understand that certain terms, appearing in all such equations, form the base for a TABLE 1 balance and thus directly impact the verification techniques of this work. Eq.(4) is a greatly simplified; more complexity can be seen in related Input/Loss papers. Its nomenclature is self-explanatory in that brackets are used for clarity: for example, the expression "$x\alpha_{10}$[Ash]" means the fuel moles of ash, algebraically simply $x\alpha_{10}$; the expression "$d_{Act}[CO_2]$" means the effluent moles of CO_2, algebraically simply d_{Act}. The stoichiometric base of Eq.(4) is 100 moles of dry Stack gas.

One can immediately understand, forming classical stoichiometric balances using Eq.(4), how TABLE 1 is formed; i.e., first computing fuel mass flow via Eq.(3), then with molar balances computing all mass flows. Note that total effluent O_2, the term G_{Act}, is composed of "Boiler" O_2 (without air leakage), and the air leakage contribution found at the Stack, $a\beta$. In like manner, total effluent water, the term J_{Act}, is composed of "Boiler" moisture (without affects of air leakage), and moisture carried by air leakage, $b_A\beta$.

$$\begin{aligned} x\,\big[\, & \alpha_1[N_2] + \alpha_2[H_2O] + \alpha_3[O_2] + \alpha_4[C] + \alpha_5[H_2] \\ & + \alpha_6[S] + \alpha_{10}[ash] \,\big]_{As\text{-}Fired} + b_Z[H_2O]_{In\text{-}Leakage} \\ & + \big[\, (1.0 + \beta)(a[O_2] + a\varphi_{Act}[N_2] + b_A[H_2O]) \,\big]_{Comb\text{-}Air} \\ & = d_{Act}[CO_2] + G_{Act}[O_2] + H[N_2] \\ & + J_{Act}[H_2O] + k_{Act}[SO_2] + x\alpha_{10}[ash] \qquad (4) \end{aligned}$$

VERIFICATION via RELATIVE HUMIDITY

With the above discussion in mind, the term describing moisture in ambient air, b_A, may be used to balance Eq.(4). It is important to recognize that the moles of moisture contained in combustion air appears as both a reactant term (via combustion air) and as a product term (via air leakage within J_{Act}). Moisture in combustion air affects the system's water balance, affects the hydrogen and oxygen balances about the system; and through this mechanism affects the carbon balance. For Eq.(4), the computation of b_A for ambient moisture is common:

$$b_A = (1.0 + \varphi_{Act})\, a\, \omega_{Air}\, N_{Dry\text{-}Air} / N_{H2O} \qquad (5)$$

Note that specific humidity, ω_{Air}, is developed from ambient air psychrometrics, either actual or computed. The choice of comparing relative humidities, versus the specific, is arbitrary but convenient for the optimization procedures as it ranges between zero and unity.

VERIFICATION via SOOT BLOWING FLOW

The treatment of soot blowing flow is not dissimilar from ambient moisture. Again, the term which affects both sides of any combustion equation is the quantity of water in-leakage into the combustion process, b_Z. Although explicitly appearing as a reactant, it obviously affects the effluent moisture term, J_{Act}. The molar and mass flow terms are computed in the following manner:

$$b_Z = m_Z\, xN_{AF} / (N_{H2O}\, m_{AF}) \qquad (6A)$$

$$m_Z = m_{AF}\, b_Z\, N_{H2O} / (xN_{AF}) \qquad (6B)$$

To balance system stoichiometrics, the b_Z term can be altered such that system stoichiometrics are balanced. Once determined, soot blowing flow, m_Z, can then be computed and compared to the metered.

VERIFICATION via DCS COMPENSATORS

DCS Compensators serve to basically balance fuel flow rates against steam production as typically gaged by turbine throttle pressure. For this work what is meant by DCS Compensators, and names vary, is either a parameter which directly adjusts fuel energy flow (herein termed an "Energy Compensator"), or a parameter which adjusts fuel feed directly (herein termed a "Flow Compensator"). Such signals are generated from the Boiler Master or Turbine Master modules within the DCS.

For verification of on-line monitoring systems, the subtitles of Energy and Flow Compensators are important. All known DCS Compensator signals are Energy Compensators. For example, if at steady generation a power plant's DCS Compensator changes fuel flow from 100% to 102%, we know that the following combination of quantities has fallen by 2%: fuel heating value, boiler efficiency and/or turbine cycle efficiency. The system's Energy Compensator has reacted to maintain a constant turbine cycle load. In summary, the Energy Compensator will adjust fuel flow to maintain a desired turbine cycle energy flow, ignoring why .

If a system has absolute knowledge of heating value and was determining a valid Fuel Compensator, a change in the signal driving fuel feed from 100% to 102% would singularly indicate degradation in boiler and/or turbine cycle efficiencies of 2%, all other parameters remaining steady; the unit must fire harder to maintain generation. In summary, the Fuel Compensator will adjust fuel flow to maintain a desired turbine cycle energy flow.

Unless the DCS acquires knowledge of the fuel's heating value, a Boiler Master's signal is an Energy Compensator. Scaling a signal with a constant heating value, as is often done within DCS logic, does not change an Energy Compensator to one of "Flow". An expression for the Energy Compensator is given by Eq.(7) in which "A" and "B" are scaling constants. "A" includes the affects of a constant boiler efficiency assumed for Eq.(7). HHV_{AF} is an arbitrarily chosen constant representative of the fuel burned. As used in Eq.(7), the fuel flow parameter, $m_{AF/Plant}$, is simply the plant's indication of flow, being continuously adjusted to meet demand. Meeting demand is to balance Eq.(7) which simply states that fuel energy flow (left side) is proportional to the steam energy demands of the turbine cycle (right side).

$$HHV_{AF}\, A \int m_{AF/Plant}\, dt \;\; [=] \;\; B \int \sum Q_{WF}\, dt \qquad (7A)$$

For verification of an on-line monitoring system, all components for an absolute calculation are present. It becomes obvious that comparisons to either a Energy Compensator or to a Flow Compensator are possible. By equating Eqs.(1) and (2), an expression for fuel energy flow versus turbine cycle demand is immediately had:

$$\int \eta_B\, m_{AF}(HHVP + HBC)\, dt \;\; [=] \;\; B \int \sum Q_{WF} dt \qquad (8)$$

It becomes immediately apparent that the actual signal delivered to the fuel feed mechanism is the differential, $\partial m_{AF/Plant}$. Indeed, this signal is the output from the Boiler Master and will dictate the plant's fuel flow if at constant generation. Variations in this signal, if fuel energy flow is steady, counter, in the ideal, only changes in boiler and turbine cycle Δefficiencies. If heating value drops, fuel flow must increase, the Energy Compensator will adjust. Although simple in concept, it is crucial for verifying any monitoring system for which the indicated fuel flow is absent, but where heating value, and boiler and turbine cycle efficiencies are being computed. For verification, even under variable load with changing HHVP and/or η_B, the computed Energy Compensator should track the DCS value with constant off-set. In summary, the Energy Compensator will adjust fuel flow based on desired turbine cycle energy flow.

There are two problems with this approach, illustrated through plant testing discussed below. First, the left side of Eq.(8) is an exact representation of steam generator performance, whereas, for verification purposes, it is being compared to an arguably crude control parameter (HHVP & η_B are held constant). Second, on-line systems are bound by steady state thermodynamics, and although Eq.(8) employs time weighing, there are no explicit time dependent energy terms. A transient First Law balance is simply not being made. One well-known term having considerable temporal influence is the stored energy in a steam generator's metal parts; another is the working fluid's stored energy contained in the deaerator and below the evaporator section in the steam generator [Canning, et al, 1992]. The author knows of no DCS Compensator which employs explicit ∂Energy/∂t storage rates.

VERIFICATION via FUEL FLOW

The result of Eq.(3), as the governing equation for on-line monitoring systems, when compared to the plant's indicated fuel flow should provide, in the ideal, ultimate verification. The first problem is that for a few coal-fired units, and certainly for all bio-mass and peat units, such a value does not exist. The second problem is that for all coal-fired units indication of fuel flow can not be independently calibrated with adequate precision. Yes, calibration scales are employed on coal feeder belts, etc., but absolutely accuracy with better than 2% error is rare; this, in spite of ill-based claims to the contrary. As thermal performance engineering begins at the "2% level", relying on, at best, 2% absolute accuracy from a coal belt system is a fool's errand.

It is noteworthy that early development of the Input/Loss Method was carried out at natural gas-fired units; units where fuel flow could generally be measured with great absolute accuracy, and comparisons made. In several testing projects we were afforded multiple flow meters, in series, producing errors less than 0.3%. Indeed, if comparison with Eq.(3) was missed under such ideal conditions, then understanding coal-fired combustion was greatly optimistic.

However, even with these known problems, a technique has been developed - as a "sanity check" - in which the plant's fuel flow is bias such that variation in the computed fuel heating value is observed, the heating value then compared to a best estimate. At a minimum, this technique has provided the plant engineer with a visceral understanding of the inter-dependency of system stoichiometrics (effluent CO_2, etc.) and fuel flow.

MECHANICS OF VERIFICATION

Again, the proposed technique is <u>not dependent</u> on any specific monitoring system. If a given system can back-calculate a term which affects system stoichiometrics, which is then compared to an independent measurement, verification is possible. Having said this, one must recognize the great sensitivity a balanced set of stoichiometrics has on back-calculated b_A or b_Z terms. Data must be expected to scatter. Indeed, even for comparisons of Energy Compensators, external system factors can adversely influence. In addition to data scatter, external factors include instrumentation errors affecting stoichiometrics; e.g., errors in CEMS data. .

Input/Loss Method, assumes that no CEMS instrument is free of error. To this end the Part IV paper (Lang 2004a) explains in detail methods used to correct CEMS data. Indeed, such methods are applied to all important parameters which may affect stoichiometrics.

Such parameters are termed "Choice Operating Parameters" (COPs, termed Λ_i). For Input/Loss, COPs are chosen by the power plant engineer based on the system circumstances, from any combination of those listed in TABLE 2.

TABLE 2:
COPs Affecting System Stoichiometrics

Λ_{1S}	$= d_{Act}$,	Stack CO_2 with air leakage affects
Λ_{1B}	$= d_{Act}\, R_{Act}$,	Boiler CO_2 w/o air leakage affects
Λ_{2S}	$= J_{Act} = j + b_A\beta$,	Stack H_2O with air leakage affects
Λ_{2B}	$= j\, R_{Act}$,	Boiler H_2O w/o air leakage affects
Λ_3	$= AF$,	Air/Fuel ratio, for fuel ash calcs
Λ_4	$= R_{Act}$,	Air pre-heater Leakage Factor
Λ_5	$= A_{Act}$,	Fraction of O_2 in combustion air
Λ_6	$= m_{LS}$,	System's indicated limestone flow
Λ_{7S}	$= G_{Act} = g + a\beta$,	Stack O_2 with air leakage
Λ_{7B}	$= g\, R_{Act}$,	Boiler O_2 w/o air leakage affects
Λ_8	$= m_T$,	Tube leakage mass flow
Λ_9	$= H_{Amb}$,	Relative humidity of ambient air.

Commonly used COPs include, for example, Stack CO_2, Stack H_2O, air pre-heater Leakage Factor and Boiler O_2. For verification purposes COPs may include ambient relative humidity (Λ_9), or tube leakage flow which emulates soot blowing (Λ_8), or Stack moisture when optimized to match m_{AF} of Eq.(3) against plant fuel flow (Λ_{2S}). The selection of one or more of the Choice Operating Parameters must depend on common understanding of power plant stoichiometrics and associated relationships to physical equipment.

However, the point here is not how one might correct any give COP - whether by historical trending, by judgement, by guess, or by using Input/Loss - but that an operational on-line system computes a relative humidity which agrees with the measured ambient !

The developed technique is implemented using the following procedure using relative humidity as an example. It is assumed, as found at most coal-fired plants, that the plant's indicated fuel flow is at least a consistent signal. Also assumed is that a fuel flow is being determined by a monitoring system based on computed (or assumed) fuel chemistry and heating value, and a monitored turbine cycle.

While On-Line:

Monitor the system in a routine manner using a measured ambient relative humidity of the combustion air. Calculate fuel mass flow based on Eq.(3), i.e., summarizing the monitoring system's understanding (or not) of system stoichiometrics, boiler efficiency, $\sum Q_{WF}$ and heating value.

Periodically:

At an established frequency (say once every 30 minutes), adjust the relative humidity until the calculated fuel flow of Eq.(3) agrees with the plant's indicated value. Make certain system stoichiometrics need to be converged, to this end: a) the monitoring system might require to be taken off-line; or b) compute automatically using repetitive runs with static data to assure convergence. After fuel flows agree, then compare the adjusted relative humidity to the locally measured. If agreement of humidities is not had, place a bias on the indicated fuel flow. Repeat from above, adjusting the fuel flow bias for zero error.

Duration:

Typically, relative humidity will not greatly influence system stoichiometrics, thus data scatter associated with a back-calculated humidity must be expected. The lack of sensitivity means this procedure should be run (with the same bias on fuel flow) for at least 24 hours, implying a multi-day verification.

Of course such a procedure is amenable to automation. For Input/Loss, the procedure is automated such that at a pre-set number of ΔRuns, a comparison is made to ambient humidity. Typically, Input/Loss monitoring will adjust relative humidity (COP of Λ_9) once every 30 minutes. However, as stressed, there is no reason this procedure can not be employed by any monitoring system, it is generic.

RESULTS

The viability of this work can only be demonstrated by comparisons to actual data, i.e., on-line experience. To this end the following paragraphs present a sampling of results. However, it must be understood that verification suitable for regulatory use would involve several months of continuous application of these techniques.

Using Relative Humidity

FIGURE 1A presents one iteration of the above procedure for relative humidity; this presenting a +0.5% bias on the plant's indicated fuel flow. For this example the bias was altered four times, using -0.5, 0.0, +0.5 and +2.0% bias, each bias taking a day of monitoring. Of course, given inherent data scatter it is difficult to visually discern results. Results should be determined using a sign sensitive, square-root-sum-of-squares procedure which examines differences in specific humidities. Such results are presented in FIGURE 1B. For this plant (600 MWe, coal-fired), results indicated that the plant's indicated fuel flow should be multiplied by a bias of 0.896 (plant indication is high).

Using Soot Blowing Flow

Study of emulating soot blowing flow using the Input/Loss Tube Failure Model has been reported (Lang, Rodgers and Mayer 2004b). This work was conducted at the Boardman Coal Plant (Portland General Electric), burning Powder River Basin coal and producing 640 MWe. Results of this testing indicated an unexpectedly high sensitivity; as-tested sensitivity approached 0.1% of feedwater flow (3,000 to 5,000 lbm/hr out of a 4.2 million-lbm/hr feedwater flow system). FIGURE 2 represents typical results. As commented, this technique is sound, but for the fact it relies on in-plant data.

Bear in mind that use of a computed soot blowing flow was originally intended to emulate tube failures, an Input/Loss feature. Although the use of this technique is applicable for monitoring verification, perhaps its greater service lies with daily checks for steam generator tube leaks. It is suggested that the plant engineer use this technique on a routine bases, say each morning for an hour, to emulate soot blowing flow. Such use will yield patterns: if soot blowing flow is consistently matched, all is well; if beginning to drift it is indication of either a tube leak or mis-monitoring. For Input/Loss, most users place great credence in time plots of computed COP correction factors; they should be drawing straight lines. Although there are automatic provisions for detecting tube leaks; as observed by users, tube leaks best reveal themselves through changes in COP correction factors, and most importantly to Λ_1 and Λ_2.

Using DCS Compensators

Two examples of verification using DCS Compensators are presented, one an Energy Compensator and the other comparing Compensators, a computed Fuel versus a DCS Energy. FIGURE 3A compares Energy Compensators as computed by Input/Loss monitoring and a plant's DCS value. The plant was a 150 MWe peat-fired unit in Ireland (West Offaly). Firing peat is quite unique in that there is absolutely no indication of fuel flow. Further, it has high variability in heating value due to variable moisture content. Fuel is delivered by screw feeds, but given variation in peat density, relying on screw turns to produce mass flow is simply not credible. Given this, verification using the Energy Compensator implies that a constant off-set between the computed and the relative DCS value is proof that the system is understood. Comparison to the Input/Loss computed Energy Compensator is quite reasonable given the nature of the fuel; see FIG. 3A.

FIGURE 3B compares an Input/Loss computed Fuel Compensator to a plant's DCS Energy Compensator. The plant is the 640 MWe Boardman Coal Plant burning Powder River Basin coal. Comparison of Compensators over illustrators fundamental differences discussed above. As observed, the Input/Loss Fuel Compensator is more reasonably behaved than the DCS Boiler Master output (Fuel Compensator). It is believed this reflects variable fuel heating value (opening the question of the real variability of As-Fired coal ...). But to gain verification, the Energy Compensator should be linear with the Boiler Master output, given constant load. FIGURE 3C plots the Input/Loss Energy Compensator against the Boiler Master signal over a three day period. Reasonable agreement is observed.

Using Biased Fuel Flow

To study the verification process, the Input/Loss Method was set-up to match a 660 MWe unit firing Powder River Basin coal flow rate. The fuel flow was biased by ±2%. The biased flow was matched by optimizing Stack moisture (Λ_{2S}); and thus affecting fuel water content and heating value. Results are presented in FIGURES 4A, 4B and 4C in which the plant indicated flow is shown before bias. For the case presented, the best judgement of heating value, based on reported train samplings, was 8300 ±100 Btu/lbm as indicated on the plots. In FIG. 4A, using a 0.980 bias, the computed fuel flow is seen lower than the reported before bias, while heating value (given lower fuel water) is higher than the "best estimate". FIG. 4C indicates the opposite affects. Since this technique requires knowledge of the average heating value, it is clearly not preferred. It does demonstrate sensitivities which have been appreciated for visceral understanding. However, this verification technique clearly would have merit for specialized testing involving real-time fuel samplings (if viable). Also, the technique may have merit if applied over long periods in which fuel heating value can be reasonably established.

CONCLUSIONS

This work demonstrates that verification of on-line monitoring systems is possible. Verification of coal-fired monitoring systems requires recognition that if accurate boiler efficiency is to be computed, that fuel chemistry and heating value are required; this implies that system stoichiometrics are knowable. System stoichiometrics are fundamentally important to thermal understanding; as such, back-calculated terms based on stoichiometrics becomes key for verification. Four techniques were studied, using ambient relative humidity, soot blowing flow, DCS Compensators and fuel flow. Of these, the preferred technique involves matching a computed ambient relative humidity to a directly measured. Back-calculated soot blowing flow is also useful for either verifying the general health of the on-line system, and/or for assisting in the detection of tube leaks.

ACKNOWLEDGMENTS

The author would like to thank Tom Canning of the Electricity Supply Board, Republic of Ireland and Dave Rodgers of Portland General Electric, Oregon, USA for their general support and providing needed on-line monitoring results.

REFERENCES

Canning, T, McNamara, F, Egan, A, and Naughton, P, “Novel Stored Energy Techniques for Spinning Reserve”, Conference of the International Federation of Automatic Control, Munich, Germany, **1992**.

Lang, FD, "Monitoring and Improving Coal-Fired Power Plants Using the Input/Loss Method (Part I)", ASME, IJPGC **1998**-Pwr-33.

Lang, FD, and Lang, AF, "Monitoring and Improving Coal-Fired Power Plants Using the Input/Loss Method - Part II", ASME, IJPGC **1999**-Pwr-34, pp.373-382.

Lang, FD, "Monitoring and Improving Coal-Fired Power Plants Using the Input/Loss Method - Part III", ASME, IJPGC **2000**-15079/CD; revised Jan. 6, 2003.

Lang, FD, "Monitoring and Improving Coal-Fired Power Plants Using the Input/Loss Method - Part IV", ASME, IJPGC **2004a**-52026/CD.

Lang, FD, Rodgers, DAT, and Mayer, LE, "Detection of Tube Leaks and Their Location Using Input/Loss Methods", ASME, IJPGC, **2004b**-52027/CD.

Lang, FD, “Discord in Boiler Efficiency Standards and Calorimetric Temperature”, unpublished, **2006**. Available at: *www.ExergeticSystems.com*.

U.S. Patents: 5367470, 5790420, 6522994, 6560563, 6584429, 6651035, 6691054, 6714877, 6745152, 6799146, 6810358, 6868368, 6873933, 7039555, 7328132, 7809526; Canadian 2325929, 2479238, 2541197; Australian 762836, 2006-201203; European (GB, IE) 1502188 and (GB, IE, DE & CH) 1835228; Patent applications are also pending and/or have been granted; **1994-2011**.

ERRATA

An August 13, 2008 revision to the original paper corrects and clarifies the use of DCS Compensators. The original paper defined a “Fuel Compensator”, offering rather nebulous differences with a defined “Energy Compensator”. Hopefully this is now clarified. Testing continues with all verification methods. A Dec. 15, 2011 revision incorporated minor changes.

FIGURE 1A: Verification using Relative Humidity (+0.50% bias)

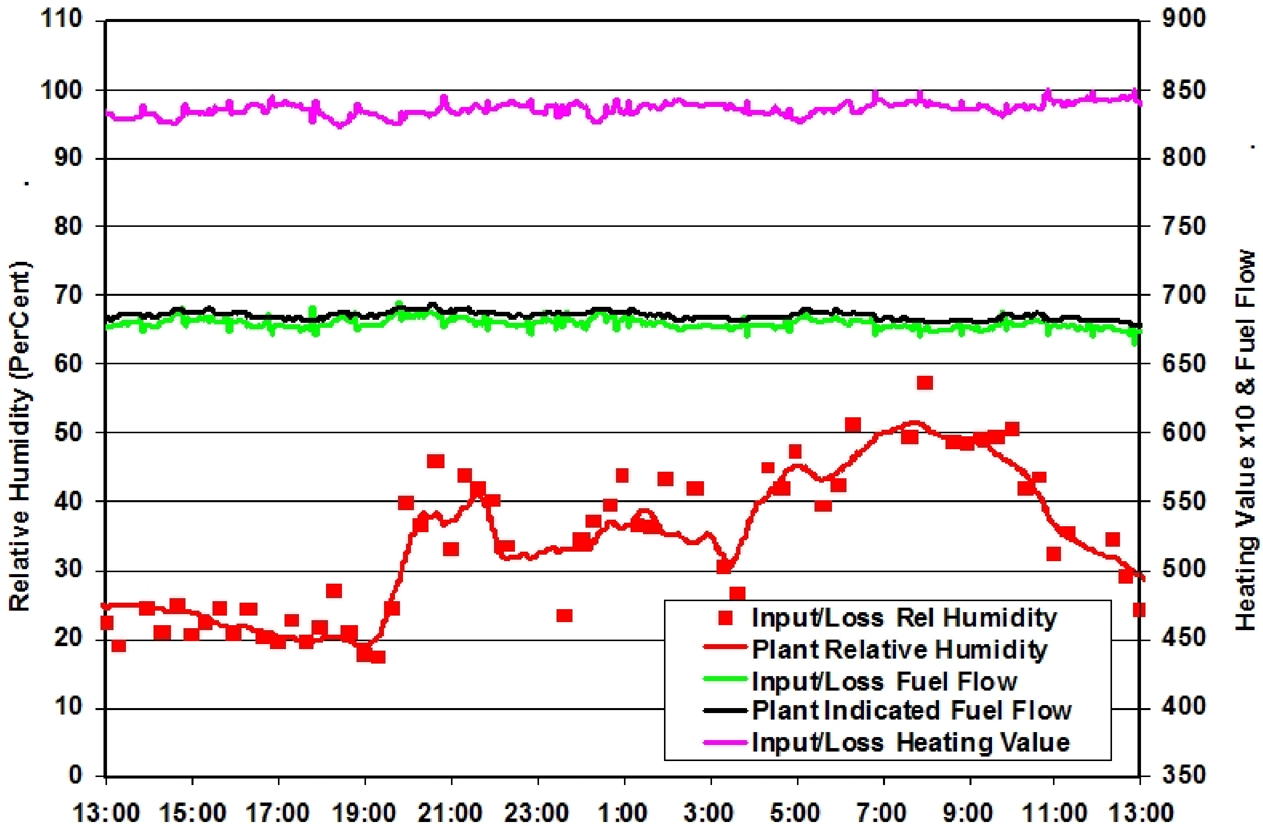

FIGURE1B: Resolution of Bias in Fuel Flow

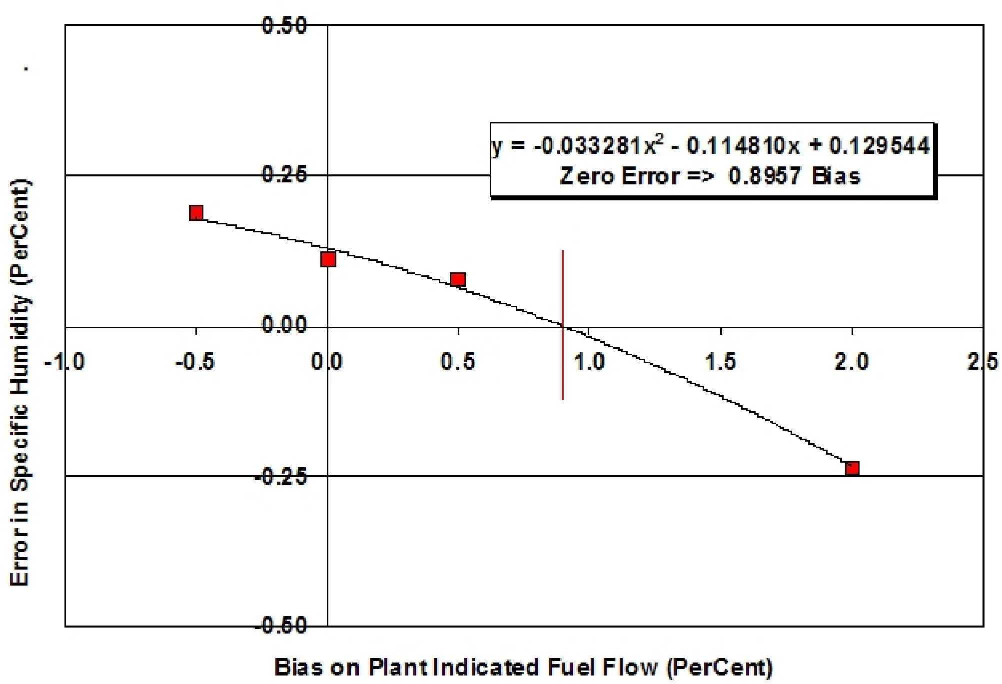

FIGURE 2: Verification using Soot Blowing Flow

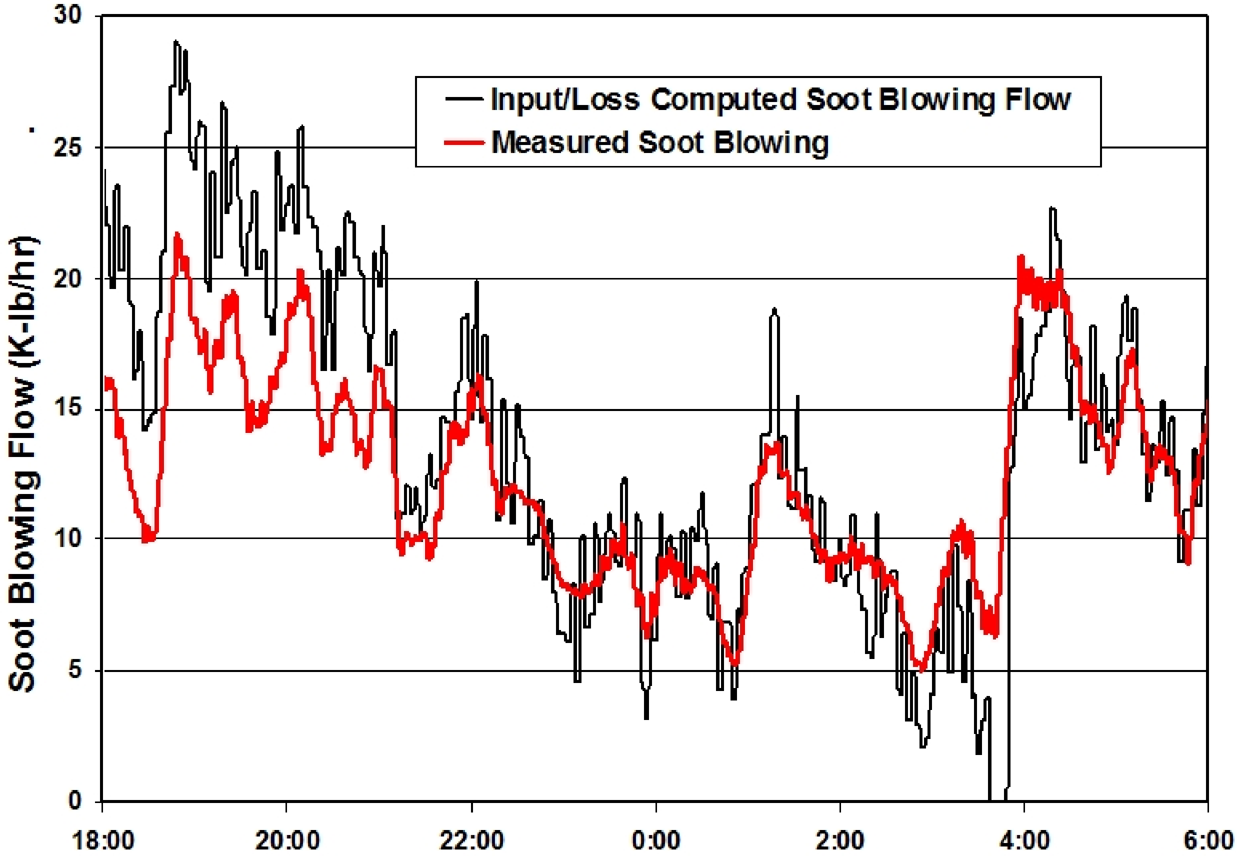

FIGURE 3A: Verification using Energy Compensator (150 MWe, Peat-Fired)

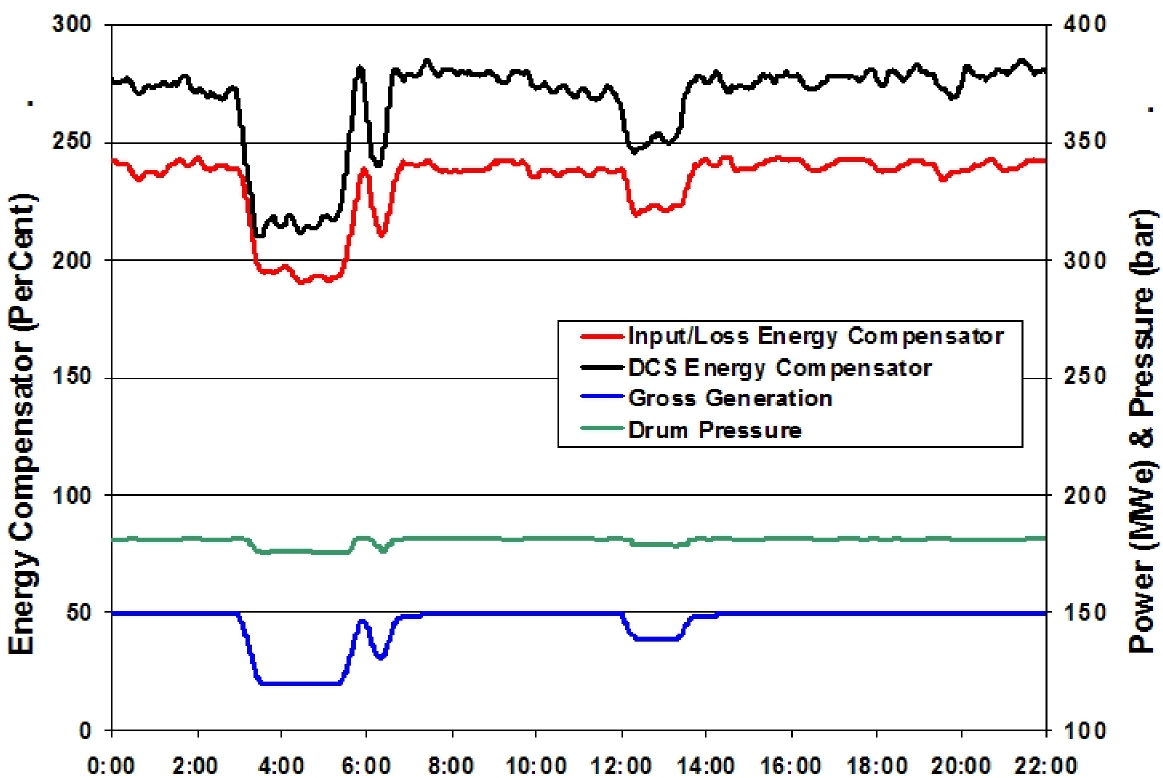

FIGURE 3B: Comparing DCS Compensators (640 MWe, Coal-Fired)

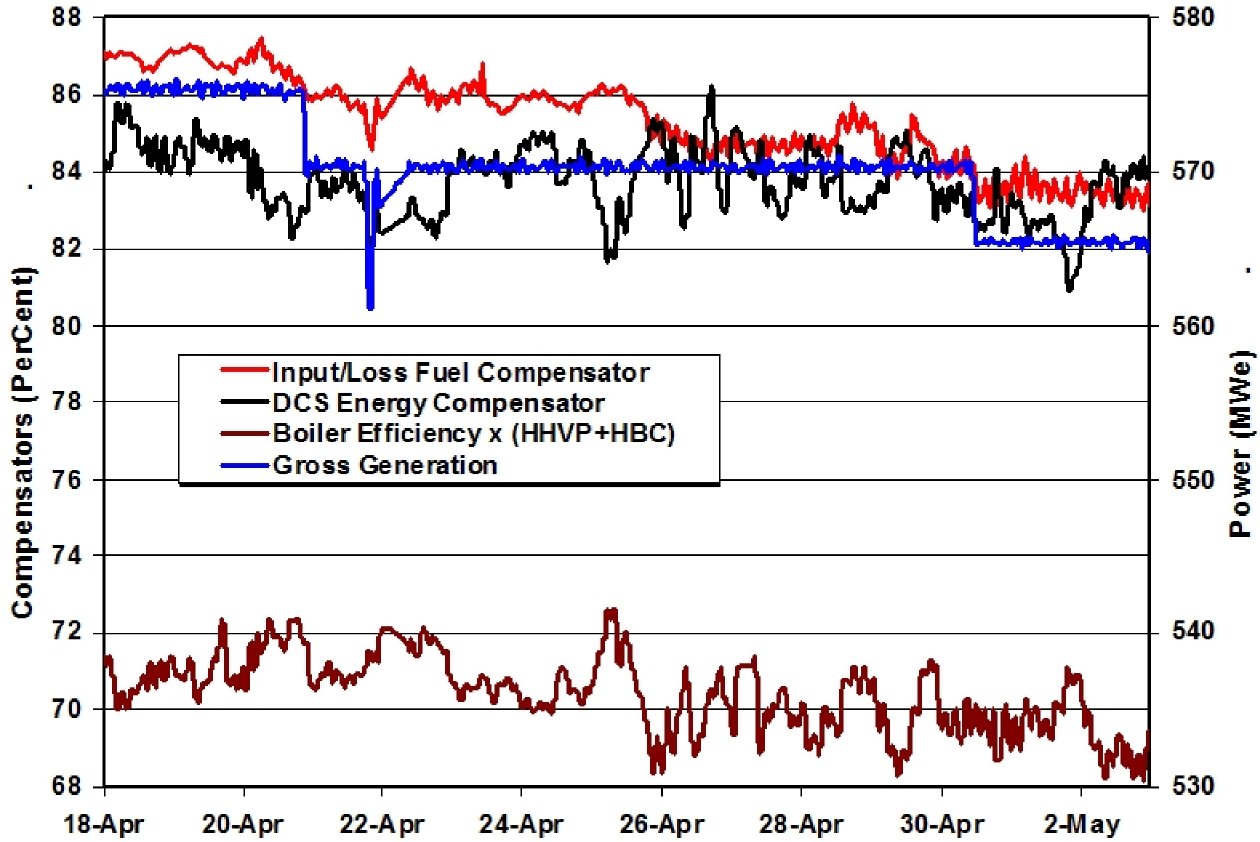

FIGURE 3C: Resolution of True Fuel Energy Flow versus Computed Flow Compensator (640 MWe, Coal-Fired)

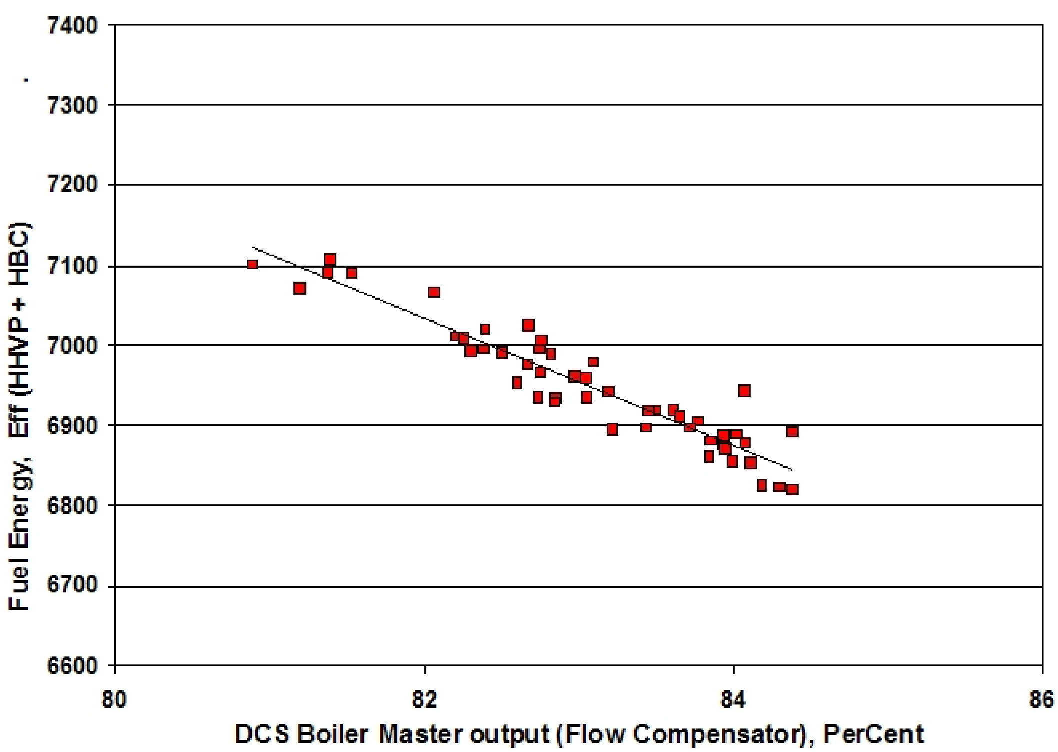

FIGURE 4A: Verification using Biased Fuel Flow (0.98 Factor)

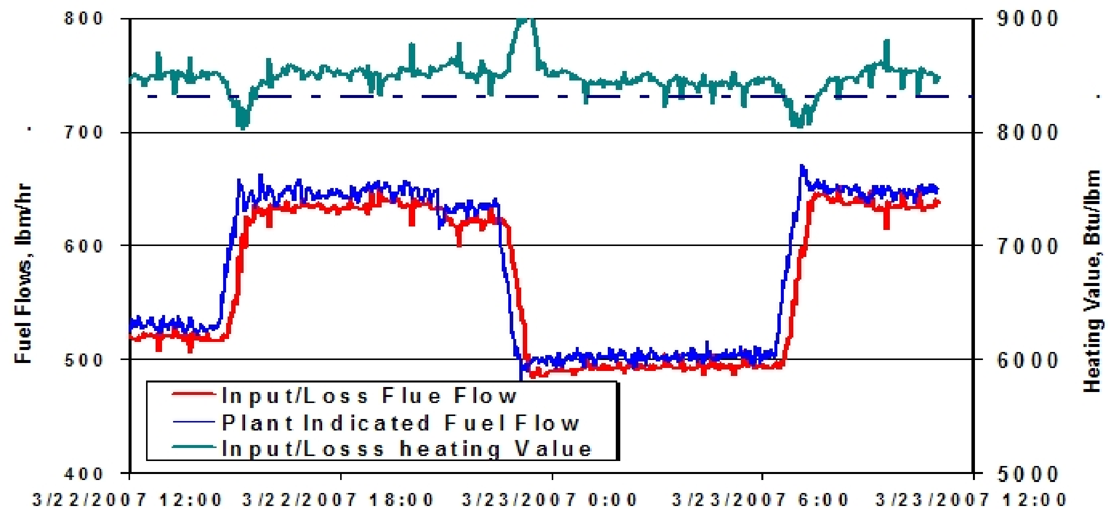

FIGURE 4B: Verification using Biased Fuel Flow (1.00 Factor)

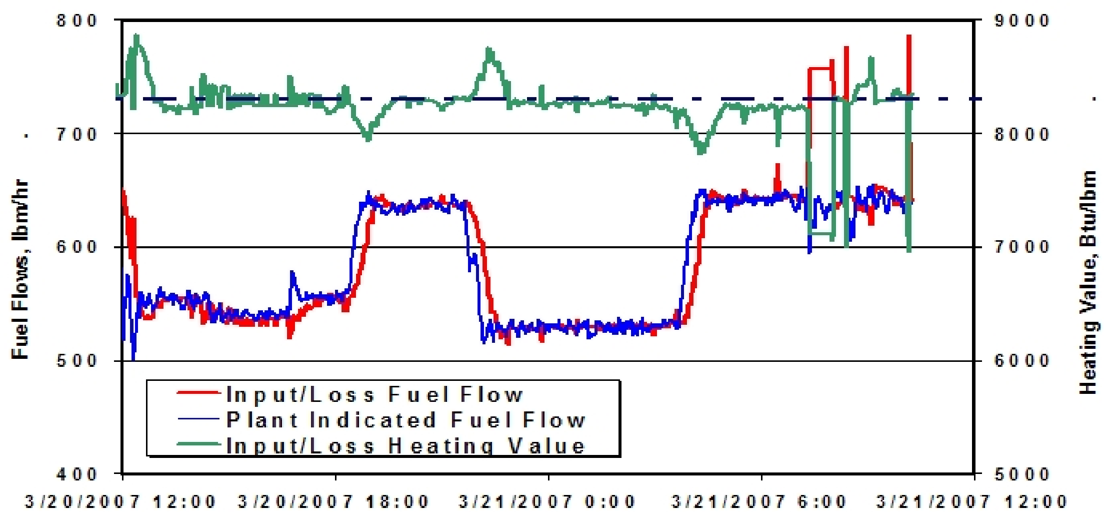

FIGURE 4C: Verification using Biased Fuel Flow (1.02 Factor)