

Discord in Boiler Efficiency Standards and Calorimetric Temperature (a supplement to “Part III Input/Loss Paper”)

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Summary

The established standards for computing boiler efficiency err as they do not maintain the fundamental definition of how the energy content of a fossil fuel is determined. No error need exist if: 1) the referenced temperature used for computing boiler efficiency is taken as the calorimeter temperature at which heating value is obtained; and 2) consistent application is made of Enthalpy of Product and Reactant terms as based on the calorimetric process, the interpretation of such terms affecting the treatment of boiler losses and “credit” terms (e.g., fan powers, pulverizer shaft powers, etc.). Boiler efficiency is intrinsically bound with calorimetric temperature. Boiler efficiency associated with high energy fossil fuels, whose Heats of Combustion are insensitive to calorimetric temperature, will have intrinsically high uncertainty. However, for those fuels where adequate sensitivity exists, and the accuracies of modern calorimeters invoked, then boiler efficiency can be well understood such that fuel flows can be accurately computed.

However, no present boiler efficiency standard addresses calorimetric fundamentals; reference temperatures and treatment of shaft powers are by happenstance. Although the error for highly energetic fossil fuels is typically slight ($<0.2\% \Delta\eta_{HHV}$), the error associated with fuels producing 10% or more product water (such as high volatile B bituminous (hvBb) ... to the lignites and peat) are appreciable at $0.5\% \Delta\eta_{HHV}$ and higher. Such errors derive from assuming a reference temperature for boiler efficiency, while the heating value was determined at another. For example, a $0.5\% \Delta\eta_{HHV}$ error is produced for a sub-bituminous B coal when 25C is the assumed reference temperature while the heating value was determined at 35C. Note that modern bomb calorimeters have repeatability accuracies at the 0.1% level, it is this fact which adds imperative. From a commercial view point, the worth of a 0.5% change in boiler efficiency (i.e., 84.0 to 84.5%) regards a performance test of a large steam generator may be worth many millions of dollars in incentives or penalties. There are other errors in the established standards which are discussed, principally the treatment of shaft powers; again, all related to the thermodynamic bases of heating value and its calorimetric temperature.

Calorimeters

Heating values are obtained either by adiabatic or isoperibol bomb calorimetry following ASTM D5865 or ISO 1928. An adiabatic bomb calorimeter detects the net energy liberated from combustion by maintaining a constant water bath temperature about the bomb, which is T_{Cal} . An isoperibol bomb calorimeter detects the net energy liberated by accurately monitoring the water bath temperature, its resultant average value being T_{Cal} . Many modern bomb calorimeters are automated to run at a programmable T_{Cal} . The author has found various labs in North America using 27C

(80.6F), 28.5C (83.3F), 30C (86F) and, commonly, 35C (95F). The author has yet to find any lab in North America determining coal heating value at 25C, the reference for most boiler efficiency standards.

The case for change lies in the definition of higher heating value (HHV) as obtained from a bomb calorimeter: the energy from products formed are relative to the equilibrium temperature, this includes, of course, the water produced as reduced to the liquid state. Energy liberated from a bomb calorimeter is relative to the equilibrium temperature at which the bomb functioned.

$$\oint \delta_{T-\text{Cal}} Q = -\text{HHV} = -\text{HHVP} + \Delta H_{V/P} \quad (\text{S1})$$

$$\text{HHVP} \equiv -\text{HPR}_{\text{Ideal-HHV}} + \text{HRX}_{\text{Cal-HHV}} \quad (\text{S2})$$

Heating value, when converted to a constant pressure process (HHVP) via a $\Delta H_{V/P}$ term, must be the difference between the energy of ideal combustion products ($\text{HPR}_{\text{Ideal-HHV}}$) and the energy of the reactants ($\text{HRX}_{\text{Cal-HHV}}$); both evaluated at that temperature at which the difference between these quantities was obtained, the bomb's calorimetric temperature.

The sources of numerical error lie with the sensitivity to temperature of the latent heat of water and Heats of Formation. The temperature dependency for water is great (Table 2) indicating a 1% sensitivity per $10\Delta C$ change in latent heat. This implies that when fuel water and fuel hydrogen exceed 10%, the sensitivity of HHV exceeds the repeatability accuracy of modern calorimeters ($\geq 0.1\%$). As seen in Table 3 the SO_2 sensitivity is slight, while CO_2 is minimal. Thus for fuels with high water contents, the latent heat is of obvious import when condensing vapor in a bomb calorimeter. It can be argued, for example, that a fossil fuel having low fuel hydrogen but high water contents has little sensitivity to calorimetric temperature if its starting and ending calorimetric temperature is the same; there will be no net change to vaporizing and then condensing the water. Thermodynamically such an argument only has merit if the calorimeter's temperature is uniquely controlled. Eq.(S1) is path dependent. If the bomb's condensation process, $-\Delta h_{fg}$ at some $T(\text{cond})$, follows the same path in reverse as its vaporization process, $+\Delta h_{fg}$ at $T(\text{vap})$, then no net change will be observed; further discussed below by example.

The latent heat of water also has obvious import when converting from a gross to a net heating value. Although laboratories routinely report the as-tested gross value, when a fossil fuel is burned, its net energy is liberated. There can be no distinction imposed at the time a fuel is burned commercially, versus how its energy was determined in the laboratory. If calorimetry process were to end mid-path, with vaporized water, the derived energy liberated must be the same as would be determined from a routine combustion/vaporization/condensation process. The measured net energy liberated must employed when evaluating commercial combustion, to do otherwise implies thermodynamics is a capricious science.

The ideal product of combustion, $\text{HPR}_{\text{Ideal-HHV}}$, is defined by the Heats of Formation of the composing ideal products: $\Delta H_{f-\text{CO}_2}^0$, $\Delta H_{f-\text{H}_2\text{O}}^0$ and $\Delta H_{f-\text{SO}_2}^0$. The sensitivity of these terms is reflected in the ratio ($\Delta \text{HPR}_{\text{Ideal}} / \text{HPR}_{\text{Ideal}}$) present in Table 1 for all Ranks of coal, etc.. Note that the indicated arrow points to a hvBb fuel (and to those below) whose associated boiler efficiencies can be sufficiently affected by a $10\Delta C$ change in an assumed reference temperature. The sensitivity of the ($\Delta \text{HPR}_{\text{Ideal}} / \text{HPR}_{\text{Ideal}}$) term explains why boiler efficiencies associated with the poor quality fuels, having very high water contents, have greater sensitivity to T_{Cal} ; and also have reduced uncertainty versus very high energy fuels.

These tables also illustrate the paradox of fossil fuels: as a fuel's energy content increases - whose weight fraction of carbon increases relative to fuel water and hydrogen - the dependency of chemical reaction on temperature decreases (unless well recorded), thus functionally causing uncertainty in the reference energy level. Boiler efficiency becomes a relative indicator. However,

the “advantage” of poorer quality fuels lies with water’s sensitivity to temperature, and thus substantiates an absolute boiler efficiency, one through which fuel flow can be computed.

**Table 1: As-Received (wet) Properties of Fossil Fuels
(data from Penn. State, Input/Loss installations & NIST)**

Substance or Coal Rank	Fuel Hydrogen (% wt)	Fuel Water (% wt)	Fuel Ash (% wt)	Avg. HHV at 25C (Btu/lbm)	HHV Temp.Coeff. (x10 ⁻⁶ /1ΔC)	$\frac{\Delta HPR_{Ideal}}{HPR_{Ideal}}$ (x10 ⁻⁶ /1ΔC)
an	1.94	3.55	9.85	12799.75	19.56	376.6
sa	3.01	1.44	16.51	12466.17	30.10	285.0
lvb	3.97	1.69	13.22	13155.11	39.22	347.7
mvb	4.44	1.75	11.48	13371.75	41.88	380.5
Benzoic Acid	4.95	0.00	0.00	11364.57	45.0 (NIST)	---
hvAb	4.91	2.39	10.86	13031.61	47.77	444.2
hvBb	4.63	5.61	11.83	11852.63	56.53	446.7 ←
hvCb	4.26	9.89	12.32	10720.40	60.18	450.6
subA	3.94	12.93	7.06	10292.89	51.16	398.3
subB	3.76	17.87	9.57	9259.75	61.15	408.0
subC	3.50	23.79	10.67	8168.69	75.14	423.3
ligA	3.02	29.83	9.64	7294.66	83.56	439.4
Methane	25.33	0.00	0.00	23867.31	105.39	424.3
Irish Peat	2.73	46.78	1.72	4856.07	112.00 (est.)	542.7
ligB-PSU	2.16	28.84	22.95	4751.83	122.17	481.3
ligB-Greek	1.39	54.04	16.93	2926.82	246.01	685.2

Table 2: Sensitivities of H₂O

Reference Temp.	Latent Heat for Water (ΔBtu/lbm)	Change (%)	H ₂ O Heat of Formation _{LIQ} (Btu/lbm)	PerCent Change (%)	H ₂ O Heat of Formation _{VAP} (Btu/lbm)	Change (%)
25C (77F)	1050.001	0.0000	-6821.142	0.0000	-5771.141	0.0000
30C (86F)	1044.916	0.4866	-6817.358	0.0555	-5772.442	0.0226
35C (95F)	1039.818	0.9793	-6813.584	0.1109	-5773.766	0.0455

Table 3: Sensitivities of SO₂

Reference Temp.	SO ₂ Heat of Formation (Btu/lbm)	PerCent Change (%)
25C (77F)	-1992.0027	0.00000
30C (86F)	-1992.1867	0.00924
35C (95F)	-1992.3670	0.01829

Table 4: Sensitivities of CO₂

Reference Temp.	CO ₂ Heat of Formation (Btu/lbm)	Change (%)
25C (77F)	-3844.1174	0.00000
30C (86F)	-3844.1465	0.00076
35C (95F)	-3844.1750	0.00150

Opposing Arguments and Responses

If a coal sample is completely dried before calorimetric testing, desensitizing water's influence, why not then choose any reference temperature of opportunity when converting the measured dry-base HHV to an As-Received base?

- 1) ASTM D5865 and ISO 1928 standards do not specify complete drying, and for the very good reason that harsh drying affects volatiles associated with many of the common coals. Water's presence is a practical fact in calorimetry; indeed, its removal would clearly affect the very measurement one is trying to determine.
- 2) If a fuel sample were completely dried, any resultant boiler efficiency based on the measured dry HHV would only be a relative measure, dependent on the chosen reference temperature of conversion. This conclusion is incompatible with the determination of fuel flow based on boiler efficiency (discussed below). Further, relative boiler efficiencies are contrary to commercial practices, contrary to the US Clean Air Act (requiring "absolute" measures) and contrary to principles involving thermal performance evaluation of equipment.
- 3) Such practices would inherently suggest that Heats of Combustion are independent of temperature. The very good accuracy of the modern calorimeter does not support the application of such concept in the laboratory. Making such a statement in any internationally recognized standard would invite legitimate criticism.
- 4) To allow post-test corrections implies, practically, that one is allowed to mix two substances (a dried or partially dried coal with its As-Fired water), but where each substance could have a different temperature base. For example, if high volatile B bituminous (hvBb) coal, having approximately equal parts fuel water and fuel hydrogen, were tested in a dried state, the effects from a 25C calorimeter might mix with fuel water assumed at 50C.
- 5) The older ASTM calorimetric standards specified a "reference temperature" (either 20 or 25C), but offered no supporting procedures. The current standards do not require a specific calorimetric temperature. It is argued they, indeed, should not, but if the older standards thought it viable to add such specificity, the current standards should at least be required to report the T_{Cal} employed (and to use it consistently in gross to net conversions).

If a fuel sample with high water, but a low fuel hydrogen content, begins a calorimetric test at T_{Cal} and ends at the same temperature, a subsequent conversion to another reference temperature becomes a mathematical exercise (only dependent on water properties); what is the harm?

- 1) This argument counters the First Law of Thermodynamics. Standards must not prostitute science to industrial expediency. As is well known, work and heat terms are path dependent, thus they are inexact differentials: $\delta Q = mdh + \delta W$. For example, if an equal mix of water and graphite were placed in a bomb calorimeter all in equilibrium with its water bath at 25C, and if the system is then brought to 10C, then ignited vaporizing the water followed by condensation at 10C, then returned to 25C; the bath's energy flow ($\oint \delta Q$) for this process would not be the same if the system was maintained at 25C throughout. Water's latent heat

at 10C differences from that at 25C by 1.45%; this difference is not off-set by sensible heat affects which, of course, cancel: 25C to 10C, versus 10C to 25C.

2) If, however, what is meant is to perform the calorimetry in a more conventional manner, such mathematical exercises would be acceptable if the chemistry of the dry fuel is known. For gaseous fuels and pure graphite this is routinely done; indeed such computations are more accurate than direct calorimetry (and, of course, temperature dependent - even given $\Delta H_{f-CO_2}^0$ insensitivity to temperature it would be unthinkable to report a computed Heat of Combustion without also reporting its reference temperature). However, the vagaries of solid fuels - the interstitial nature of coal matrices, complex hydrocarbon linkages, etc. - demands that no back-calculated corrections be attempted (unlike those allowed by European standards, discussed below). If a Heat of Formation has a weak temperature dependency, it could lead to uncertainty in computed boiler efficiency (that is simply the nature of chemical-thermal properties of high energy coals); it is not however a license to use capricious references.

Since no present calorimetric standard requires the recordation of T_{Cal} why is one not free to use any temperature when converting from gross to net heating values, and especially for those fuels producing low product water? Would not such conversion, at some convenient temperature, then establish a new T_{Cal} at least viable for the low water fuels?

1) Indeed, there is no present requirement for reporting T_{Cal} . The author argues for reporting T_{Cal} , but also argues for use of T_{Cal} when converting from gross to net, and when correcting to constant pressure from the constant volume bomb (see Recommendations below).

2) Allowing for arbitrary conversion temperatures will add only chaos to the practice. No two labs would necessarily use the same temperature when making such conversions. The only logical temperature is indeed the temperature at which the calorimetry was performed; and dutifully reported on every lab sheet.

3) Thermodynamics knows nothing of the sensitivities of Heats of Formation. Chemical reactions occur and, the author argues, must be reported as-tested. To do otherwise assumes knowledge one does not have, which it is not the business of standards to attempt supplement.

Natural gas-fired power plants (both conventional and combustion turbines) around the world use computed heating values without employing a consistent T_{Cal} , are their system efficiencies all wrong?

Yes. The justification of such an answer is fully developed in the following two paragraphs, leading to Eq.(S6-A) & (S6-B). Justification lies with computed fuel flow. For an in-situ system, burning the same fuel, producing the same useful energy flow (BBTC), its fuel flow (m_{AF}) must then be the same no matter the conditions under which heating value was determined. The following three efficiency calculations assume the same methane fuel, the same combustion air (25C & 60% humidity), the same fuel temperature (5C), the same gaseous boundary temperature (145C) and 20% excess air; but different values of computed HHV and consistent T_{Cal} . The computed useful energy flow per fuel flow (BBTC/ m_{AF}) should remain constant. Calculations are based on Input/Loss Methods of computing efficiency, per Eq.(S5).

$$\begin{aligned} \text{BBTC}/m_{AF} &= \eta_{B-HHV} (\text{HHVP} + \text{HBC}) \\ &= (0.84840)(23867.31 - 19.09) = 20233 \text{ Btu/lbm}; \text{ at } T_{Cal} = 77.0F (25.0C) \\ &= (0.84419)(23891.00 + 75.62) = 20232 \text{ Btu/lbm}; \text{ at } T_{Cal} = 60.0F (15.6C) \\ &= (0.83863)(23918.80 + 201.32) = 20228 \text{ Btu/lbm}; \text{ at } T_{Cal} = 37.4F (3.00C) \end{aligned}$$

Of course as argued here, all results should be exactly identical; the observed difference of 0.025% over a 22 ΔC range in T_{Cal} is most likely due to slight inconsistencies in properties. The point to be made is that there is no thermodynamic difference between a natural gas-fired

system and a coal-fired system, the same basic principles must apply as based on Eq.(S2) leading to (S4) & (S5). Note that without consistently applying HHV with its T_{Cal} as the reference temperature, the above consistency demonstration would not be possible, resultant errors in efficiency will approach 0.5%. For example, using a methane heating value of 23867.31 Btu/lbm at a “reference temperature” of 95F (35C), produces a 85.307% efficiency; versus the correct 84.840% at 77.0F (25.0C).

Boiler Efficiency

It is argued here that boiler efficiency must follow directly from Eq.(S2). Boiler efficiency is formed by considering losses relative to ideal products, and Firing Corrections relative to reactants. Firing Corrections are referenced to the reactants as supplied and burnt in a calorimeter, relative to T_{Cal} . Note the term “Firing Correction” denotes the correction required to alter the energy level from the calorimetric to the actual, as opposed to an arbitrary “boiler credit” term in common use. A steam generator has no “credits” to its conversion efficiency, it is what it is as measured by the fuel energy it consumes relative to that fuel’s established energy level. Boiler efficiency then becomes an indicator of energy conversion, from chemical to useful output, relative to a common energy level. The calorimetrics of Eq.(2) becomes, after adding the Firing Correction to each side, an expression for gross- or net-based boiler efficiency:

$$\eta_{B-HHV} (HHVP + HBC) = [- HPR_{Ideal-HHV} - \sum Losses/m_{AF}] + [HRX_{Cal-HHV} + HBC] \quad (S3-A)$$

$$\eta_{B-LHV} (LHVP + HBC) = [- HPR_{Ideal-LHV} - \sum Losses/m_{AF}] + [HRX_{Cal-LHV} + HBC] \quad (S3-B)$$

Note that if the $\sum Losses/m_{AF}$ term is zero, efficiency becomes unity, a sanity check on the calorimetric foundation. If the fuel is fired at a temperature different from T_{Cal} , the reactants must be corrected for the fuel’s sensible heat relative to T_{Cal} (the so-called “Firing Correction” term of HBC). If combustion air enters the system at a temperature different from T_{Cal} , the reactants must be corrected for the air’s sensible heat relative to T_{Cal} (the bomb’s O_2 being in equilibrium at T_{Cal}). If the system has an additional input of water in-leakage (a tube leakage), air leakage, limestone injection, etc., the traditional reactant term from calorimetrics, HRX_{Cal} , must be so corrected. All inputs to the system must be corrected to a common energy level associated with T_{Cal} . There are no “credits” nor “losses” associated with such corrections; without the $\sum Losses/m_{AF}$ term boiler efficiency will always be unity. However, if the outputs (products) from combustion are not ideal, they are then “corrected” through loss terms. Bear in mind that all loss terms must be consistently evaluated at the same energy level for which the $HPR_{Ideal-HHV}$ term and its associated Heats of Formulation, were established. **In summary, Firing Corrections affect reactants, while loss terms correct ideal products - both relative to how these terms were established at a specified T_{Cal} .**

Since boiler efficiency (η_B , gross or net) is intrinsically related to heating value through Eq.(S2), its reference temperature is then set by how the heating value was obtained. It is tacitly assumed that back-correcting an as-measure heating value of a solid or liquid fuel to some chosen T_{Cal} is not possible given chemical complexities of such fuels. It is for this reason that the reactant term $HRX_{Cal-HHV}$ of Eq.(S3) is evaluated as $[HHVP + HPR_{Ideal-HHV}]$, following Eq.(S2); the ideal products term being well defined, HHV being measured in a modern calorimeter.

For gaseous fuels, given knowledge of the composition, heating values are routinely computed at a chosen T_{Cal} . For example, in North America T_{Cal} is taken at 60.0F for gaseous fuels, while in Europe 0.0C is employed, resulting in a 1.51% difference in gross HHV for methane! (the temperature coefficient increases as water’s triple point is approached). Even with such obvious dependency on T_{Cal} , efficiencies of natural gas fired steam generators and combustion turbines do

not recognize the importance of consistent use of T_{Cal} (see ASME PTC 4 and 22).

Finally, an expression for gross boiler efficiency is developed by simply dividing Eq.(S3-A) through by $(HHVP + HBC)$, again flowing from basic calorimetric principles:

$$\eta_{B-HHV} = \frac{[-HPR_{Ideal-HHV} - \sum Losses/m_{AF}] + [HRX_{Cal-HHV} + HBC]}{HHVP + HBC} \quad (S4)$$

Different procedures divide the $\sum Losses$ term of Eq.(S4) into different categories. For example, Exergetic Systems divides $\sum Losses$ into stack-related quantities and into non-stack quantities (through an absorption efficiency term η_A):

$$\eta_{B-HHV} = \frac{-HPR_{Act-HHV} + HRX_{Act-HHV}}{HHVP + HBC} - \eta_A \quad (S5)$$

However, the principles stated through Eqs.(S2) and (S4) apply fundamentally to all determinations of boiler efficiency, using any form of the Heat Loss Method, the Input-Output Method, the Input/Loss Method, methods advocated by Babcock & Wilcox, etc.

Computed Fuel Flow as the Absolute Test

Why does adherence to such thermodynamic consistency matter? Is not any definition of efficiency valid when taken as a relative measure (say for high energy fuels)? The answer lies with a system's As-Fired fuel flow, m_{AF} . Computed fuel flow is based on: useful energy flow produced (BBTC), boiler efficiency and heating value corrected for how it is fired. The canonical test for any Loss or Firing Correction term is whether the term impacts fuel flow. Efficiency, in the broadest sense, is useful energy flow developed from a system, relative to the supply of fuel energy. The fuel's energy content is dependent on fuel chemistry and how heating value was obtained, not on any parameter of the physical system nor its environs *per se*. If, indeed, fuel energy flow were so dependent (say on an arbitrary "reference" temperature, e.g., combustion air temperature, or an arbitrary 25C, etc.), then computed fuel flow would be arbitrary. As-Fired fuel flow is not an arbitrary parameter, it is absolute and solely dependent on the system's capability of converting fuel energy to useful output. From the Input-Output Method:

$$m_{AF} = \frac{BBTC}{\eta_{B-HHV} (HHVP + HBC)} \quad (S6-A)$$

$$m_{AF} = \frac{BBTC}{\eta_{B-LHV} (LHVP + HBC)} \quad (S6-B)$$

Thus adding house electrical loads to the Firing Corrections term (HBC) which has no impact on the energy conversion process, is wrong. Using the power of an ID fan as a Firing Correction is wrong (it effects the products stream or could be left outside the boundary). Correcting the HBC term in Eq.(S4) for a stack loss $C_p \Delta T$ term is wrong (Firing Corrections only the reactants stream). Including the coal pulverizer shaft power as a Firing Correction is wrong as no thermal energy is added to the fuel (crushing coal increases its surface energy, not its internal energy - indeed coal prepared for a calorimeter is ground to a fineness not atypical of pulverizer action; the measured HHV reflects such changes in surface energy). Arbitrarily setting the reference temperature is wrong. Use of these terms, in the manner suggested, as they would impact boiler efficiency is functionally wrong because the computed fuel flow would then have arbitrary dependencies. Use of such terms, in the manner suggested, is clearly wrong thermodynamically as it destroys the connectedness with what heating value means via Eq.(S2). **Fuel flow supplied to an in-situ system, firing a defined fuel can not change, it is what it is - it can not be a function of capricious references!!**

Boiler Efficiency Standards

To illustrate the need for thermodynamic consistency, set out below are some of the errors made in traditional standards. This list is by no means complete, but concentrates on so-called “energy credits” and “heat credits” (i.e., Firing Corrections), and the use of reference temperatures. This is followed by recommendations.

ASME PTC 4.1 (United States):

- §1.04.5, shaft powers from pulverizers & circulating pumps are included as energy credits.
- §7.2.8.1, reference temperature (T_{RA}) is taken as the air’s ambient temperature.
- The FD and ID fans are considered outside the thermodynamic envelope.

ASME PTC 4 (United States):

- §5.13.1, the reference temperature is set at 25C; no mention of calorimetric temperatures.
- §5.15.5.1, thermal power from steam driven equipment is included as an energy credit.
- §5.15.5.2, power from electrically driven equipment is included as an energy credit.
- The FD and ID fans are considered outside the thermodynamic envelope.

DIN 1942 (German):

- §6.2, the reference temperature (t_b) is set at 25C. However, “other temperatures may be agreed upon” by correcting the net heating value with fuel and air Δ sensible heat terms, but also corrects for combustion gases with: $C_p(t_b - 25)$; effectively a “heat credit” appearing in the efficiency equation’s denominator. Adding such a term as a heat credit is quit wrong as combustion gases must be properly referenced in the η_B numerator as a product term. Product Δ energies can not affect reactants (even when being corrected to actual firing conditions).
- §6.3.2.3, heat credits (denoted as Q_Z) includes shaft powers from pulverizers, recirculating gas fans, working fluid circulating pumps and “power from any other motors”. DIN 1942 employs its heat credit term (Q_Z) in both its Input-Output and Heat Loss methods. Using DIN 1942 nomenclature [where: Q_N is the useful output (BBTC); Q_{ZB} is fuel energy flow ($m_{AF}LHVP$); and Q_{Vtot} is the system losses term which does not include Q_Z heat credits], the following are presented:

$$\eta_{B-LHV} = \frac{Q_N}{Q_{ZB} + Q_Z} \quad (144)$$

$$\eta_{B-LHV} = 1.0 - \frac{Q_{Vtot}}{Q_{ZB} + Q_Z} \quad (147)$$

The problem with DIN’s Eqs.(144) and (147) lies with a postulated change in the heat credits, Q_Z , due to a change in shaft powers. If an increase in shaft powers results in a lower boiler efficiency when using Eq.(144), it results in a higher efficiency when using Eq.(147); with resulting impossible differences in computed fuel flows. This same conundrum exists with the ASME and the draft European standards. For Input/Loss Methods, recirculating gas fans are treated the same as ID fans; the negative of their powers appear within the \sum Losses/ m_{AF} term of Eq.(S4), in the numerator, to counter higher boundary temperatures. FD fan power effects Firing Corrections, HBC, which appears in both the numerator (through HRX_{Act}) and in the denominator ($LHVP + HBC$), a balancing via Eq.(S3) based on maintaining Eq.(S2). Input/Loss employs no other shaft powers.

In DIN 1942, the ID fan is considered outside the thermodynamic envelope; the FD fan may be considered inside the envelope.

Draft European Standard:

This standard closely follows DIN 1942, employing the same nomenclature and general methods.

§7.2, the reference temperature (t_b) is set at 25C, but “other temperatures may be agreed upon” which corrects heat credits as done in DIN 1942.

The ID fan is considered outside the thermodynamic envelope; the FD fan may be considered inside the envelope.

BS 2885 (British):

§2 (bottom), all fuels shall use a calorimetric temperature of 25C.

Items 708, 804 and 907, the reference temperature for sensible heats in the dry flue gas, moisture in the combustion air, and fuel is the combustion air temperature (as done in ASME PTC 4.1), not 25C its stated calorimetric.

Item 901, the Input-Loss method (“Method A”) does not consider energy credits; it invokes a simple “fuel efficiency”. However Item 902, invoking the Heat Loss method (“Method B”) considers the “heat equivalent of auxiliary power” as a loss, carrying the same sign as a radiation & convection loss term. Again, such inconsistencies will result in impossible differences in computed fuel flows.

Standard for Recovery Boilers (TAPPI, United States):

§0 (page 4), the reference temperature is set at 25C.

For recovery boilers burning black liquor is it common industrial practice to correct the measured heating value for Heats of Formation associated with reactions particular to recovery boilers, specifically the reduction of Na_2SO_4 . Such corrections address the difference between ideal combustion products associated with a bomb calorimeter versus actual products associated with further reduction of certain black liquor compounds. However, such corrections are thermodynamically inconsistent with Eq.(S4). They correct the heating value with a computed ΔHR term: $(\text{HHVP} - \Delta\text{HR} + \text{HBC})$; this term effecting the Eq.(S4)’s denominator. The ΔHR term is an intrinsic portion of Eq.(S4)’s numerator; an affect of describing actual products & reactants via the HPR_{Act} and HRX_{Act} terms.

Recommendations (old, dated to 2003)

Recommendations become obvious. Formal and detailed revisions to ASTM D5865 have been prepared and are under review (ASTM Work Item 5174). Modifications to ISO 1928 can be easily prepared. The following summarizes the principle changes needed to improve these standards:

- 1) Report the calorimetric temperature, T_{Cal} , on the result data sheet.
- 2) List on the result data sheet the constant volume gross heating value, and the converted constant pressure gross heating value on an As-Received bases.
- 3) List the converted constant pressure net heating value on an As-Received bases.
- 4) Specify as part of the standard, the conversion procedures, all based on T_{Cal} .
- 5) Standards must not allow corrections made to an As-Determined calorific value, other than those conventional conversions as specified therein.

References

- “Standard Test Method for Gross Calorific Value of Coal and Coke”, ASTM D5865-03.
- “Solid Mineral Fuels - Determination of Gross Calorific Value by the Bomb Calorimetric Method, and Calculation of Net Calorific Value”, International Organization for Standardization, ISO 1928:1995(E).
- “Gross Heating Value of Black Liquor”, TAPPI, T684 om-02.
- “Steam Generating Units”, American Society of Mechanical Engineers, Power Test Code 4.1: 1973 & 1991 (also: ANSI PTC 4.1-1974); the old US standard.
- “Fired Steam Generators”, American Society of Mechanical Engineers, Performance Test Code 4: 1998; the current US standard.
- “Acceptance Testing of Steam Generators, DIN 1942: February 1994, DIN DEUTSCHES Institut Fur Normung E.V.; the German standard.
- “Water-Tube Boilers and Auxiliary Installations - Part 15: Acceptance Tests”, prEN 12952-15: November 1999, European Committee for Standardization, Brussels (also: CEN/TC 269/WG 3 N 337); the draft European standard.
- “Code for Acceptance Tests on Stationary Steam Generators of the Power Station Type”, BS 2885: 1974 (also: ISBN: 0 580 08136 2); the British Standard.
- “Performance Test Procedure Sodium Based Recovery Units”, CA Report No. 84041601, March 1996, TAPPI Press, Atlanta Georgia; the US standard for recovery boilers.
- Lang, F.D., “Monitoring and Improving Coal-Fired Power Plants Using the Input/Loss Method - Part III”, Proceedings of the ASME 2000 International Joint Power Generation Conf. (Miami Beach, Florida, July 23-26); IJPGC 2000-15079(CD). Revised January 6, 2003, download available from www.ExergeticSystems.com.