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Energy Balance Validation: Investigation of the residual energy of thermal efficiency tests on gas and oil boilers

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Author(s)	John Hayton, BRE

Contents

Foreword (*by Bruce Young, BRE*)

This paper describes the Energy Balance Validation (EBV) method that has been designed to help validate boiler thermal efficiency measurements by estimating the energy balance. The purpose is to identify boilers with unrealistic thermal efficiencies derived from tests where the measurements are inconsistent. Efficiency results are examined in conjunction with a number of measured values obtained during tests so as to determine the energy balance.

If the test measurements were perfect, the energy balance would be exact and the residual (Q_r) in the energy balance equation would be zero. The energy balance equation is:

$$Q_r = Q_i + Q_e - Q_o - Q_f - Q_c - Q_s$$

where:

Q_r = residual energy (unaccounted, out of balance,)

Q_i = heat content of the fuel

Q_e = electrical energy converted into heat

Q_o = heat transferred to the boiler water

Q_f = heat loss in the flue products

Q_c = heat loss in the liquid condensate

Q_s = heat loss from the boiler case

In practice the residual energy is never zero, because of the many measurement inaccuracies. If the residual energy is positive, the total measured output energy is less than the input and efficiency is likely to be under-estimated. If it is negative, the total measured output energy is greater than the input and efficiency is likely to be over-estimated. Only if the residual is zero are the measurements self-consistent. The magnitude of the residual is therefore a measure of inconsistency, and an indicator of test quality. Depending on purpose, if it exceeds some threshold then the boiler efficiency results can be regarded as unreliable and unacceptable.

1   Introduction

The document introduces a method to help determine the quality of laboratory thermal efficiency measurements of a boiler tested for the purposes of the Boiler Efficiency Directive (BED). It is based on estimating the energy balance during a test, hence the method name "energy balance validation" or EBV. Tests with a large imbalance or residual indicate inconsistent results.

The method uses a combination of standard[1] and some additional data (e.g. flue carbon dioxide concentration and temperature) obtained during an efficiency test to estimate the heat flow components (e.g. flue heat loss, heat transfer to water) and hence the energy balance. In practice the energy balance is unlikely to be zero due to measurement uncertainties, and hence a residual energy value will usually remain.

The EBV method applies only to natural gas, liquid petroleum gas and oil boilers. The scope of the method excludes appliances with permanent pilot ignition and with natural draught open or balanced flues. The method also presently excludes range cooker-boilers.

The method could be extended by adjusting the heat flows to achieve an energy balance of zero. Any such adjustments should be proportionate to the uncertainties in the individual flows (see section 7)

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[1] Collected as part of boiler efficiency testing for the Boiler Efficiency Directive - Council of the European Communities Directive 92/42/EEC

2   Principles of EBV

The principle is to estimate the energy balance or *residual (Q_r)* during a boiler efficiency test by deducting the sum of the individual energy loss rates from the sum of the energy supply rates. That is:

$$Q_r = Q_i + Q_e - Q_o - Q_f - Q_c - Q_s$$

where

Fuel supply rate (gross input power) - Q_i

Heat rate transferred to the boiler water (output power) - Q_w

Heat loss rate in the flue products - Q_f

Heat loss rate in the condensate - Q_c

Heat emission rate from the casing - Q_s

Electrical heat conversion rate - Q_e.

The component flow rates and hence the residual are estimated from laboratory data obtained during an efficiency test at 100% load and 30% load.

For the method to work, the data (section 3) must be measured with reasonable accuracy and reliability. For tests under steady continuous firing conditions this is achievable. For cyclic tests (i.e. where boiler cycles on and off) it is impractical since transient flue temperature and carbon dioxide concentrations are difficult to measure.

For boiler efficiency tests carried out under cyclic operation a strategy is incorporated to avoid the need for these transient quantities by requiring an additional efficiency test at a minimum heat-input rate under steady continuous firing conditions. This is discussed in section 4.

2.1   What does the energy residual represent?

The energy residual is the apparent net energy flow rate entering or leaving the boiler during a test. Heat entering the boiler (i.e. the energy content of the fuel) is assigned a positive value and heat leaving the boiler (including the energy entering the heating circuit) is assigned a negative value. Hence, a negative residual has apparently more energy leaving than entering the boiler (that is, energy is somehow created – this is obviously not true but due to experimental errors), so the efficiency is generally overstated.

A positive residual means that apparently more energy enters than leaves boiler (that is energy is somehow destroyed – this is not true but due to experimental errors), so the efficiency is generally understated.

When expressed as percentage of the gross input power, the residual is:

- the difference between the thermal efficiency based on the boiler heat output (i.e. that quoted for BED purposes but converted to gross terms) and that based on losses, i.e. what is commonly known as the "flue loss method".

Here the term "subtraction method" is introduced to avoid ambiguity with the flue heat loss rate.

In short, the percentage residual is the difference between two estimates of efficiency. Where the percentage residual is negative, the BED estimate is higher than the subtraction method estimate.

Provided the percentage residual can be reliably estimated, a large negative percentage residual implies the boiler efficiency is probably unrealistically high[2]. It is shortly estimated (section 3.3) that the subtraction method is potentially more accurate where the boiler is capable of firing continuously at 30% of the full-load compared to results obtained for BED purposes.

2.2 Re-balancing and acceptance limits

The main concern is for boilers with overstated efficiencies, therefore only negative residuals give cause for concern. Possible solutions include:

a) Re-balancing: Adjusting the component heat flows to achieve a residual of zero and then revising the full and part-load efficiency based on the adjusted power input and output. This is described in section 6.

b) Acceptance limit: Only accepting data when the percentage residual is positive or a small negative quantity, below some specified limit.

Both solutions have their merits and drawbacks.

Although reasonably straightforward conceptually, the procedure to estimate the residual contains a lot of detailed calculation steps making it cumbersome to do by hand. A spreadsheet with the procedure implemented is provided to ensure consistency and ease of calculation.

2.3 Acceptance limit

To give an indication of an acceptable limit, the experimental uncertainty in the residual is estimated for a full-load and a part-load test.

Table 1 shows the estimated pooled uncertainty in efficiency based on the following:

Individual uncertainty for the:

- Carbon dioxide reading is ±0.25% in 9% by volume
- Flue temperature is ±2°C in 35°C (part-load) or in 65°C (full-load)
- Laboratory temperature is ±2°C in 20°C
- Laboratory humidity is ±10% points in a relative humidity of 70%
- Water temperature is ±0.1°C in 7°C (part-load) or 20°C (full-load)
- Standby loss is ±24W in 120W
- Electrical gains is ±10W in 80W
- Fuel flow rate is ±1%

Combining errors (or uncertainties)

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[2] This does not necessarily mean it is unreliable for its original purpose - to show that the boiler exceeds the minimum BED efficiency levels.

- The pooled uncertainty assumes the individual uncertainties are independent and identically distributed[3]. If this is the case, the pooled uncertainty is the square root of the sum of the square of the individual uncertainties.

Independence of each measurement uncertainty is reasonable as each quantity is measured by different instruments. Identically distributed requires knowledge of the uncertainty distribution of each instrument or source of uncertainty, but there is no obvious reason why these should differ.

Table 1 Estimated experimental uncertainties				
	Full-load		Part-load	
	% change	% of input	% change	% of input
1. Boiler input (typical value)		100%		100%
gas flow rate	±1%		±1%	
gas temperature (0.5K in 293K)	±0.171%		±0.171%	
gas pressure (0.4mb in 1013mb)	±0.039%		±0.039%	
Calorific value	±1%		±1%	
Combined uncertainty	±1.43%	±1.43%	±1.43%	±1.43%
2. Boiler output (typical value)		86.8%		96.3%
Water temperature is ±0.1K in 7K (part-load) or 2K (full-load)	±0.25%		±0.714%	
Mass flow rate	±0.6%		0.6%	
Combined uncertainty	±0.65%	±0.56%	±0.932%	±0.90
3. Flue loss/input		11.71%		3.05%
CO_2 ±0.25% points in 9%	±0.33%		±2.31%	
Laboratory temperature ±2°C in 20°C	±0.91%		±5.45%	
Flue temperature ±2°C in 65°C/36°C	±0.76%		±15.08%	
Humidity ±10% points in 60%	±0%		-2.93%	
Combined uncertainty	±1.23%	±0.15%	±16.46	±0.50%
4. Condensate loss/input		0%		0.13%
CO_2 ±0.25% points in 9%		n/a	±2.31%	
Laboratory temperature ±2°C in 20°C		n/a	±19.11%	
Flue temperature ±2°C in 65°C/35°C		n/a	±5.13%	
Humidity ±10% points in 60%		n/a	±1.19%	
Combined uncertainty	±0%	±0%	±19.96%	±0.03%
5. Casing loss /input		1.02%		0.20%
Laboratory temperature ±2°C in 20°C	±4.97%		±18.85	
Standby loss is ±24W in 120W	±20.00%		±20.00%	

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[3] Identically distributed means each distribution of uncertainties follows the same probability function (e.g. a normal distribution).

Table 1 Estimated experimental uncertainties		Full-load		Part-load	
		% change	% of input	% change	% of input
	Input	±1.43%		±1.43%	
	Combined uncertainty	±20.66%	±0.21%	±27.52	0.05%
6. Electrical gains/input			0.24%		0.20%
	Electrical gains is ±10W in 80W	±18.90%		±15.16%	
	Input	±1.43%		±1.43%	
	Combined uncertainty	±18.95%	±0.05%	±15.20	±0.03%
Efficiency by heat to water			±1.53%		±1.66%
Efficiency by subtraction			±0.26%		±0.50%
Residual[4]†			±1.79%		±1.84%

† This indicates that most measurements should have a residual in the range of ±1.8%, suggesting acceptance limits of -1.8 for the full-load and part-load respectively, or say a generous -2% for simplicity.

Uncertainty in efficiency derived from the heat to water method and by the subtraction method (table 1) suggests that the subtraction method is more accurate than heat to water method. And therefore, when the percentage residual (the difference in efficiency estimates) is a large negative quantity the credibility of the heat to water efficiency is questionable.

[4] Uncertainties for heat-to-water, items No5, No6 depend on the boiler input. So the overall uncertainty is the square root of uncertainties for item $(\text{Heat-to-water}+No5+No6)^2 +No3^2+No4^2$.

3   Data requirements

Data is required to show compliance with the BED. This requires efficiency data at full and 30% part-load.

The data requirements are complicated by the number of possible test methods employed to show conformity at 30% part-load; namely the direct and indirect methods.

The EBV method will require additional readings when these tests are undertaken and depending on the part-load method used, may require a further test under continuous firing at full-load or at the minimum firing rate (see table 2).

Table 2 – Test options			
Method: (from EN 297, 483, 677 or 304)	Boiler water temperature		
	Gas Condensing	Oil Condensing	Non-condensing
1. Full-load test (compulsory)	flow/return 80/60°C	flow/return 80/60°C	flow/return 80/60°C
2. Part-load test: *one of* 2a to 2e			
Boiler tested using *direct* method:			
a) Firing rate of 30%, if possible	return 30°C	Mean 40°C	mean 50°C
b) Minimum firing rate, if >30%	return 30°C	Mean 40°C	mean 50°C 55/45°C
c) 100% firing rate (i.e. on/off)	flow/return 50/30°C	flow/return 50/30°C	flow/return 60/40°C
Boiler tested using *indirect* method:			
d) Minimum firing rate, if >30%	return 30°C	Mean 40°C	Mean 50°C 55/45°C
e) 100% firing rate (i.e. on/off)	flow/return 50/30°C	flow/return 50/30°C	Flow/return 60/40°C
3. If method 2b or 2c applies an additional continuous firing rate test 3a or 3b is required because method 2b and 2c impose cyclic conditions			
a) Minimum firing rate, if >30%	return 30°C	Mean 40°C	mean 50°C (55/45°C)
b) Full-load	flow/return 50/30°C	flow/return 50/30°C	flow/return 60/40°C

For range-rated boilers the data must be consistent with the heat inputs required to establish conformity to the BED.

For each test option (in table 2) the information recorded is shown in table 3.

Table 3 Test information required	
Measurement	**Units**
Compulsory	
Net heat input	kW
Heat output	kW
Flow temperature	°C
Return temperature	°C
Flue gas temperature†	°C
Ambient air temperature	°C
Carbon dioxide concentration in flue gas (dry) †	% v/v
Optional	
Condensate flow rate	kg/hour
Ambient air relative humidity	%
Circulating pump power	Watts
Fan power (gas boilers)	Watts
Oil pump power (oil boilers)	Watts

† For the part-load efficiency results, flue gas temperature and carbon dioxide concentration is only required under continuous firing conditions and so not required for direct part-load tests where the burner cycles on and off (i.e. method 2b or 2c). Instead data for additional test at the minimum or full firing rate is required.

Where the indirect part-load efficiency method is used, data from the standby heat loss test is required (e.g. as in EN 297, 483).

Where the direct part-load efficiency method is used, standby heat loss or case loss data is not compulsory. However data from a standby heat loss test or case heat loss test (e.g. as in EN304), for a stated mean water rise above the ambient air temperature, may also be provided optionally.

A cautious default is used in the absence of optional data (see section 5.4, 5.5 and 5.6 for details), so it may prove beneficial to supply the optional information.

When the optional condensation rate is measured (see 5.4) there is the opportunity to check whether it is consistent with condensation rate predicted from the flue temperature and carbon dioxide concentration, particular important as there is no standard way to measure the condensate rate.

Therefore, the measurements are inconsistent when the measure condensation rate is greater than the estimated rate based on the flue temperature minus a small margin. Based on measurement uncertainty, the margin will be at least 5K. The exact amount should be determined from experience in using the EBV method.

4 Cyclic test considerations

4.1 Boiler efficiency test methods

Boiler efficiencies for Boiler Efficiency Directive (BED) are measured using procedures in EN BS 297, 483, 677 or 304 depending on boiler type and fuel.

The efficiency test at full-load is carried out at a steady firing rate with water return and flow temperature of approximately 80°C/60°C.

The tests at 30% part-load are carried out using one of two direct methods or using one indirect method at mean water temperature of 50°C for non-condensing and a water return temperature of 30°C for condensing boilers using gaseous fuels (mean of 40°C using liquid fuels).

If the burner can modulate down to 30%, the direct part-load tests will be at a continuous firing rate. If not, the burner will cycle on and off probably at its minimum rate, which is 100% for on/off boilers.

The indirect test method for part-load efficiency assessment consists of:
- a continuous test at a low temperature and minimum continuous firing rate
- a standby loss test (electrical method)
- an adjustment to alter continuous firing results to an equivalent 30% part-load efficiency.

4.2 Part-load cyclic tests

As measurements of transient carbon dioxide concentration and temperature of the flue products are unreliable, application to cyclic test data is problematical. Cyclic conditions occur during direct tests for 30% part-load tests when the minimum firing rate is more than 30%.

To overcome this problem, the residual is estimated from the heat output and input from the direct test, in conjunction with measurements from a steady test at the minimum firing rate and an optional standby heat loss (or case loss) estimate. In effect, the BED part-load efficiency is compared to the efficiency at minimum rate plus a small reduction due to the higher standby heat loss per unit of fuel input.

Other solutions considered were using carbon dioxide and flue temperature measurements during the start-up part of the direct test or using estimated values. The favoured solution is more accurate and unambiguous so does not require the development of new methodologies.

4.2.1 Heat loss during the off-time

Heat loss through the flue during the burner off-time is taken as zero. Neglecting these losses in the *residual* estimate (it is still in the heat to water measurement*)* means the residual is slightly overestimated reducing the chance of a data submission being deemed as inconsistent. Natural draught open-flue or balanced-flue boilers may have considerable heat losses during the off-period and therefore the procedure excludes them. It is assumed that all new gas and oil-fired boilers (excluding range-cooker boilers) will have forced-draft combustion.

4.2.2 Heat loss during purge periods

Purging of air in the combustion system in boilers is necessary for safety reasons before ignition. Some boilers also have a post-purge period after firing stops. Typically pre-purge times of 10 seconds and 30 seconds apply to gas and oil boilers respectively. Post-purging is less common.

Purging is only relevant during the cyclic part-load test, that is, for the direct part-load test where firing rate is higher than 30%. Here the heat lost during purging is directly measured and so implicit in the "heat to water" measurement.

The effect of purging is to replace hot air in the combustion chamber with cold air and hence heat is lost.

The potential amount of energy that may be purged is the same as that required by a boiler over the purge time (i.e boiler input x purge time). For pre-purge this potential is reduced, probably considerably, because the central heating pump is operating whilst the burner is off forcing water through the heat exchanger. The amount extracted during a pre-purge is difficult to estimate.

In the case of on/off boiler with a pre-purge of 30s, the firing time is 3 minutes and off-time is 7 minutes, so there is 6 ½ minutes period before the purge is applied when heat is being extracted across the heat exchanger in the water.

Laboratory data is required to determine the extent to which heat is lost due to purging. Most new gas boilers have modulating controls and an increasing number are able to operate at a continuous firing rate of 30%. Therefore the effect of purge-losses is expected to be small (for gas). For oil-fired boilers, which are higher thermal capacity, have larger combustion chambers and longer purge times, the effect may not be small particularly since virtually all domestic oil-fired boilers have on/off controls. However, data to determine the effect of purging is not available.

Therefore at present, the possible heat lost as a result of purging is neglected in the *residual estimate* (it is still accounted-for in the heat to water measurement*)*, this means the residuals may be slightly overestimated (more positive).

4.3 Pilot lights

The provision of permanent pilot ignition is another possible heat flow. However, as virtually all new boilers exclude permanent pilots the heat associated with permanent pilot ignition is discounted. Therefore the procedure is restricted to boilers without permanent pilots.

5   Calculation procedure

This chapter explains the method step by step, and may be omitted by readers not interested in the detail.

Two separate residual estimates are required to validate the boiler submission

- i)   full-load figure
- ii)   30% part-load figure

Calculate the individual heat transfer rates for the full and 30% part-load test separately as described in 5.1 to 5.7. Each sub-section first notes the principles and assumptions and then describes the calculation steps.

For brevity the direct test method at 30% part-load is shortened to "test D30" and to "test D30+" when the firing rate is higher than 30%.

Also, in this chapter data items from the "Statement of boiler test results" are referred by "template" followed by section number. The full statement of results is shown in appendix A.

5.1   Energy content of the fuel supplied

5.1.1   Principles

The energy balance uses the convention of the gross (or higher) calorific value because this accounts for all the energy that is extractable from burning the fuel by cooling the combustion products; that is, it contains the energy released when condensing water.

The variation with temperature of calorific value per unit <u>mass</u> between 5°C and 30°C is neglected as this is very small[5]. For gaseous fuel the variation with temperature of the calorific per unit <u>volume</u> is significant but is it accounted for already in the relevant test standards by adjusting for fuel pressure and temperature.

For the indirect test method and test D30+, to ensure the effects of cycling are appropriately represented the minimum input power is converted to 30% of the full-load. This ensures the flue heat loss (6.2), which is proportional to the boiler input, is representative of the 30% part-load test.

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[5] Typically it varies from -0.02% to +0.06% over 10°C to 30°C due to changes in enthalpy of the fuel, oxygen gas and liquid water over this range.

5.1.2 Calculation steps

1a) For the full-load or direct part-load calculation:

Obtain the energy rate of the fuel supplied during the full-load test or the direct part-load ($Q_{i,test}$ - template, section 3) and set it to an intermediate value $Q_{i,net}$ thus:

$$Q_{i,net} = Q_{i,test}$$

(Note for the case of part-load direct test where the firing rate cycles select the input from the direct cyclic test.)

1b) For the part-load indirect calculation:

Obtain the measured heat output and input during the full-load 80/60°C test ($Q_{i,full,net}$ and $Q_{o,full}$ template, section 3), the heat input and output ($Q_{i,min}$ and $Q_{o,min}$ template, section 6) during the indirect minimum rate (full-load for on/off boilers) test.

$$Q_{i,net} = 0.3 \times Q_{i,min} \times \frac{Q_{o,full}}{Q_{o,min}} \qquad \text{kW}$$

(The 0.30 comes from the 30% part-load definition).

2) Convert the net power in kW to gross power terms using the calorific value per unit <u>mass</u> in kJ per kg in table B1 (H_{gross} and H_{net})

$$Q_i = Q_{i,net} \times \frac{H_{gross}}{H_{net}} \qquad \text{kW}$$

For other test fuels not tabled ensure the calorific values apply at constant pressure, at 15°C and are in units of kJ/kg.

5.2 Heat to water transfer rate

5.2.1 Principles

It is not practical to measure transient carbon dioxide concentration or flue product temperature. This occurs under the cyclic part-load test method, that is, for direct method when the continuous minimum firing rate is more than 30%.

To avoid this problem, test data from a steady continuous firing rate is used, either an additional test at minimum rate or the indirect test at minimum rate. The heat output uses the additional

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steady test data but replaces the output power with 30% of the full-load. This replacement ensures the cyclic effects of the component flow rates are correctly accounted for.

5.2.2   Calculation steps

1a) For the full-load or direct part-load calculation:

Obtain the measured energy rate entering the water ($Q_{o,test}$ - template, section 3) and set it to intermediate value Q_o thus:

$$Q_o = Q_{o,test}$$

(Note for the case of part-load direct test where the firing rate cycles select the output from the direct cyclic test.)

1b) For the part-load indirect calculation:

Obtain the measured heat output during the full-load 80/60°C test ($Q_{o,full}$ - template, section 3) and set Q_o:

$$Q_o = 0.3 \times Q_{o,full}$$

(The 0.30 comes from the 30% part-load definition).

5.3   Energy lost in flue products

5.3.1   Principles
There are no suitable standards to cover the scope of fuels with sufficient accuracy.

- BS 845 part 1 is restricted to non condensing boilers
- BS 845 part 2 is too general (it applies to solid fuel also) making it unwieldy and yet also makes some approximations.
- EN 304 is applicable to oil boilers and not gaseous fuels

Therefore, a new method is proposed that follows the same principles of the EN 304 but is extended to include gaseous fuels and simplifies when accuracy is not compromised.

The principles and assumptions are:

i)   It uses the enthalpy of individual species rather than a bulk specific heat capacity

ii)   The heat loss rate of a species is estimated from the change in enthalpy due to a temperature difference between the flue products and the laboratory.

iii) The flue products are water vapour, carbon dioxide, molecular nitrogen and oxygen. This is considered reasonable as there are very low limits on carbon monoxide and nitrous oxides production.

iv) Any sulphur, carbon dioxide, carbon monoxide and water content of the fuel are negligible.

v) The mass flow rate of the flue species is determined from the excess air inferred from the measured carbon dioxide concentration and the assumption of complete oxidation (that is, every two hydrogen atoms and one carbon atom in the fuel is oxidised into one water and one carbon dioxide molecule respectively).

vi) The measured rate of condensation is optional. When the condensation rate is stated, it is used to estimate the amount of water vapour in the flue products and hence the latent heat loss and the amount of water condensed.

vii) When measured rate of condensation is not stated, it is estimated by assuming the relative humidity of flue products is 100%, provided there is there is sufficient water produced by combustion and contained in the incoming air. If there is insufficient water produced and contained in the incoming air then the flue products are not saturated hence no water is condensed. This is a cautious estimate as a little water may condense on the cooler heat exchanger surface. It is preferable to measure the condensation rate if possible.

viii) The change in calorific value per unit mass between 10°C and 30°C is negligible[6].

ix) The flue product temperature is taken as the highest of the flue temperature or the return water temperature.

5.3.2 Calculation step

This part requires four data items from the template: the flue temperature, the boiler return temperature, carbon dioxide concentration, laboratory air temperature and humidity. They are obtained from the template section 6 for test D30+ and section 3 for the other tests.

0. Firstly take the higher of flue temperature and boiler return as the flue temperature for the purposes of the calculation.

1. Obtain the gross input power (Q_i - section 5.1.2) and the gross calorific value (H_{gross}) per unit mass from the fuel reference table (table B1) and calculate the mass flow rate of the fuel as follows:

$$M_{fuel}(kg/s) = \frac{Q_i(kW)}{H_{gross}(kJ/kg)}$$

2. Obtain the carbon (m_C), hydrogen (m_H) and nitrogen(m_N) content in the fuel by mass (table B1, appendix B), the oxygen content of the air by mass (m_{o_2}) the relative atomic weight

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[6] Typically it varies from -0.02% to +0.06% over 10°C to 30°C due to changes in enthalpy of the fuel, oxygen gas and water over this range

of carbon (mw_C) and hydrogen (mw_H), relative molecular weight of water (mw_{H_2O}), nitrogen (mw_{N_2}) and carbon dioxide (mw_{CO_2}) from appendix B2.

Calculate the following species flow rates:

2.1 Carbon dioxide produced during combustion:

a) $M_{CO_2,mo} = \dfrac{m_C}{100} \times \dfrac{M_{fuel}}{mw_C}$ mol/s

b) $M_{CO_2} = M_{CO_2,mo} \times mw_{CO_2}$ kg/s

2.2 Water produced during combustion by mass:

$M_{H_2O} = \dfrac{m_H}{100} \times \dfrac{mw_{H_2O}}{2 \times mw_H} \times M_{fuel}$ kg/s

2.3 Minimum molecular oxygen:

a) $M_{O_2,min,mo} = \left(\dfrac{m_H}{4 \times mw_H} + \dfrac{m_C}{mw_C} \right) \times \dfrac{M_{fuel}}{100}$ mol/s

b) $M_{O_2,min} = M_{O_2,min,mo} \times mw_{O_2}$ kg/s

2.4 Minimum air requirement by mass:

a) $M_{air,min} = \dfrac{M_{O_2,min}}{m_{O_2}} \times 100$ kg/s

2.5 Obtain the percentage of dry air by volume that is oxygen, (m_{O_2}) (see B2) and calculate minimum amount of molecular nitrogen:

a) $M_{N_2,min,mo} = \left(\dfrac{2 \times m_N}{100} \times \dfrac{M_{fuel}}{mw_{N_2}} \right) + \left(\dfrac{(100 - v_{O_2})}{v_{O_2}} \times M_{O_2,min,mo} \right)$ mol/s

b) $M_{N_2,min} = M_{N_2,min,mo} \times mw_{N_2}$ kg/s

3. Note the values calculated in 2.1a and 2.5a and calculate the maximum carbon dioxide concentration in percent by volume of dry products

$$V_{CO_2,max} = 100 \times \frac{M_{CO_2,mo}}{(M_{CO_2,mo} + M_{N_2,min,mo})}$$

Obtain the percentage concentration of carbon dioxide measured (V_{CO_2}) from the template (for test D30+ section 6 otherwise section 3), the molar flow rates in 2.1a, 2,3a and 2.5b and the maximum carbon dioxide concentration ($V_{CO_2,max}$ above). Calculate the excess air factor (X_{air}) and the remaining species flow rates.

$$X_{air} = 1 + \left(\frac{M_{CO_2,mo} + M_{N_2,\min,mo}}{M_{O_2,mo} + M_{N_2,\min,mo}} \right) \times \frac{(V_{CO_2,\max} - V_{CO_2})}{V_{CO_2}}$$

3.1 Molecular nitrogen in the flue products (see 2.5b for $M_{N_2,\min}$):

$$M_{N_2} = M_{N_2,\min} \times X_{air} \qquad \text{kg/s}$$

3.2 Molecular oxygen in the flue products (see 2.3b for $M_{O_2,\min}$):

$$M_{O_2} = M_{O_2,\min} \times (X_{air} - 1) \qquad \text{kg/s}$$

3.3 Incoming air moisture content.

Lookup the laboratory relative humidity (rh)[7] and temperature (template section 6 for test D30+ and template section 3 for other tests) and the saturated vapour pressure at the laboratory temperature ($svp[T_{lab}]$ - table B3).

Calculate the moisture content in the incoming air ($M_{vapour,inlet}$) from:

$$M_{vapour,inlet} = \frac{rh}{100} \times \frac{mw_{water}}{mw_{air}} \times \frac{svp[T_{lab}] \times M_{air,\min} \times X_{air}}{(0.101325 - svp[T_{lab}])}$$

(0.101325 is standard pressure in MPa and for $M_{air,\min}$ see step 2.4)

4. These steps estimate the liquid water and water vapour flow rates of the combustion products.

4.1 Omit this step if condensation rate is not given. Obtain the condensation rate ($M_{c,kg/hr}$ - template section 3 for test D30+ otherwise section 6).

a) Calculate the condensation rate (M_c) from:

$$M_c = \frac{Q_{i,net}}{Q_{i,cont}} \times \frac{M_{c,kg/hr}}{3600} \qquad \text{kg/s}$$

(For $Q_{i,net}$ see section 5.1.2 and $Q_{i,cont}$ is the heat input during the continuous test (section 6 for D30+ and section 3 for other methods)

b) Calculate the vapour flow rate in the flue products from:

---

[7] If none stated assume 60%.

$$M_{vapour} = \left(M_{H_2O} + M_{vapour,inlet} - M_c \right) \qquad \text{kg/s}$$

If M_{vapour} is negative set it zero – this is the case where measure condensation rate is higher than water produced by combustion and that that within the incoming air.

(See step 2.2 for M_{H_2O} and step 3.3 for $M_{vapour,inlet}$)

4.2 Omit this step if condensation rate is stated. Calculate the water vapour content of the products first and the condensation rate next as follows.

a) Calculate the mass flow rate of dry products:

$$M_{dryproducts} = M_{O_2} + M_{N_2} + M_{CO_2} \qquad \text{kg/s}$$

b) Calculate the average relative molecular weight of the dry products:

$$\text{mw}_{dryproducts} = \frac{(M_{CO_2,mo} \times \text{mw}_{CO_2}) + (M_{N_2,mo} \times \text{mw}_{N_2} \times X_{air}) + (M_{O_2,mo} \times (X_{air} - 1) \times \text{mw}_{O_2})}{M_{CO_2,mo} + (M_{N_2,mo} \times X_{air}) + (M_{O_2,mo} \times (X_{air} - 1))}$$

c) Locate the average temperature of flue products (T_f - template section 6 for test D30+ or for other methods section 3 – reduce it to the return temperature if it is higher), the saturated vapour pressure at the flue temperature ($svp[T_f]$ - table B3) and calculate the saturated moisture content of the flue products:

$$M_{satvap} = \frac{\text{mw}_{water} \times svp[T_f] \times M_{dryproducts}}{\text{mw}_{dryproducts} \times (0.101325 - svp[T_f])} \qquad \text{kg/s}$$

d) Estimate the vapour content of the products M_{vapour} from:

If the temperature of flue products is less than 98°C then

M_{vapour} is the smaller of M_{satvap} and $(M_{H_2O} + M_{vapour,inlet})$.

If flue products temperature is 98°C or more:

$$M_{vapour} = M_{H_2O} + M_{vapour,inlet}$$
(see step 2.2 for M_{H_2O} and step 3.3 for $M_{vapour,inlet}$ in kg/s)

e) Estimate the condensation rate

$$M_c = \left(M_{H_2O} + M_{vapour,inlet} - M_{vapour} \right) \qquad \text{kg/s}$$

5. Estimate the heat loss rate through the flue.

5.1 Obtain the temperature of the laboratory air and flue products to lookup the enthalpy of each species (e.g. $E_{CO_2}\left[T_f\right]$ - table B3) and the latent heat of vaporisation ($L[T_{Lab}]$ - table B3) at the laboratory temperature.

Use linear interpolation for the enthalpy and latent heat at the flue temperature and the nearest whole degree for the enthalpy and latent at the laboratory temperature.

Calculate individual heat loss rates as follows:

a) $Q_{CO_2} = M_{CO_2} \times \left(E_{CO_2}\left[T_f\right] - E_{CO_2}\left[T_{lab}\right]\right)$

b) $Q_{N_2} = M_{N_2} \times \left(E_{N_2}\left[T_f\right] - E_{N_2}\left[T_{lab}\right]\right)$

c) $Q_{O_2} = M_{O_2} \times \left(E_{O_2}\left[T_f\right] - E_{O_2}\left[T_{lab}\right]\right)$

d) $Q_{vapour} = (M_{vapour} - M_{vapour,inlet}) \times \left(E_{vapour}\left[T_f\right] - E_{vapour}\left[T_{lab}\right]\right)$

(See step 2.1b for M_{co_2}, step 3.1 M_{N_2}, step 3.2 for M_{o_2}, step 3.3 for $M_{vapour,inlet}$ and step 4.1b or 4.2d for M_{vapour} in kg/s.)

e) $Q_{lat} = (M_{vapour} - M_{vapour,inlet}) \times L\left[T_{lab}\right]$ see B3 col 3 for L[..]

5.2 Sum the individual heat loss rates to obtain the total rate via the flue products (Q_f).

$$Q_f = Q_{N_2} + Q_{O_2} + Q_{CO_2} + Q_{vapour} + Q_{lat} \qquad \text{kW}$$

5.4   Heat lost rate in the condensate

5.4.1   Principle
An optional condensation rate measurement may be used. If not available, the amount of condensation is estimated using the moisture content of the flue products inferred from steam-water tables and the dry species composition and temperature.

The temperature of the condensate leaving the boiler is assumed to be the same as return temperature. In practice, it will lie between this and flue temperature. As this assumption is not critical[8] the advantageous return temperature is assumed.

5.4.2   Calculation steps

Obtain M_c (part 5.3.2, step 4.1a or step 4.2e depending on test and whether condensate rate is stated or not) to estimate the heat loss rate in the condensate as:

$$Q_c = M_c \times E_{water}\left[T_f\right] - E_{water}\left[T_{lab}\right] \qquad \text{kW}$$

---

[8] The difference between assuming the return temperature and the flue temperature is 0.06%

$E_{water}[T]$ is the enthalpy of liquid water (table B3) at temperature T_f or T_{lab} - the flue products temperature and laboratory temperature respectively (template section 6 for test D30+ and section 3 for other tests).

5.5 Loss rate from the casing

5.5.1 Principle

Note the *similar* but *distinct* terms.

- The *casing loss* refers to estimated heat loss from the boiler by convection and radiation to the surroundings.
- The *case loss* refers to heat loss determined from boiler surface temperatures obtained using a procedure such as that described in EN304.
- The *standby loss* is the heat loss obtained from an electrical standby test.

The case loss method is based on the boiler operating using gas or oil to maintain a given water temperature rise. Surface temperatures are measured and calculations made to estimate losses due to radiation and convection. This is the preferred method if data is available.

The standby test measures the electricity required by an electric immersion to keep the flow and return water typically 30°C above ambient temperature with the burner off and is usually only measured for the indirect method.

The casing loss is estimated from the case loss or standby loss measurement. The estimate is scaled by the water temperature rise above ambient applied to a power law of an index of 1.25. This power index is used in BS EN 297, 304[9] and 483 and is an approximation for the heat lost by convection and radiation from a metal surface at room temperatures.

Only one of case heat loss or standby heat loss is required. If neither is supplied on the datasheet, a cautious default value is supplied (indicated by the upper line in **Figure 1**). The default value is based on test results from 37 gas-fired condensing boilers. No equivalent data is presently available for oil boilers. Whilst oil-boilers are usually much larger and heavier than gas units they are also usually well-insulated. Therefore for the present, the values in Figure 1 are used as a default for both gas and oil units.

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[9] En 304 states 1.25 in the main body of the text but 1.15 in the appendix.

Figure 1
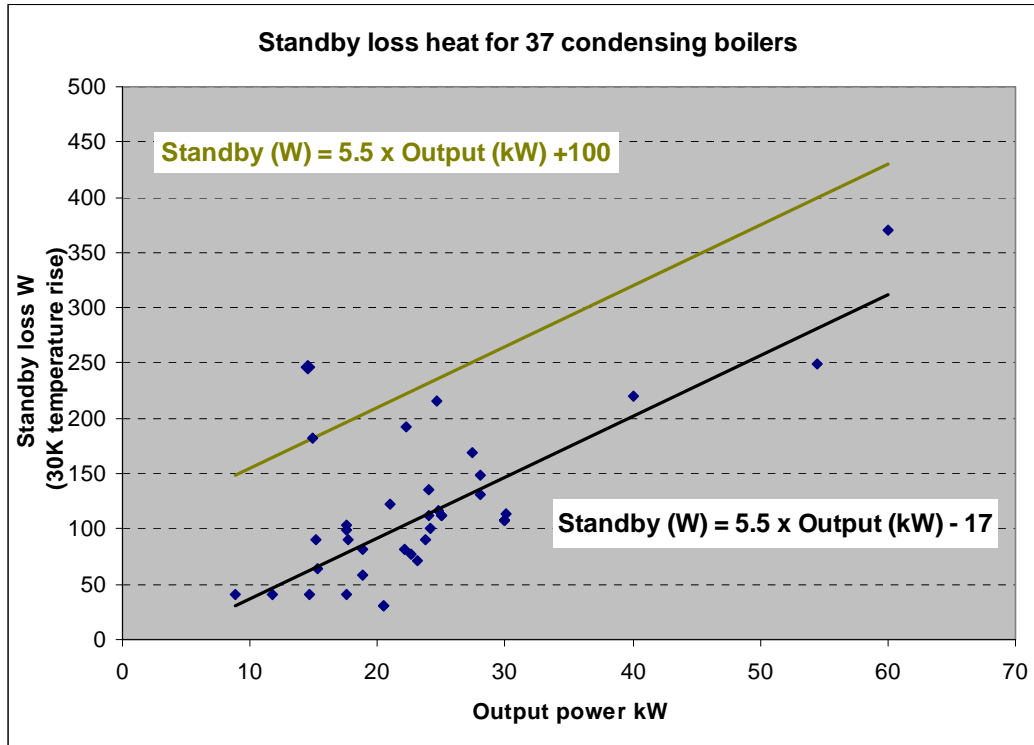
5.5.2   Calculation steps

Locate the case loss or standby heat loss (Q_{st} template section 4), if any, and temperature rise above ambient from T_{rs} (template section 4), if any.

1. Omit step 1 if either the case loss or standby loss is stated. Obtain the power output during the full-load test ($Q_{o,full}$ - template section 3), the rise above ambient during the standby test (T_{rs} - template section 4, default 30°C) and calculate the default standby loss and mean temperature above ambient from:

For $Q_{out,fulload}(kW) < 8.8$ $Q_{st}(W) = 148W$

For $Q_{out,fulload}(kW) \geq 8.8$ $Q_{st}(W) = 100 + \{5.5 \times Q_{out,fulload}(kW)\}$

2. Casing loss rate

a)   For the indirect test or test P30+ calculate the casing loss rate as follows.

Obtain the temperature rise above ambient (T_{rs} - template section 4), the case heat loss or standby heat loss (Q_{st} - template section 4 or step 1 above if applicable, the laboratory air temperature (T_{lab} - template section 3 and section 6 for test D30+), the flow and return temperature (T_{ret} & T_{flow} - template section

3 for the indirect test and section 6 for test D30+) to calculate the casing heat loss lost rate(Q_s) from:

If $47°C \leq 0.5 \times (T_{ret} + T_{flow}) \leq 53°C$ (i.e. non-condensing boiler)

$$Q_s = \frac{Q_{st}}{1000} \times \left(\frac{50 - T_{lab}}{T_{rs}} \right)^{1.25}$$

If $37°C \leq 0.5 \times (T_{ret} + T_{flow}) \leq 43°C$ (i.e. oil condensing boiler)

$$Q_s = \frac{Q_{st}}{1000} \times \left(\frac{40 - T_{lab}}{T_{rs}} \right)^{1.25}$$

If $0.5 \times (T_{ret} + T_{flow}) < 37°C$ (i.e. gas condensing boiler)

$$Q_s = \frac{Q_{st}}{1000} \times \left(\frac{33.5 - T_{lab}}{T_{rs}} \right)^{1.25}$$

b) For the full-load and P30 test calculate the casing loss rate as follows. Locate the temperature above ambient (T_{rs} - template section 4), the return (T_{ret} - template section 3), flow (T_{flow} template section 3) and laboratory air temperature (T_{lab} -template section 3) to calculate the casing heat loss rate (Q_s) thus:

$$Q_s = \frac{Q_{st}}{1000} \times \left(\frac{T_{ret} + T_{flow} - (2 \times T_{lab})}{2 \times T_{rs}} \right)^{1.25}$$

5.6 Electrical input

5.6.1 Principle

Most of the electricity used by devices inside a boiler operated during a test is converted into heat and may end up in the primary water circuit. Only resultant heat that enters the boiler water is accounted for, because the SEDBUK definition of efficiency is the amount of the energy in the fuel that is converted into useful heat and in good laboratory practice only a proportion of the electrical heat is deducted from the boiler heat output.

Some test laboratories already account for the heat from internal water pump circulator power. If not accounted for, a correction devised by Labnet[10] is proposed which applies to circulators with nominal power consumption of 30W to 95W.

Electricity consumed by fans in the inlet air or an oil pump on the fuel feed will also contribute to this heat component. When a fan is fitted to the boiler outlet (i.e induced draught) all the energy is wasted. Any fan or oil pump consumption occurs mainly while the boiler is firing (apart from purge times). Some fans/oil pumps modulate with boiler output.

Therefore for the full-load test it is assumed that the fan/oil pump operates continually at full power. For the part-load, it is assumed that it operates for 30% of time at full power.

The proportional of heat from electricity used by a fan or oil pump/fan that enters the water will vary by boiler design. A reasonable assumption is to assume the proportional is the same as the gross thermal efficiency. Thermal efficiencies for modern boilers vary from around 80% to well over 90% (gross), so assuming a typical figure 90% is reasonable. The actual efficiency can not be used as this is the unknown being estimated

If no power consumption data is provided then cautious defaults are applied. For calculating the residuals cautious defaults are zero. For the alternative approach of re-balancing the residual (see section 6) to achieve perfect balance the defaults of 30W and 90W are suggested for gas and oil boilers respectively.

The situation is complicated by the fact that some boilers are fitted with more than one internal pump, for example, some but not all, combined primary storage units have extra pumps to circulate the water between the boiler and store or to mix the stored water, as well as a circulator to push the water around the radiators. It would be grossly unfair to apply the same default values to each pump and unnecessarily complicate the template for most other boiler submissions. Therefore boilers where more than internal pump operates during an efficiency test will be treated on an individual basis.

5.6.2   Calculation steps

If two or more pumps are fitted and used during the efficiency test then more detail is required (template section 5) than requested at present. Provision will be made in the future only if there is demand.

Obtain from the template (template section 5) whether or not the power of any internal circulator is included in the efficiency results.

1. If one internal pump was used and its power was not accounted for, obtain the nominal power during the full-load test (Q_{circ} template section 3), the laboratory air (T_{lab} template section 3) and return water temperature (T_{ret} template section 3) to calculate the heat gain due to the circulator as:

$$Q_{circ} = [Q_{circ,e} - 9.5 - \{0.44 \times (T_{ret} - T_{lab})\}] / 1000 \qquad \text{kW}$$

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[10] Section 8, Good Laboratory Practice for Full and Part-load, Efficiency Measurement for Boilers, Revision of the document 1998-2000, Version 08, Preparation of the document to be sent to CEN in September 2000
http://labnet.dgc.dk/public/BEDAC/glp_eff08.htm#_Toc455905161, 10 Aug 2006

If no pump power was submitted assume the cautious 0W. Cautious means the resultant residual will be underestimated (i.e. if it is negative with the stated pump power, then without it will be more negative)

If the calculated value of Q_{circ} is less than zero set it to zero.

If there is no internal pump, or its power has already been subtracted from the output, then set the advantageous heat gain to zero ($Q_{e,circ}$).

2. Determine whether any fan or oil pump is upstream of the heat exchanger (template section 5). If the fan/oil pump is upstream of the heat exchanger obtain the electrical power (Q_{fan} template section 3) and calculate any advantageous electrical heat gains from:

If electricity values are not stated apply the value of zero.

For the full-load test

$$Q_{fan} = 0.9 \times Q_{fan,e} / 1000 \qquad \text{kW}$$

For the test D30 and D30+ and indirect part-load test

$$Q_{fan} = 0.9 \times 0.3 \times Q_{fan,e} / 1000 \qquad \text{kW}$$

If there is no fan/oil pump upstream of the heat exchanger then set the electrical heat gain to zero (Q_{fan}).

Total electrical heat gains

$$Q_e = Q_{fan} + Q_{circ} \qquad \text{kW}$$

5.7 Totalling the residual

5.7.1 Principle

The residual is the sum of heat flow rates entering the boiler and the negated heat flow rates leaving the boiler. It can be expressed as a fraction of the input power based on the gross calorific values.

The residual can be positive or negative. A negative residual implies the thermal efficiency is mostly likely overstated and a positive residual implies it is mostly likely to be understated.

To allow for fair comparison across boiler sizes the residual is expressed as percentage of gross input. This has an added advantage; in that it represents the difference in the efficiency estimates measured by the "subtraction method" and the BED (heat to water) method.

5.7.2   Calculation step

Gather together the component heat flow rates calculate (5.1 to 5.6) and calculate the percentage residual:

$$Q_r(\% \text{ gross}) = \frac{100 \times (Q_i + Q_e - Q_w - Q_f - Q_c - Q_s)}{Q_i}$$

5.8   Nomenclature

Table 4: Symbols used

Symbol	units	Description
E_{CO_2}	kJ/kg	Enthalpy of carbon dioxide gas
E_{N_2}	kJ/kg	Enthalpy of nitrogen gas
E_{O_2}	kJ/kg	Enthalpy of oxygen gas
E_{vapour}	kJ/kg	Enthalpy of water vapour
E_{water}	kJ/kg	Enthalpy of liquid water
FLE	% net	The BED full load efficiency
FLE'	% net	A revised BED full load efficiency
Frate	%	Minimum percentage firing rate
H_{gross}	kJ/kg	Calorific at constant pressure at 15°C (gross or higher value) per unit mass
$H_{gross,vol}$	MJ/m^3	Calorific at constant pressure at 15°C (gross or higher value) per unit volume
H_{net}	kJ/kg	Calorific at constant pressure at 15°C (net or lower value) per unit mass
$H_{net,vol}$	MJ/m^3	Calorific at constant pressure at 15°C (net or lower value) per unit volume
$L[T]$	kJ/kg	Latent heat of vaporisation of water at temperature T°C
m_C	%	Carbon content of fuel by mass
m_H	%	Hydrogen content of fuel by mass
m_N	%	Nitrogen content of fuel by mass
mw_C	kg/mol	Relative atomic mass of carbon
mw_{CO_2}	kg/mol	Relative molecular mass of carbon dioxide
mw_{CO_2}	kg/mol	Relative molecular mass of carbon dioxide
$mw_{dryproducts}$	kg/mol	Relative molecular mass of dry products
mw_H	kg/mol	Relative atomic mass of hydrogen
mw_{H_2O}	kg/mol	Relative molecular mass of water

Symbol	units	Description
mw_{N_2}	kg/mol	Relative molecular mass of nitrogen
mw_{O_2}	kg/mol	Relative molecular mass of oxygen
$M_{air,min}$	kg/s	Minimum mass flow rate of dry air for complete combustion
M_c	kg/s	flow rate of condensate
$M_{c,kg/hr}$	kg/hr	Measured mass flow rate of condensate
M_{CO_2}	kg/s	Mass flow rate of carbon dioxide
$M_{CO_2,mo}$	mol/s	Flow rate of carbon dioxide
$M_{dryproducts}$	kg/s	Mass flow rate of dry products
M_{fuel}	kg/s	Mass flow rate of fuel
M_{H_2O}	kg/s	Mass flow rate of water from combustion
M_{N_2}	Kg/s	mass flow rate of molecular
$M_{N_2,min}$	kg/s	Minimum mass flow rate of molecular nitrogen for complete combustion
$M_{N_2,min,mo}$	mol/s	Minimum flow rate of molecular nitrogen for complete combustion
M_{O_2}	kg/s	Mass flow rate of molecular
$M_{O_2,min}$	kg/s	Minimum mass flow rate of molecular oxygen for complete combustion
$M_{O_2,min,mo}$	mol/s	Flow rate of oxygen gas
M_{satvap}	kg/s	Flow of flue products if saturated
$M_{vapour,inlet}$	kg/s	Moisture content in incoming air
PLE	% net	BED part load efficiency
PLE'	% net	A revised BED part load efficiency
Q_{circ}	kW	Heat gains associated with internal pumps
$Q_{circ,e}$	W	Electrical power of internal pump
Q_{CO_2}	kJ/kg	Heat flow rate of carbon dioxide gas
Q_e	kW	Unaccounted for advantageous heat gains
Q_{fan}	kW	Advantageous heat gains due to fan/oil pump
$Q_{fan,e}$	W	Electrical power of fan/oil pump upstream of heat exchanger
Q_i	kW	Gross input power
$Q_{i,full}$	kW	Full input power (net)
$Q_{i,cont}$	kW	Net input power measured during a continuous steady firing test (full-load, 30% firing rate or minimum load test)
$Q_{i,net}$	kW	Net input power used in main calculation
$Q_{i,test}$	kW	Net input power measured during the full-load, direct and indirect part-load test
Q_{lat}	kW	Heat flow rate due to the released of latent heat of vaporisation of water
Q_{N_2}	kJ/kg	Heat flow rate of nitrogen gas

Symbol	units	Description
Q_o	kW	Measured heat transfer rate to water used in calculations
$Q_{o,cont}$	kW	Heat transfer rate to water for a steady continuous firing
$Q_{o,full}$	kW	Heat out at full-load at 80/60°C
$Q_{o,test}$	kW	Output power measured during the full-load, direct and indirect part-load test
Q_{O_2}	kJ/kg	Heat flow rate of oxygen gas
Q_r	kW or % gross	Residual heat flow rate
Q_s	kW	Heat loss rate through the casing
Q_{st}	kW	Measure case heat loss rate or standby heat loss
Q_w	kW	Heat transfer rate to water used in energy balance
Q_{vapour}	kJ/kg	Heat flow rate of water vapour
$svp[T]$	Mpa	Saturated vapour pressure at temperature T
r	kW	The energy imbalance or residual
rh	%	Relative humidity
R_{com}	% gross	Combine residual
R_{fle}	% gross	Residual for the full load efficiency
R_{ple}	% gross	Residual for the part load efficiency
t_{on}	minutes	On-time during a direct test
T_f	°C	Temperature of flue products
T_{flow}	°C	Temperature of water flowing from the boiler
T_{lab}	°C	Temperature of laboratory air
T_{ret}	°C	Temperature of water returning to the boiler
T_{rs}	°C	Temperature rise above ambient associated with case heat loss or standby heat loss measurement
V_{CO_2}	%	Carbon dioxide concentration in dry air (% volume by volume)
$V_{CO_2,max}$	%	Maximum carbon dioxide concentration in dry air (% volume by volume)
X_{air}	none	Excess air factor (1 plus the excess air fraction)
W_i	none	weighing factor of boiler input
W_o	none	weighing factor of boiler output
$\rho_{r,gas}$	none	Relative density of the gaseous fuel
$\rho_{air,stp}$	kg/m^3	Density of the air at 15°C and 0.101325 MPa
ΔC_{com}	% gross	The combined amount the full and part exceed the SEDBUK maximum
ΔC_{full}	% net	The amount the full load efficiency exceeds the maximum
ΔC_{part}	% net	The amount the part load efficiency exceeds the maximum
η		Generic efficiency

Symbol	units	Description
η'		Revised generic efficiency
η_s	% gross	SEDBUK efficiency
η_s'	% gross	Revised SEDBUK efficiency

η_s

η_s'

6 Eliminating the residual

6.1 Principle

Instead of judging data quality by the size of the residual, the component heat flows could be adjusted so that the residual becomes zero. This is best based illustrated by example.

Consider the heat balance illustrated in figure 2. Due to experimental error more heat appears to be leaving the boiler than entering it.

Figure 2 Heat balance with a negative residual.
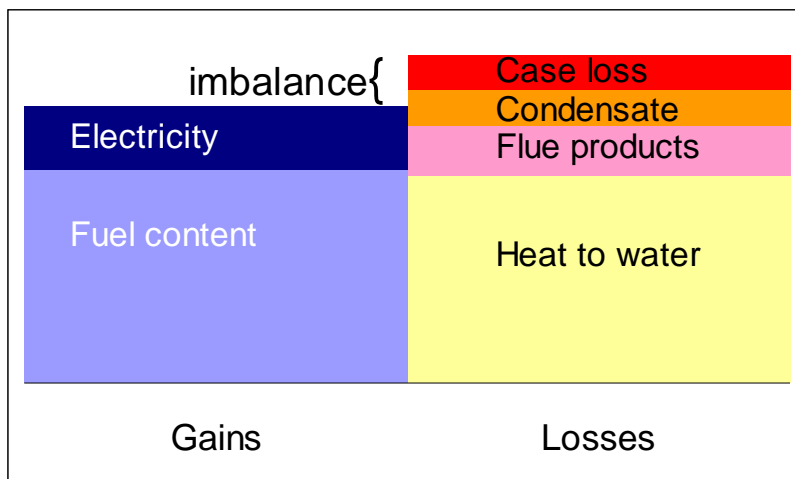
Figure 3 shows the heat losses reduced to achieved balance. A revised efficiency based on the revised "heat to water" amount could form the basis of a revised SEDBUK value.

Figure 3 Heat balance perfectly balanced
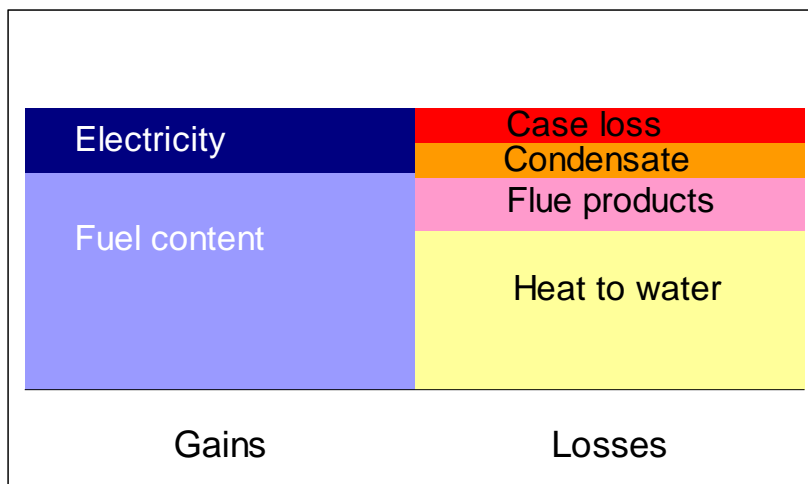
6.2 Revised fuel efficiency

6.2.1 Adjustment constraint

Steps 1 to 7 show the derivation of a necessary constraint to ensure the adjusted unbalanced heat quantities can achieve an energy balance of zero.

Step 1) From the definition of the residual (that is the total heat gains minus the total heat losses), the residual (r in kW and not in % terms as in section 5) is:

$$r = (Q_i + Q_e - Q_f - Q_c - Q_s - Q_o)$$

(The Q's are the unbalanced heat quantities into and out of the boiler.)

Step 2) Let the adjusted heat flows be noted by apostrophes, then the adjusted heat gains minus the adjusted heat losses must sum to zero, giving:

$$0 = (Q_i^{'} + Q_e^{'} - Q_f^{'} - Q_c^{'} - Q_s^{'} - Q_o^{'})$$

Step 3) Let the adjusted heat quantities be related to the unbalanced heat quantities by a series of weighting factors, ($W_i .... W_o$), whose value will be set later, then:

$$Q_i^{'} = Q_i - (r \times W_i) \qquad Q_e^{'} = Q_e - (r \times W_e)$$
$$Q_f^{'} = Q_f + (r \times W_f) \qquad Q_c^{'} = Q_c + (r \times W_c)$$
$$Q_s^{'} = Q_s + (r \times W_s) \qquad Q_o^{'} = Q_o + (r \times W_o)$$

Step 4) Substituting the adjusted heat quantities (step 3) into the equation (step 2) results in:

$$0 = Q_i - (r \times W_i) + Q_e - (r \times W_e) - Q_c + (r \times W_c)$$
$$- Q_f + (r \times W_f) - Q_s + (r \times W_s) - Q_o + (r \times W_o)$$

Step 5) Rearranging so that heat quantities and weighting factor are placed together gives:

$$0 = Q_i + Q_e - Q_c - Q_f - Q_s - Q_o$$
$$- r \times (W_i + W_e - W_c - W_f - W_s - W_o)$$

Step 6) Notice that the unbalanced heat quantities (i.e. the Q s is step 5) are equal to the residual (r) - see definition of the residual in step 1. So replacing them with r and some more rearranging gives:

$$0 = r \times (1 - (W_i + W_e - W_c - W_f - W_s - W_o))$$

Step 7) The two solutions to the above are:

1) $r = 0$ (That is, when the measurements are perfect)

2) $(W_i + W_e - W_c - W_f - W_s - W_o) = 1$

The first solution is trivial.

The second solution shows the constraint necessary to ensure the adjusted heat quantities will balance perfectly.

To summarise:

- Adjusting the unbalance heat quantities to achieve perfect balance means that the total of the heat gain *factors* minus the total of the heat loss *factors* must be unity.

6.2.2   Fuel or overall energy efficiency

There is one more complication to contend with - the electrical heat gains. These gains were not solely introduced to represent measurement uncertainties, but also because some tests may not account for them.

This means there is the concept of the efficiency of heat transfer of the "fuel plus the electricity" or that of the fuel only. The latter is used in SEDBUK.

The revised fuel only efficiency requires the "heat to water" quantity after the deduction of any electrical heat gains.

Therefore, provided the weighting factors meet the constraint above, the revised fuel efficiency is:

$$Re\text{vised efficiency} = \frac{Q_o^{'} - Q_e}{Q_i^{'}} = \frac{Q_o - Q_e + (r \times W_o)}{Q_i - (r \times W_i)}$$

6.2.3   Revised efficiency solutions

There are an infinite number of unique solutions to the constraint, but the three most pertinent are:

1) Place *all* the residual heat into the "heat to water" component (i.e. set $W_i = 1$ and $W_o = 1$ and the other factors to zero).

    This is equivalent to using the efficiency estimate by the "subtraction method" and is illustrated in figure 2 and figure 3.

2) Keep the boiler input fixed and distribute the residual heat pro-rata depending on magnitude of individual heat quantities (i.e. $W_i = 1$ and $W_o = \dfrac{Q_o}{Q_i}$).

This assumes the experimental uncertainties are a fixed proportion of measured quantity. Without information on measurement uncertainties this is a reasonable assumption.

3) Distribute the residual heat in line with the expected experimental uncertainties of each individual component.

This is the most likely case statistically.

Typical weighting factors based on individual measurement uncertainties listed in section 2.3 are shown below in table 5.

Table 5 Estimated uncertainties		
	Uncertainty	Weighting factor
Heat input	1.43%	0.49 - W_i
Heat to water	0.9%	0.31 - W_o
Flue products	0.5%	0.17
Condensate	0.03%	0.01
Casing	0.05%	0.02
Electrical input	0.03%	0.01
Total		1.00

The revised efficiency can also be viewed as part way between two independent estimates: the "heat to water" estimate and subtraction method estimate. If the uncertainty of the "heat to water" estimate is larger than subtraction method, the revised efficiency will be weighted towards the subtraction estimate and visa versa.

The third option is preferred as it is statistically the most likely.

6.2.4 Simplified revised efficiency solution

The revised efficiency solution noted in 6.2.3 involves three parameters in addition to the residual and does not convey concept of the reliability of laboratory data is a straightforward manner.

A simpler solution is therefore suggested.

Any revised efficiency, η', as result of a residual is:

$$\eta' = \frac{Q_o - Q_e + (r \times W_o)}{Q_i - (r \times W_i)}$$

Dividing the numerator and denominator by Q_i gives:

$$\eta' = \frac{\dfrac{Q_o - Q_e}{Q_i} + \dfrac{(r \times W_o)}{Q_i}}{1 - \dfrac{(r \times W_i)}{Q_i}}$$

Noting $\quad \dfrac{r}{Q_i} = Q_r \quad$ (i.e. the residual expressed as fraction the boiler input)

$$\eta' = \dfrac{\dfrac{Q_o - Q_e}{Q_i} + (Q_r \times W_o)}{1 - (Q_r \times W_i)}$$

As $Q_r << 1$ the binomial expansion approximation can be used in the divisor, that is:

$$(1 - W_i Q_r)^{-1} \simeq 1 + W_i Q_r$$

Applying this approximation and neglecting higher powers of Q_r means the revised efficiency (η') is related to the unrevised efficiency (η) by:

$$\eta' \simeq \eta + Q_r (W_o + W_i)$$

Recall that W_o and W_i are constants that add up to less than one (see table 5), so the revision to the efficiency is a proportion of the residual. A negative residual means the measured efficiency is over stated hence the revised efficiency is downward.

6.2.5   Application to SEDBUK

The main concern of the report is with efficiencies that are overstated with a negative residual and so that any revision is always downward. So a possible approach for SEDBUK is to only revise the full and part load efficiency when the respective residuals are negative.

If such a revision approach was adopted one of the following two procedure equivalent but alternatives could be adopted.

1. Revise the full and part load efficiency before applying the SEDBUK procedure as follows;

> Step 1) Calculate the residuals in percentage gross for the full and part load tests (R_{fle} and R_{ple})

> Step 2) Calculate revised full load efficiency (FLE') and part load efficiency as follows (PLE') as follows:

> If $R_{fle} < 0 \qquad FLE' = FLE + R_{fle}(W_o + W_i)/f$

> If $R_{fle} \geq 0 \qquad FLE' = FLE$

> If $R_{ple} < 0 \qquad PLE' = PLE + R_{ple}(W_o + W_i)/f$

> If $R_{ple} \geq 0 \qquad PLE' = PLE$

> PLE is the BED part load efficiency

FLE is the BED full load efficiency

f is net-to-gross factor (see table D2.2, SAP)

$(W_o + W_i)$ is a constant less than 1 - see table 5.

Step 3) Calculate the SEDBUK using the revised efficiencies.

2. Equivalently the strategy adopted could directly revise the SEDBUK as follows:

Step 1) Calculate the combined residual, R_{com} :

If $R_{fle} \geq 0$ set $R_1 = 0$ otherwise $R_1 = R_{fle}$

If $R_{ple} \geq 0$ set $R_2 = 0$ otherwise $R_2 = R_{ple}$

$$R_{com} = (R_1 + R_2)/2$$

where R_{fle} and R_{fle} is the residual for the full and part load test expressed as fraction of the boiler input.

R_{com} is always zero or less.

Step 2) Calculate the amount the laboratory full load efficiency exceeds (ΔC_{full}) the maximum permitted in the SEDBUK procedure. Set it to zero if the laboratory efficiency does not exceed the maximum. Repeat for the part efficiency excess (ΔC_{part}) and sum to derive the combined amount the efficiencies exceed the maximum.

$$\Delta C_{com} = \frac{(\Delta C_{full} + \Delta C_{part}) \times f}{2}$$

f is net-to-gross conversion factor, e.g. 0.901 for natural gas.

ΔC_{com} is always zero or more.

Step 3) Calculate the revised SEDBUK ($\eta_S^{'}$) from the unrevised SEDBUK (η_S)

If $\Delta C_{com} \geq -R_{com} \times (W_i + W_o)$ $\quad \eta_S^{'} = \eta_S$

(i.e. no revision necessary because downward revised efficiencies would be still above the permitted maximum or because there is no reduction as combined residual is zero).

If $\Delta C_{com} < -R_{com} \times (W_i + W_o)$

$$\eta_S^{'} = \eta_S + R_{com} \times (W_i + W_o) + \Delta C_{com}$$

(i.e. the revision to SEDBUK is the amount the full and part load efficiencies were reduced because of the residual plus any amount they would have been capped in the unrevised SEDBUK)

7 Examples of EBV

7.1 Introduction

The EBV method was applied to some existing efficiency test data obtained previously from BRE projects. The data was obtained prior to the development of the EBV method and not all the required measurements were available from all tests. Data was available from 3 accredited test laboratories with results from a total of 28 gas condensing boilers and 2 oil-fired non-condensing boilers.

7.2 Full-load efficiency

The data was applied to the EBV method and the results are shown in the following plot which illustrates the range of residuals obtained.

For full-load efficiency at 80°C/60°C, the residuals indicate that 3 (about 10%) of the 28 boilers tested would be outside a limit of -2% (figure 4).

Figure 4
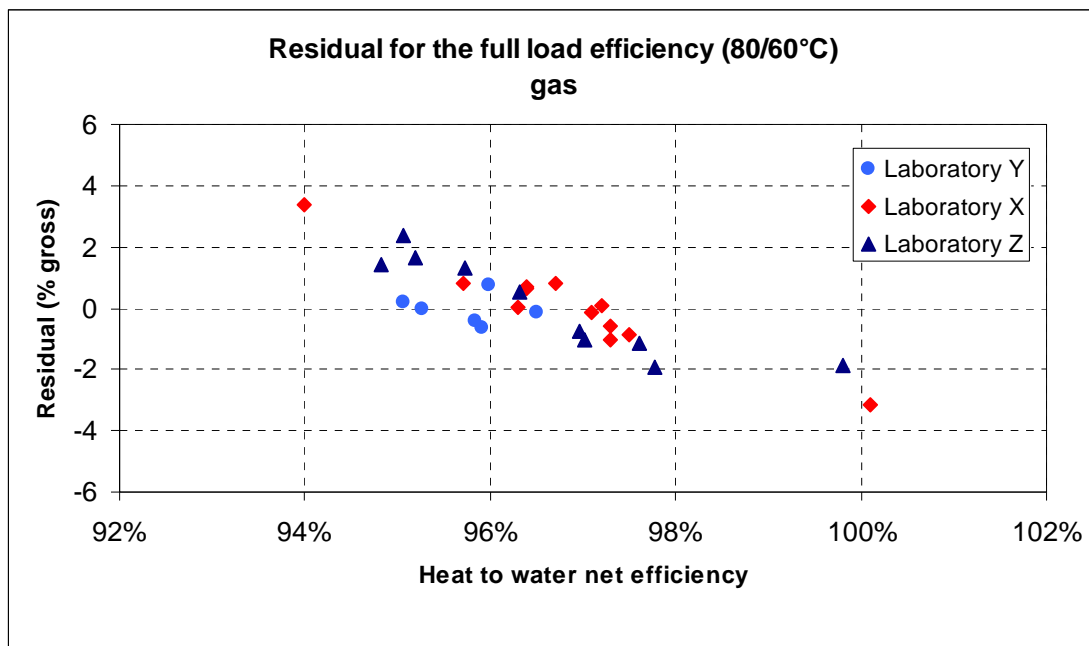
Furthermore, the three reported efficiencies are higher than 97% (net): the expected maximum theoretical efficiency based on a flue temperature of 60°C, standby loss of 0.5% of the boiler full output and an excess air fraction of 20% is just under 97% (net), so potentially the EBV method appears to successfully filter the outliers.

7.3   Part-load efficiency

A smaller set of data (from 16 gas condensing boilers) with sufficient measurements for evaluation using the EBV method was available from two of the accredited test laboratories (figure 5). As expected the scatter is significantly greater than was obtained from full-load tests. It is already well established that measurement uncertainties for tests at part-load are greater than at full-load due to the transient conditions of the tests, the need to measure a smaller temperature differential and the effect of the three different tests methods that can be used.

Figure 5
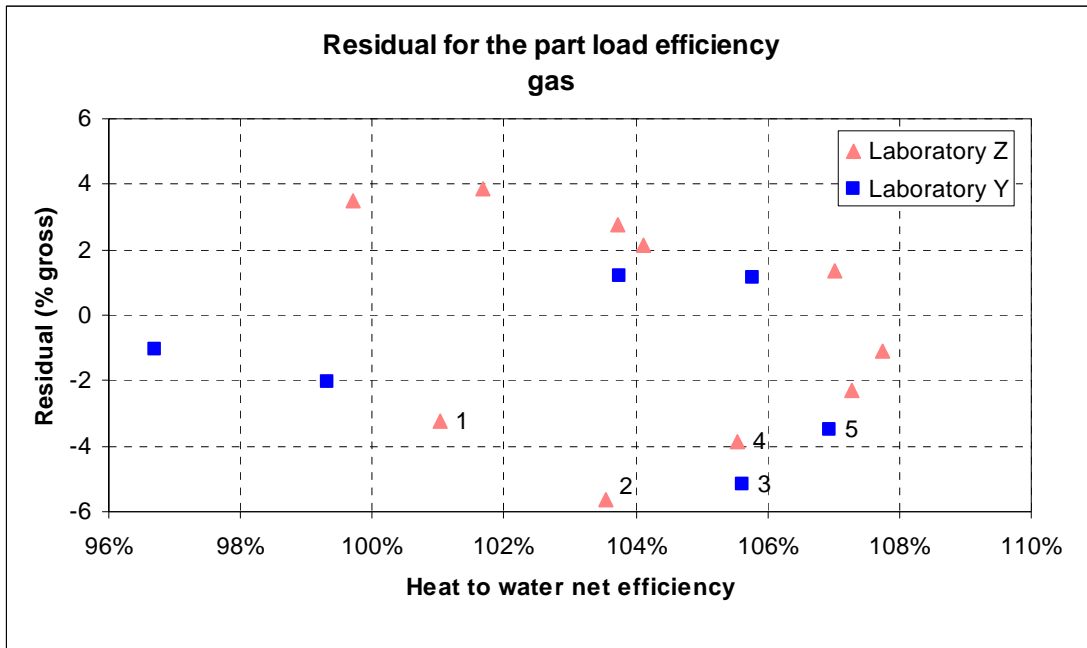
Figure 6 illustrates the expected part load efficiencies for a given carbon dioxide reading and flue product temperature for natural gas.

Boilers labelled #1 to #5 have part-load results with residuals outside -2.5 points (gross) because the "heat to water" efficiency is inconsistent with the reported carbon dioxide concentration and flue product temperature.

Figure 6

Part Load Efficiency for gas boilers
by carbon dioxide concentration and temperature
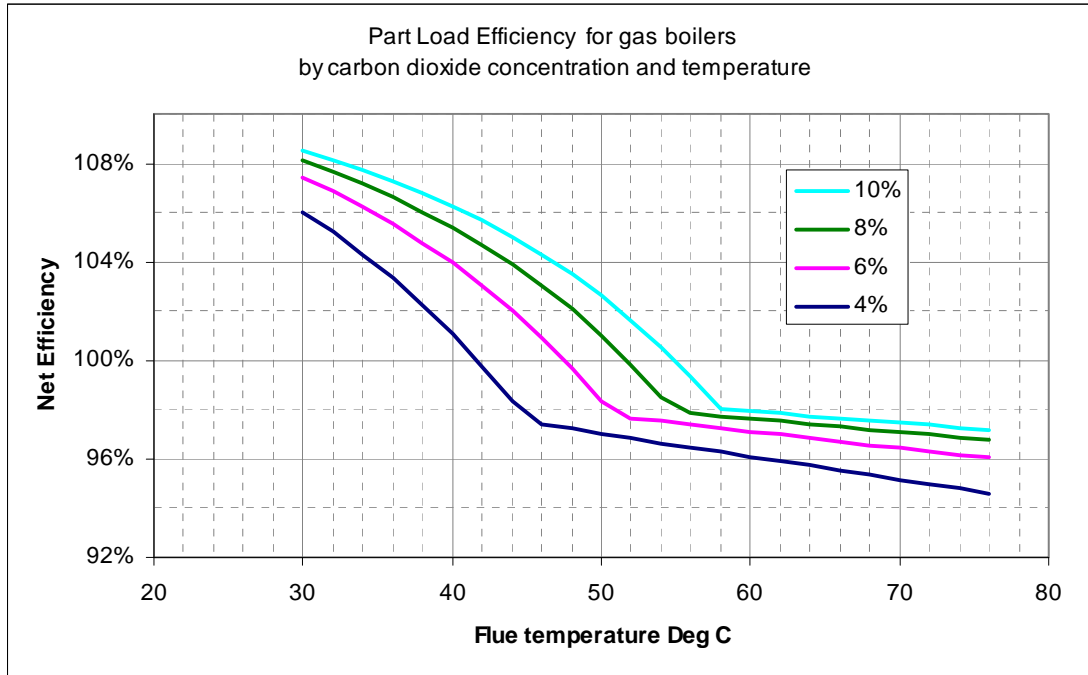
Oil boiler (non-condensing)

Full and part-load figures for two oil boilers (non condensing) based on data from one accredited laboratory are shown below (figure 7).

Figure 7

Residual for two oil boilers (non condensing)
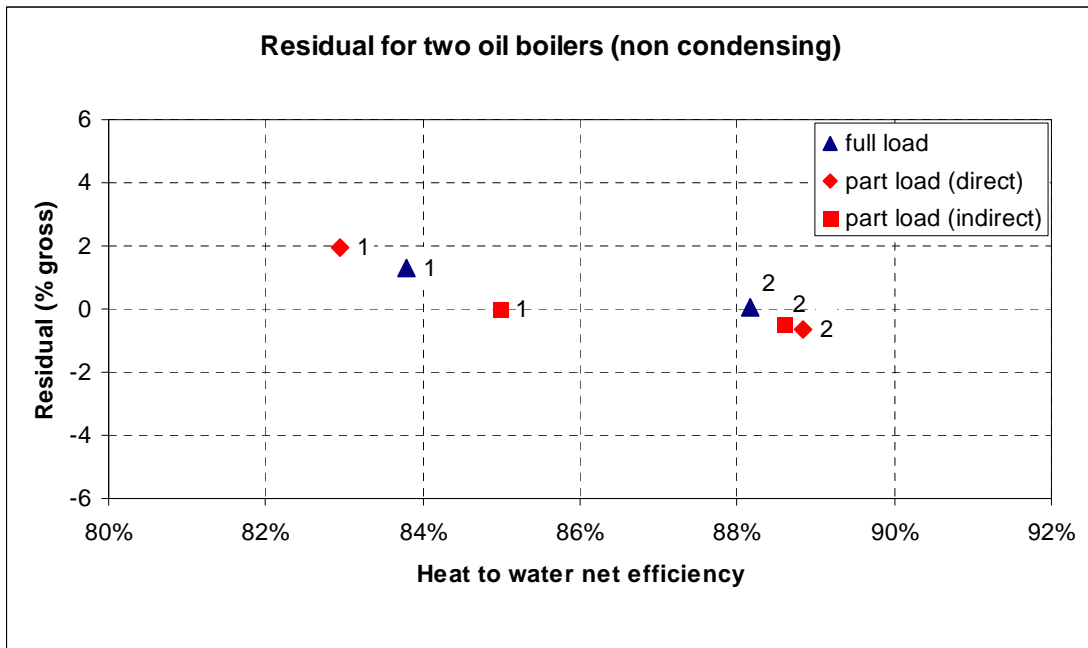
Both boilers show reasonable self consistency within experimental uncertainty.

Indirect and direct Comparison

The European Standards (e.g. EN 297, 483, 303) allow for the choice of a direct or indirect part-load method (see section 4 for a fuller description). The essential difference is that:

- the direct test can have cyclic temperatures

- the indirect test always has steady temperatures

Results for six boilers tested at the same laboratory using the indirect and direct part-load method are shown in figure 8.

Figure 8

Part load residuals for six gas boilers tested by the direct and indirect method at the same laboratory
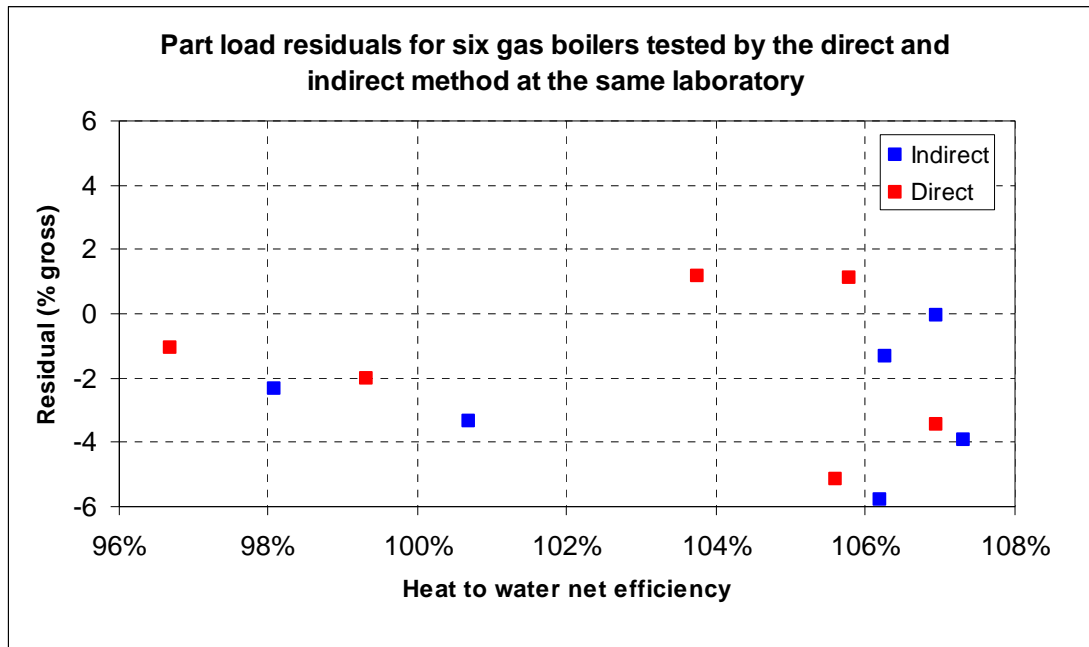
The points from the same boilers are diagonally adjacent from top left to bottom right.

Notice firstly that indirect method has efficiencies of about 1-2% points higher than the direct method. It is not possible to give exact reasons for this difference but as well as experimental uncertainty they may include the fact that start up and stop effects, including purge periods, are neglected in the indirect method. There is insufficient evidence to conclude that the indirect method efficiency is higher in general.

For oil boilers, one boiler has higher efficiencies at part-load when the indirect method is used and the other has a lower efficiency (figure 7).

Secondly the indirect method residual is less by an amount similar to the difference between the "heat to water" efficiency. The difference in the residual between the direct and indirect method is a consequence of the difference in efficiencies as the subtraction estimate is the same for both methods.

8   Findings

It has been shown that the EBV method is capable of identifying, where sufficient data measurements are available, whether heat-to-water and subtraction methods give consistent results.

As expected, results from full-load tests at higher temperatures (80/60°C) show more consistency than results from tests at part-load.

Where poor agreement is evident, it is due to the inconsistency between the "heat to water" efficiency and corresponding flue product temperature and carbon dioxide readings.

Based on this small sample of results an acceptance limit of around 2% is indicated. However this may prove too onerous in practice and should be reviewed in the light of experience.

Appendix A: Statement of test results

The "statement of test results" template is shown solely to clarify what data are required. For each calculation step in the made main body of the report, reference to each required data item is made by the word "template" followed by "section number".

Note, the format of the statement of results may change but it is not envisaged that content will change.

STATEMENT OF BOILER EFFICIENCY RESULTS

This form is to be completed for all boiler models submitted for inclusion on the UK Boiler efficiency database. All boxes of sections 1 to 7 must be completed (in yellow) except those marked optional (in pink).

The information will be used in a comprehensive procedure (energy balance validation) to help authenticate the results, thereby improving their consistency and reliability.

Section 1	Reference Data	
Notified Body		
Manufacturer		
Original Boiler Name		
UK market Name		
Is it a condensing boiler (yes or no)		

Section 2	Declared BED Efficiency test data			
Test Standard used	EN 297	EN 483	EN 677	EN 304
(mark box with x)				
Part–load mode of operation	Direct mode	No 1	No 2	Indirect
(mark box with x)				
Part-load condition operation number from EN 297, 483 or 304		*(enter 1, 2, 3, 4, 5 or 6)*		
Test fuel used	gas G20	gas G31	oil class C2	oil class D
(mark box with x)				
For fuels C2 or D only, enter calorific values from fuel analysis, if available (MJ/kg)		net		
		gross		
Declared full load efficiency %		Declared part-load efficiency %		

Section 3	Efficiency test data set			
Quantity		Full-load	Part-load	Part-load
		100%	30%	Minimum rate
			(direct method)	(Indirect method)
Net input	kW			
Heat output	kW			
Flow temperature	°C			
Return temperature	°C			
Flue gas temperature [#]	°C			
CO_2 in flue gas [#]	%			
Ambient air temperature	°C			
Condensate flow rate *	Kg/hour			
Ambient air humidity *	%			
Circulating pump power *[#]	Watts			
Fan power (gas boilers only) *	Watts			
Oil pump power including fan*	Watts			

[#] Leave blank if firing is cyclic - only required for continuous firing   + See note 10   * Optional

Section 4	Case/standby loss (enter one of case or standby loss)		
Case loss (optional). Surface temperature method (e.g EN304)	Power	Watts	
	Mean water temperature above ambient	°C	
Standby loss (optional). Electrical method – used in indirect part-load efficiency method	Power	Watts	
	Mean water temperature above ambient	°C	

Section 5	Supplementary questions
	yes, no, or as instructed
Confirm that gas condensing boilers tested for part load using direct operating mode No 2 were undertaken at a **constant** return temperature of 30 $\pm$ 0.5 °C. (If not condensing nor gas enter n/a)	
Confirm that boilers with a modulating fuel supply were tested as such and not as an on/off boiler. (If on/off boiler enter n/a)	
If the boiler was tested at part-load using the direct method, was it fired continuously at 30% load? If the indirect method was used insert n/a.	
Is the boiler is fitted with two or more internal circulating pumps that were used during the test? (yes or no) See note 11.	
If the boiler is fitted with one internal circulating pumps was it operated during the test? (If no internal pump or more one enter n/a)	
Has the electrical power from the water circulating pump referred to above been accounted for in the declared boiler efficiency results (see Note 10)? (If none or more one pump enter n/a)	
Is a combustion fan fitted upstream of boiler heat exchanger?	
Has the efficiency data, based on "heat to water" been checked against the flue/case loss to ensure reasonable agreement and consistency of results e.g using recommendations of Labnet?	
What quality monitoring organisation has checked the test rig and procedure used for the tests?	

Section 6	Supplementary efficiency test results .			
Required only where the direct part-load efficiency results are based on cyclic tests. Complete one column only				
Parameters	On/off - full load		Modulating - minimum load	
(* optional entries)	condensing	non condensing	condensing	non condensing
	flow/return of 50/30°C (gas) or mean of 40°C (oil)	flow/return of 60/40°C (oil or gas)	return of 30°C (gas)	mean of 50°C (oil or gas)
Net input kW				
Heat output KW				
Flow temperature °C				
Return temperature °C				
Flue gas temperature °C				
CO_2 in flue gas (%) dry by v/v				
Ambient air temperature °C				
Condensate flow rate* kg/hour				
Ambient air humidity * (%)				

Section 7	Declaration
We declare that the full and part load efficiency test results and other information detailed above have been obtained by following the relevant requirements given in EN 297, 483, 304 or 677.	
Signed on behalf of	
[Insert name of Notified Body]:	
Notified Body Number	
Date:	
Print Name:	
Position:	

Put form onto official headed paper

or

Insert Notified Body Official stamp here

NOTES

1. Data requested will be used to test the consistency between efficiency data based on heat-to-water with those from estimates of flue loss using an energy balance validation method. Absolute agreement is not expected due to measurement uncertainties.

2. Please indicate the test fuel used ie G20 or G31 for gas or C2 or D for oil. Provide gross/net calorific values where certified analysis of test fuel used is available

3. The declared full-load and part-load data should refer to those used to determine the SEDBUK.

4. Part-load operation: tick box to indicate which method was used (from BS EN 297, 483, 304 or 677) to determine efficiency.

5. Part-load conditions of operation: Indicate 1, 2, 3, 4, 5 or 6 as given in BS EN 297, 304 or 483. Where the boiler control includes a number of reduced heat input rates, the results at minimum continuous firing rate should be included in section 3.

6. Where boilers are tested using the indirect method, section 3 should include results at minimum continuous firing rate.

7. Where boilers are tested at part-load using the direct method (Operating mode 1 or 2), supplementary data may be required. Complete one column of section 6, if either the boiler operates with on/off control or with modulating control and not capable of continuous firing at 30% of full-load. These supplementary efficiency test results should be carried out using the procedures given in BS EN 297, 304 or 483 but taking account of the stated temperature requirements.

8. Where available condensate rate and ambient air humidity should be provided. Provision of this data is optional but where it is not provided, estimated values will be used in any assessment.

9. Where available an estimate of the boiler standing heat losses should be provided using a surface temperature method (e.g. BS EN 304). Boilers tested at part-load using the indirect method should include a standby loss data (electrical method as required by BS EN 297, 304 or 483).

10. If the boiler is fitted with one and only one internal water circulating pump the electric power (in watts) should be given. If the internal pump was in operation during the efficiency tests and was not accounted for in the measurements, an estimate of its effect will be included in the energy balance validation. Similar estimates will be made for fan and oil pump power.

11. Some boilers may contain *additional* internal circulating pumps, for example some but not all combined primary storage units have extra pumps to circulate the water between the boiler and store or to mix the stored water, as well as a circulator to push the water around the radiators. If *two or more* pumps are fitted and used enter "yes", otherwise enter "no". If there two pumps or more, the applicant is referred to the database manager.

Appendix B: Reference data

Table B1 Fuel data

Test Fuel Description	G20 Methane	G31 Propane	Kerosene Class C2	Gas oil Class D
Required values				
Fuel composition by mass				
% of atomic hydrogen	25.1	18.087	14.1	13.6
% carbon*	74.9	81.913	85	86
% atomic nitrogen	0	0	0	0
Calorific values (MJ per kg) at 15°C at constant pressure				
Gross $H_{gross,mass}$	55.57	50.38	46.633	45.804
Net $H_{net,mass}$	50.04	46.35	43.575	42.936
Source of calorific values				
Gross calorific (MJ/m^3) (EN 483)	37.78	95.65		
Net calorific (MJ/m^3) (EN 483)	34.02	88.00		
Relative density of gaseous fuel (EN 483)	0.555	1.5500		
Gross calorific (MJ per kg) at constant volume (EN 483)			46.548	45.721
Net calorific (MJ per kg) at constant pressure (EN 483)			43.575	42.936
Density of liquid fuel (kg/dm^3) (EN 483)			0.79	0.85
Sulphur content % (m/m) (EN304)			0.4	0.3
Constant to add to gross value at constant volume to get the gross at constant pressure (BS 7420:1991)			0.09	0.08

*include any sulphur as carbon content

For oil, the gross calorific value (or specific enthalpy) at constant volume and net calorific at constant pressure is calculated from the density and sulphur content using the formula in BS 2869:2006 page 12 (water and ash content are taken as zero). The gross value at constant volume is converted into a value at constant pressure by the addition of constant as stated in BS 7420:1991 (oxygen content of fuel is taken as zero). This addition represents the work done by the atmosphere filling the partial vacuum. The fuel and molecular oxygen take up less volume than the liquid water and carbon dioxide produced.

For gaseous fuels the calorific value per unit mass is:

$$H_{gross} = \frac{1000 \times H_{gross,vol}(MJ/m^3)}{(\rho_{r,gas} \times \rho_{air,stp})}$$

$H_{gross,vol}$ calorific value per unit volume

$\rho_{r,gas}$ is the relative density of the gaseous fuel

$\rho_{air,stp}$ is the density of the air at reference temperature and pressure (kg/m^3)

Reference data dependent on temperature is tabulated overleaf (table B3) and includes the saturated vapour pressure, latent heat of vaporisation of water and the enthalpy of various gases including water vapour. The enthalpy zero datum point is 0K for the gases and 0.16°C for liquid water. The saturated vapour pressure and latent heat values are sourced from NISTIR 5078[11] and the enthalpies from formulae given in the Good Practice Guide produced by Labnet[12].

Other reference data

- Density of air at reference temperature and reference pressure 1.225 kg/m^3
- Reference temperature 15°C
- Reference pressure 1013.25 mb = 0.101325 MPa
- Dry Air is assumed to be composed of:
  - Oxygen content of dry air by volume 20.95% (23.14% by mass)
  - Nitrogen content of dry air by volume 79.05%

Table B2 Relative atomic and molecular weights

Relative atomic weight kg/mol		Relative molecular weight kg/mol				
H	C	H20	CO2	N2	O2	Air
1.008	12.012	18.015	44.01	28.17	31.998	28.964

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[11] NISTIR 5078 Thermodynamic Properties of Water: Tabulation from the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use , Allan H. Harvey , Physical and Chemical Properties Division
Chemical Science and Technology Laboratory , National Institute of Standards and Technology , Boulder, Colorado 80305 ,October 1998,
http://www.nist.gov/srd/webguide/nist10v2.2/NISTIR5078.htm, 10 Aug 2006

[12]Good Laboratory Practice for Full and Part-load, Efficiency Measurement for Boilers, Revision of the document 1998-2000, Version 08, Preparation of the document to be sent to CEN in September 2000 http://labnet.dgc.dk/public/BEDAC/glp_eff08.htm#_Toc455905161, 10 Aug 2006

Table B3: Temperature dependent data (NISTIR 5078)

Temperature	Saturated vapour pressure	Latent heat of vaporization	Specific enthalpy (kJ per kg)				
°C	MPa	kJ /kg of dry air	Liquid water	CO_2	N_2	O_2	Water vapour
10	0.001228	2479.6	42.01	183.948	290.390	247.465	489.256
11	0.001313	2477.2	46.20	184.778	291.468	248.377	491.101
12	0.001403	2474.8	50.38	185.610	292.547	249.289	492.947
13	0.001498	2472.5	54.56	186.442	293.626	250.202	494.793
14	0.001599	2470.1	58.74	187.276	294.706	251.115	496.640
15	0.001706	2467.7	62.93	188.110	295.786	252.028	498.488
16	0.001819	2465.4	67.11	188.946	296.866	252.942	500.336
17	0.001938	2463	71.29	189.782	297.947	253.856	502.184
18	0.002065	2460.6	75.47	190.620	299.028	254.770	504.033
19	0.002198	2458.3	79.65	191.459	300.110	255.684	505.883
20	0.002339	2455.9	83.84	192.298	301.192	256.599	507.734
21	0.002488	2453.5	88.02	193.139	302.275	257.514	509.584
22	0.002645	2451.2	92.20	193.981	303.358	258.429	511.436
23	0.002811	2448.8	96.38	194.824	304.441	259.344	513.288
24	0.002986	2446.4	100.56	195.667	305.525	260.260	515.140
25	0.00317	2444	104.74	196.512	306.609	261.176	516.994
26	0.003364	2441.7	108.92	197.358	307.694	262.092	518.847
27	0.003568	2439.3	113.10	198.205	308.779	263.009	520.701
28	0.003783	2436.9	117.28	199.052	309.865	263.926	522.556
29	0.004009	2434.6	121.46	199.901	310.951	264.843	524.411
30	0.004247	2432.2	125.64	200.751	312.037	265.760	526.267
31	0.004497	2429.8	129.82	201.602	313.124	266.678	528.124
32	0.00476	2427.4	134.00	202.453	314.212	267.596	529.981
33	0.005035	2425.1	138.19	203.306	315.299	268.514	531.838
34	0.005325	2422.7	142.37	204.160	316.388	269.432	533.696
35	0.005629	2420.3	146.55	205.015	317.477	270.351	535.555
36	0.005948	2417.9	150.73	205.870	318.566	271.270	537.414
37	0.006282	2415.5	154.91	206.727	319.655	272.189	539.274
38	0.006633	2413.1	159.09	207.585	320.745	273.109	541.134
39	0.007	2410.8	163.27	208.443	321.836	274.029	542.995
40	0.007385	2408.4	167.45	209.303	322.927	274.949	544.856
41	0.007788	2406	171.63	210.163	324.018	275.869	546.718
42	0.00821	2403.6	175.81	211.025	325.110	276.790	548.580
43	0.008651	2401.2	179.99	211.888	326.203	277.710	550.443
44	0.009112	2398.8	184.17	212.751	327.295	278.632	552.307
45	0.009595	2396.4	188.35	213.616	328.389	279.553	554.171
46	0.010099	2391.6	192.54	214.481	329.482	280.475	556.035

Temperature	Saturated vapour pressure	Latent heat of vaporization	Specific enthalpy (kJ per kg)				
°C	MPa	kJ /kg of dry air	Liquid water	CO_2	N_2	O_2	Water vapour
47	0.010627	2389.2	196.72	215.347	330.577	281.397	557.900
48	0.011177	2386.8	200.90	216.215	331.671	282.319	559.766
49	0.011752	2384.4	205.08	217.083	332.766	283.241	561.632
50	0.012352	2381.9	209.26	217.952	333.862	284.164	563.498
51	0.012978	2379.5	213.45	218.823	334.958	285.087	565.365
52	0.013631	2377.1	217.63	219.694	336.054	286.010	567.233
53	0.014312	2374.7	221.81	220.566	337.151	286.934	569.101
54	0.015022	2372.3	226.00	221.439	338.249	287.858	570.970
55	0.015762	2369.8	230.18	222.313	339.347	288.782	572.839
56	0.016533	2367.4	234.36	223.188	340.445	289.707	574.708
57	0.017336	2365.0	238.55	224.064	341.544	290.631	576.579
58	0.018171	2362.5	242.73	224.941	342.643	291.556	578.449
59	0.019041	2360.1	246.92	225.819	343.743	292.481	580.321
60	0.019946	2357.7	251.10	226.697	344.844	293.407	582.192
61	0.020888	2355.2	255.29	227.577	345.944	294.333	584.065
62	0.021867	2352.8	259.47	228.458	347.046	295.259	585.937
63	0.022885	2350.3	263.66	229.339	348.147	296.185	587.810
64	0.023943	2347.8	267.85	230.222	349.249	297.112	589.684
65	0.025042	2345.4	272.04	231.105	350.352	298.039	591.558
66	0.026183	2342.9	276.22	231.989	351.455	298.966	593.433
67	0.027368	2340.5	280.41	232.875	352.559	299.893	595.308
68	0.028599	2338.0	284.60	233.761	353.663	300.821	597.184
69	0.029876	2335.5	288.79	234.648	354.768	301.749	599.060
70	0.031201	2333.0	292.98	235.536	355.873	302.677	600.937
71	0.032575	2330.5	297.17	236.425	356.978	303.605	602.814
72	0.034	2328.1	301.36	237.315	358.084	304.534	604.692
73	0.035478	2325.6	305.56	238.206	359.191	305.463	606.570
74	0.037009	2323.1	309.75	239.097	360.298	306.393	608.449
75	0.038595	2320.6	313.94	239.990	361.406	307.322	610.328
76	0.040239	2318.1	318.14	240.884	362.514	308.252	612.208
77	0.041941	2315.6	322.33	241.778	363.622	309.182	614.088
78	0.043703	2313.0	326.53	242.673	364.731	310.113	615.969
79	0.045527	2310.5	330.72	243.570	365.841	311.043	617.850
80	0.047414	2308.0	334.92	244.467	366.951	311.974	619.732
81	0.049367	2305.5	339.12	245.365	368.062	312.906	621.614
82	0.051387	2302.9	343.32	246.264	369.173	313.837	623.496
83	0.053476	2300.4	347.52	247.164	370.284	314.769	625.379
84	0.055635	2297.9	351.72	248.064	371.396	315.701	627.263
85	0.057867	2295.3	355.92	248.966	372.509	316.633	629.147

Temperature	Saturated vapour pressure	Latent heat of vaporization	Specific enthalpy (kJ per kg)				
°C	MPa	kJ /kg of dry air	Liquid water	CO_2	N_2	O_2	Water vapour
86	0.060173	2292.8	360.12	249.868	373.622	317.566	631.032
87	0.062556	2325.6	364.32	250.772	374.736	318.499	632.917
88	0.065017	2323.1	368.53	251.676	375.850	319.432	634.802
89	0.067558	2320.6	372.73	252.581	376.964	320.366	636.688
90	0.070182	2318.1	376.94	253.487	378.080	321.299	638.575
91	0.07289	2315.6	381.15	254.394	379.195	322.233	640.461
92	0.075684	2313.0	385.36	255.302	380.311	323.168	642.349
93	0.078568	2310.5	389.56	256.211	381.428	324.102	644.237
94	0.081541	2308.0	393.78	257.120	382.545	325.037	646.125
95	0.084608	2305.5	397.99	258.031	383.663	325.972	648.014
96	0.087771	2302.9	402.20	258.942	384.781	326.908	649.903
97	0.09103	2300.4	406.41	259.854	385.900	327.843	651.793
98	0.09439	2297.9	410.63	260.768	387.019	328.779	653.683
99				261.681	388.139	329.715	655.574
100				262.596	389.260	330.652	657.465
101				263.512	390.380	331.589	659.356
102				264.428	391.502	332.526	661.249
103				265.346	392.624	333.463	663.141
104				266.264	393.746	334.401	665.034
105				267.183	394.869	335.339	666.928
106				268.103	395.993	336.277	668.822
107				269.024	397.117	337.215	670.716
108				269.946	398.242	338.154	672.611
109				270.868	399.367	339.093	674.506
110				271.792	400.492	340.032	676.402
111				272.716	401.619	340.972	678.298
112				273.641	402.745	341.911	680.195
113				274.567	403.873	342.852	682.092
114				275.494	405.001	343.792	683.989
115				276.421	406.129	344.733	685.887
116				277.350	407.258	345.674	687.786
117				278.279	408.388	346.615	689.685
118				279.209	409.518	347.556	691.584
119				280.140	410.648	348.498	693.484
120				281.072	411.780	349.440	695.384
121				282.005	412.911	350.382	697.285
122				282.938	414.044	351.325	699.186
123				283.872	415.177	352.268	701.088
124				284.808	416.310	353.211	702.990

Temperature	Saturated vapour pressure	Latent heat of vaporization	Specific enthalpy (kJ per kg)				
°C	MPa	kJ /kg of dry air	Liquid water	CO_2	N_2	O_2	Water vapour
125				285.744	417.444	354.154	704.893
126				286.680	418.579	355.098	706.796
127				287.618	419.714	356.042	708.699
128				288.556	420.849	356.986	710.603
129				289.496	421.986	357.931	712.507
130				290.436	423.122	358.876	714.412
131				291.377	424.260	359.821	716.317
132				292.318	425.398	360.766	718.223
133				293.261	426.536	361.712	720.129
134				294.204	427.675	362.658	722.035
135				295.148	428.815	363.604	723.942
136				296.093	429.955	364.551	725.850
137				297.039	431.096	365.497	727.758
138				297.985	432.238	366.444	729.666
139				298.933	433.380	367.392	731.575
140				299.881	434.522	368.339	733.484
141				300.830	435.666	369.287	735.393
142				301.780	436.809	370.235	737.303
143				302.730	437.954	371.184	739.214
144				303.682	439.099	372.133	741.125
145				304.634	440.244	373.082	743.036
146				305.587	441.390	374.031	744.948
147				306.540	442.537	374.981	746.860
148				307.495	443.684	375.930	748.773
149				308.450	444.832	376.881	750.686
150				309.406	445.981	377.831	752.599
151				310.363	447.130	378.782	754.513
152				311.321	448.280	379.733	756.428
153				312.279	449.430	380.684	758.342
154				313.238	450.581	381.635	760.258
155				314.199	451.733	382.587	762.173
156				315.159	452.885	383.539	764.089
157				316.121	454.038	384.492	766.006
158				317.083	455.191	385.444	767.923
159				318.046	456.345	386.397	769.840
160				319.010	457.500	387.351	771.758
161				319.975	458.655	388.304	773.676
162				320.940	459.811	389.258	775.595
163				321.906	460.967	390.212	777.514

Temperature	Saturated vapour pressure	Latent heat of vaporization	Specific enthalpy (kJ per kg)				
°C	MPa	kJ /kg of dry air	Liquid water	CO$_2$	N$_2$	O$_2$	Water vapour
164				322.873	462.124	391.166	779.433
165				323.841	463.282	392.121	781.353
166				324.810	464.440	393.076	783.273
167				325.779	465.599	394.031	785.194
168				326.749	466.759	394.987	787.115
169				327.720	467.919	395.942	789.037
170				328.691	469.080	396.898	790.959
171				329.663	470.241	397.855	792.881
172				330.637	471.404	398.811	794.804
173				331.610	472.566	399.768	796.728
174				332.585	473.730	400.725	798.651
175				333.560	474.894	401.683	800.575
176				334.536	476.058	402.641	802.500
177				335.513	477.224	403.599	804.425
178				336.491	478.390	404.557	806.350
179				337.469	479.556	405.516	808.276
180				338.448	480.723	406.474	810.202
181				339.428	481.891	407.434	812.129
182				340.408	483.060	408.393	814.056
183				341.389	484.229	409.353	815.984
184				342.371	485.399	410.313	817.912
185				343.354	486.569	411.273	819.840
186				344.338	487.741	412.234	821.769
187				345.322	488.912	413.195	823.698
188				346.307	490.085	414.156	825.627
189				347.292	491.258	415.117	827.557
190				348.279	492.432	416.079	829.488
191				349.266	493.606	417.041	831.419
192				350.254	494.781	418.003	833.350
193				351.242	495.957	418.966	835.281
194				352.232	497.134	419.928	837.214
195				353.222	498.311	420.892	839.146
196				354.212	499.488	421.855	841.079
197				355.204	500.667	422.819	843.012
198				356.196	501.846	423.783	844.946
199				357.189	503.026	424.747	846.880
200				358.183	504.206	425.711	848.815
201				359.177	505.388	426.676	850.750
202				360.172	506.569	427.641	852.685

Temperature	Saturated vapour pressure	Latent heat of vaporization	Specific enthalpy (kJ per kg)				
°C	MPa	kJ /kg of dry air	Liquid water	CO_2	N_2	O_2	Water vapour
203				361.168	507.752	428.607	854.621
204				362.164	508.935	429.572	856.557
205				363.161	510.119	430.538	858.494
206				364.159	511.304	431.505	860.431
207				365.158	512.489	432.471	862.368
208				366.157	513.675	433.438	864.306
209				367.157	514.862	434.405	866.244
210				368.158	516.049	435.372	868.183
211				369.159	517.237	436.340	870.122
212				370.161	518.426	437.308	872.061
213				371.164	519.615	438.276	874.001
214				372.168	520.806	439.245	875.942
215				373.172	521.996	440.214	877.882
216				374.177	523.188	441.183	879.824
217				375.182	524.380	442.152	881.765
218				376.189	525.573	443.122	883.707
219				377.196	526.767	444.092	885.650
220				378.203	527.961	445.062	887.592
221				379.212	529.156	446.032	889.536
222				380.221	530.352	447.003	891.479
223				381.231	531.549	447.974	893.423
224				382.241	532.746	448.946	895.368
225				383.252	533.944	449.917	897.312
226				384.264	535.143	450.889	899.258
227				385.276	536.342	451.862	901.203
228				386.290	537.542	452.834	903.149
229				387.303	538.743	453.807	905.096
230				388.318	539.945	454.780	907.043
231				389.333	541.147	455.753	908.990
232				390.349	542.350	456.727	910.938
233				391.365	543.554	457.701	912.886
234				392.383	544.759	458.675	914.835
235				393.401	545.964	459.650	916.783
236				394.419	547.170	460.625	918.733
237				395.438	548.377	461.600	920.683
238				396.458	549.584	462.575	922.633
239				397.479	550.792	463.551	924.583
240				398.500	552.001	464.527	926.534
241				399.522	553.211	465.503	928.486

Temperature	Saturated vapour pressure	Latent heat of vaporization	Specific enthalpy (kJ per kg)				
°C	MPa	kJ /kg of dry air	Liquid water	CO_2	N_2	O_2	Water vapour
242				400.544	554.422	466.479	930.438
243				401.568	555.633	467.456	932.390
244				402.592	556.845	468.433	934.342
245				403.616	558.058	469.411	936.295
246				404.641	559.271	470.388	938.249
247				405.667	560.485	471.366	940.203
248				406.694	561.700	472.344	942.157
249				407.721	562.916	473.323	944.112
250				408.749	564.133	474.302	946.067