Boiler Efficiency- traps for the unwary

At Genesis Now, we have recently been involved with two projects in which boiler selection was an issue of some interest. In both cases, the same boiler make/model was proposed and after looking at the claimed performance, we had some concerns and so decided to dig a little deeper for reasons that will become apparent shortly.

But first, a small digression into the realms of pop (as in popular) quizzes. Which of the following (if any) is true?

1. A car can run on custard
2. It is possible to make a mobile phone from fish-sticks
3. A boiler can achieve an efficiency greater than 100%
4. A liberal coating of banana skin extract on a follicly-challenged scalp will guarantee luxurious hair re-growth overnight

The brains trust in our office came to the conclusion that none of the above should be true but under certain conditions, number 3 can give the impression that it can be true. What does this mean?

First things first; the term "boiler" whilst in common use by HVAC practitioners is more confusing than enlightening. Gone are the days when water was actually boiled and the condensation of steam used for heating, although more of this anon. Now it is much more common for hot water, possibly up to around 80^{o}C or so to be the working fluid, and so we prefer the term "water heater" better, but maybe we're fighting a losing battle; as in "everybody knows what I mean", or do they?.

But this is an aside; the question is- what does it mean to suggest that it is possible to claim a boiler/water heater can achieve an efficiency of more than 100%?

Perhaps the first thing is to define what we mean by efficiency. In this context, the usual definition is the ratio of the useful thermal output over the fuel energy input. Such a definition implies that to get an efficiency value above 100% you would need to be getting more out than you were putting in. Shades of a thermal perpetual motion machine perhaps?

No such luck as the answer is somewhat mundane and involves a subtle twist to the definition which explains the paradoxical result. But first, a chemistry lesson refresher. Natural gas is a mixture of several hydrocarbons, and the predominant one is methane (CH_4) at around 90%. .The combustion of methane is as follows:

$CH_4(g) + 2\,O_2(g) \rightarrow CO_2(g) + 2\,H_2O(l)$[1]

(ΔH = −891 kJ/mol (at standard conditions))

Where bracketed "g" stands for gaseous form and bracketed "l" stands for liquid form

Source: http://en.wikipedia.org/wiki/Methane

The amount of heat released (891 kJ/mol) is not very useful to HVAC engineers and in more useful units it is 55.55 kJ/g or 55.55 MJ/kg and 37.75 MJ/m^3 at standard temperature and pressure conditions of 15^{o}C (288 K) and 101.325 kPa respectively.

Taking into account the other three main components namely methane (CH_4), ethane (C_2H_6) and butane (C_4H_{10}) in Victoria and their relative volumetric fractions[2], our

[1] See "box out at end of document for further information

finding was that natural gas should have an energy content of 38.6 MJ/m^3 which is within 1% of the value of 38.8 MJ/m^3 suggested for Victoria in the AIRAH Handbook and is also close to that shown on gas bills[3].

Finally, returning to the question: can a boiler (or even a water heater) achieve an efficiency greater than 100%? Consider the following.

BASED ON DATA IN MANUFACTURER'S LITERATURE

WATER HEATER "Bxxx": European manufacturer

Claimed performance in European data:

Rated Heat Output at 80°C/60°C	kW	85
Nominal gas consumption	kW	87.2
Efficiency	%	97.5
Rated Heat Output at 50°C/30°C	kW	94.6
Nominal gas consumption	kW	**90.0**
Efficiency	%	105.1

Note the apparently very high efficiency of 97.5% under high working temperature conditions and the, scarcely credible 105.1% under low working temperature conditions

WATER HEATER "Mxxxxxx": US manufacturer

Claimed performance:

Rated Heat Output at 80°C/60°C	kW	95
Nominal gas consumption	kW	105.56
Efficiency	%	90
Rated Heat Output at 50°C/30°C	kW	95
Nominal gas consumption	kW	**97.9**
Efficiency	%	97

Comparison: Using these figures, "B" seems to be the better performing unit under both high (97.5% versus 90%) and low working temperature conditions (105.1% versus 97%).

[2] Source: http://www.aph.gov.au/library/pubs/rp/1998-99/99rp05.htm#COMP

[3] The gas energy value varies from month to month due to changes in composition.

BASED ON ADJUSTED DATA

WATER HEATER "Bxxx": European manufacturer

Claimed performance:

Rated Heat Output at 80°C/60°C	kW	85
Nominal gas consumption	kW	96.8
Calculated efficiency	%	87.8
Rated Heat Output at 50°C/30°C	kW	94.6
Nominal gas consumption	kW	99.9
Calculated efficiency	%	94.7

Note that efficiencies are down and both are now under 100%

WATER HEATER "Mxxxxxx": US manufacturer

Claimed performance, unchanged from before:

Rated Heat Output at 80°C/60°C	kW	95
Nominal gas consumption	kW	105.56
Efficiency	%	90
Rated Heat Output at 50°C/30°C	kW	95
Nominal gas consumption	kW	97.9
Efficiency	%	97

Comparison: Using these figures, the situation is reversed with "M" now the better performing unit under both high (90% versus 87.8%) and low working temperature conditions (97% versus 94.7%).

One unfortunate situation we came across is that of a local water heater supplier who sources equipment from both European and US manufacturers, but uses original data leading to the inconsistencies noted. This is not always the case and we have also come across the datasheet for local use for water heater "Bxxx" which has the appropriate correction made for energy input. The problem is the inconsistency of application, hence the potential for great confusion.

In rare cases, a manufacturer will quote a gas volume flow rate which readily allows checking against the gas energy input to determine if HHV or LHV has been used. In the latter case a correction is required.

Some rules of thumb are:

- If the efficiency figure is greater than 100%, the chances are it has been based on LHV and may be corrected to HHV by dividing by 1.11 (see table and graph on next page for comparison)
- For non-condensing water heaters, an efficiency much higher than 80% is not realistic
- For condensing water heaters, an efficiency much higher than 90% is not credible

In summary, to allow informed decisions based on credible data, selection of water heaters must be made on the basis of directly comparable data. We strongly suggest that all performance results be always based on the higher heating value for the input fuel. In this way, efficiencies will be less than 100%.

BITS AND PIECES

Methane: HHV and LHV

Suggested values are:

- HHV 55.50 MJ/kg (slightly higher at 55.55 using other reference cited previously)
- LHV 50.00 MJ/kg

Source: http://en.wikipedia.org/wiki/Heat_of_combustion

From the earlier chemical equation, for each kg of CH_4:

- Need 4 kg O_2, making total inputs 5 kg
- Outputs: 2.75 kg CO_2 and 2.25 kg H_2O making total inputs 5 kg, same as inputs

For H_20 condensing at 15°C, the enthalpy (heat) released is 2.466 MJ/kg or 5.55 MJ for 2.25 kg. From this the estimated LHV is 55.55 less 5.55 or 50.00 MJ/kg which matches the above.

It is possible to repeat this procedure for other constituents of natural gas and combine them by mass fraction; a task for another day.

Net Efficiency and Gross Efficiency:

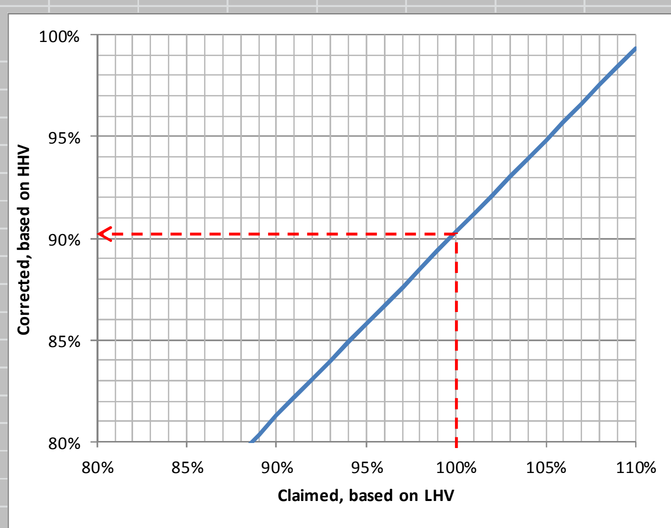
In some European literature, these two terms are used to signify:

- Gross Efficiency: means based on input fuel HHV, and
- Net efficiency: means based on input fuel LHV

Correcting Efficiency based on LHV to Efficiency based on HHV:

Water Heater Efficiency

Claimed, based on LHV	Corrected, based on HHV
110.0%	99.3%
109.0%	98.4%
108.0%	97.5%
107.0%	96.6%
106.0%	95.7%
105.0%	94.8%
104.0%	93.9%
103.0%	93.0%
102.0%	92.1%
101.0%	91.2%
100.0%	90.3%
99.0%	89.4%
98.0%	88.5%
97.0%	87.6%
96.0%	86.7%
95.0%	85.8%
94.0%	84.9%
93.0%	84.0%



Line shows example with 100% claimed efficiency based on fuel LHV equating to 90.3% efficiency based on fuel HHV.