Department for Business, Energy & Industrial Strategy

Measurement of the in-situ performance of solid biomass boilers

Annex E: Field trial efficiency calculations

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Preface

This document is the field trial efficiency calculations annex to “Measurement of the in-situ performance of solid biomass boilers”, a report prepared for BEIS which details work carried out from 2015 to 2018 where the real-life efficiencies and pollutant emissions of a range of biomass boilers were measured.

The work was carried out by a consortium of Kiwa Gastec, Ricardo Energy and Environment, Energy Saving Trust, HETAS, and Optimum Consultancy.

Table of contents

1 Introduction

The field trial measured the efficiency of the biomass boiler by the losses (indirect) method. The calculation is based on BS 845-1 [1] when the boiler is in steady operation. The calculation used is similar to that used in a number of other standards [2, 3]. Flue gas temperature and flue gas oxygen concentration were the primary indicators of boiler efficiency during steady operation.

None of the available standards define calculations that can be used in non-steady state conditions, so a bespoke algorithm was designed by Kiwa. This follows the standard approach during periods of steady state operation, with adaptations to cover startup, shutdown and off periods.

2 Phase of operation

The operation of the boiler was split into four main phases, shown in Figure 1. The boiler was determined to be operating when the flue gas oxygen was less than 17%. This period of ‘steady operation’ included the time (potentially many hours) that the boiler takes to fully warm up. It was not merely a period of ‘steady state’ as defined in boiler testing standards.

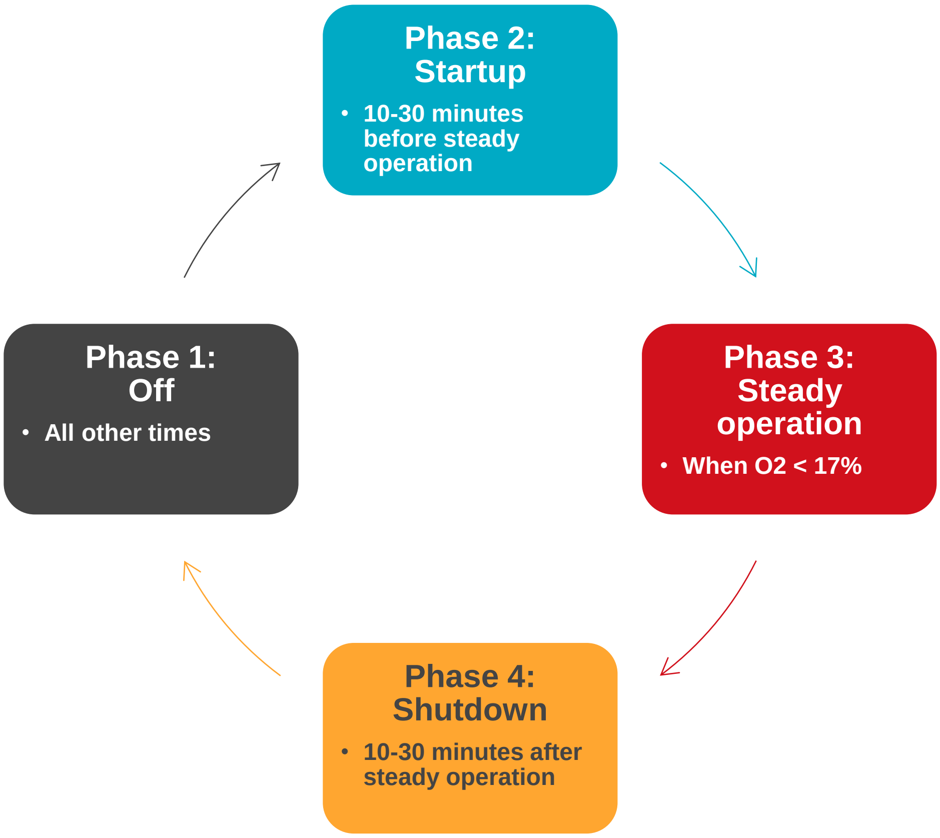

Figure 1: Four phases of operation of the boiler, and how they are identified

The startup and shutdown periods were immediately before and after each period of steady operation. There were defined as lasting between 10-30 minutes, depending on the size of the boiler, as shown in Table 1.

Table 1: Efficiency calculation – length of startup and shutdown periods[1]

Boiler rated output (kW)	Length of Startup period (minutes)	Length of Shutdown period (minutes)
< 30	10	10
30 – 800	$0.026Q_{ro} + 9.22$	$0.026Q_{ro} + 9.22$
> 800	30	30

Key: Q_{ro} *is the rated output of the boiler in kW*

[1] The values in this table have been determined from analysis of data collected in the field trial and the laboratory trials and boiler testing standards [1, 2, 3].

3 Calculation of efficiency

The efficiency over a given basis period (day, month, year, etc.) was calculated with the equation:

$$\text{Efficiency} = \frac{\text{Energy out}}{\text{Energy out} + \text{Losses}}$$

The energy out and losses in the equation were calculated by summing the total output and total losses over that basis period. The calculations used for the losses in each period are outlined in Figure 2 and shown in detail in Table 2.

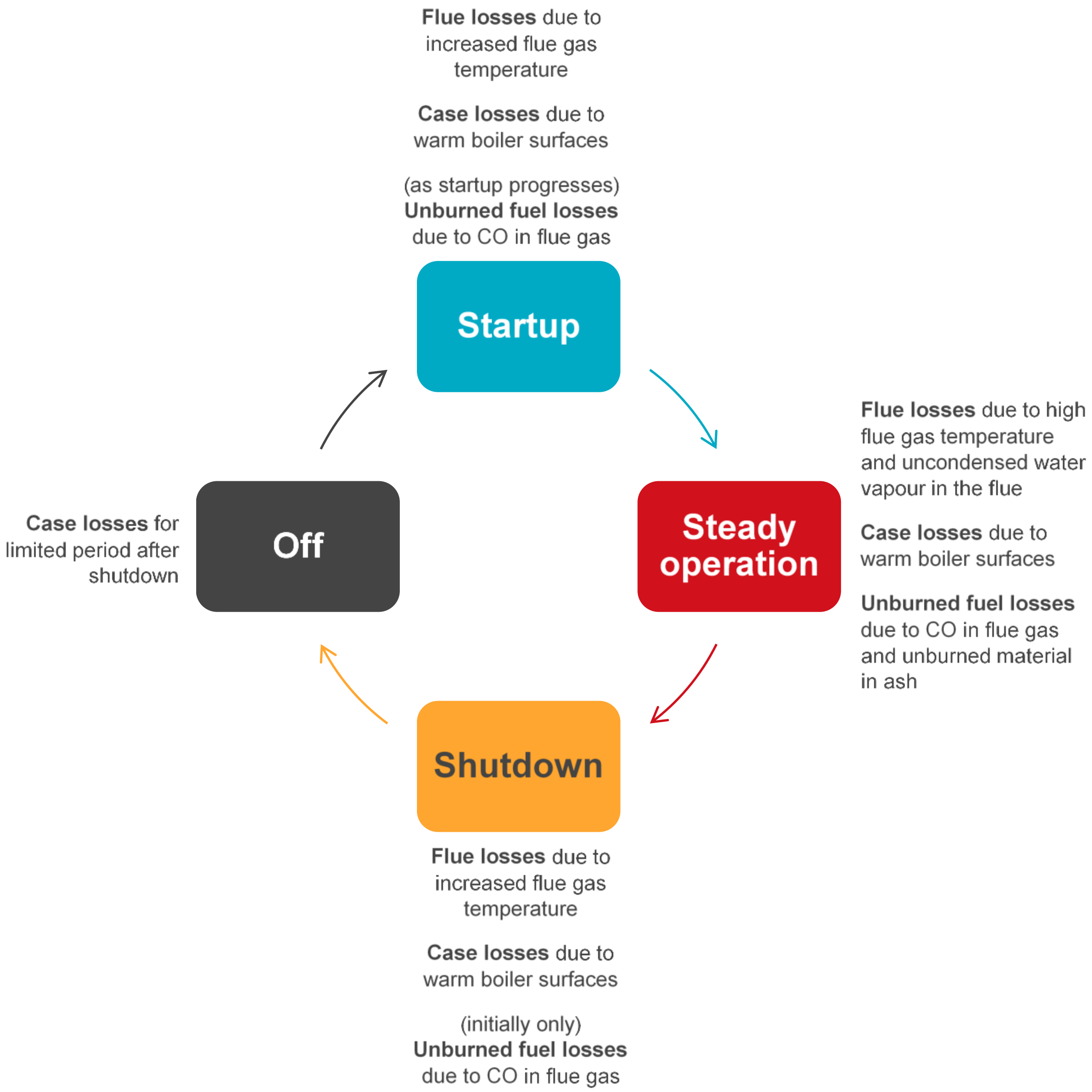

Figure 2: Outline of calculation to determine efficiency of boiler by indirect (losses) method

The efficiency was calculated on both a net and gross basis, by choosing the appropriate equations from BS 845 [1] and the appropriate net or gross calorific values. Where equations required dry CO_2 concentration, this was calculated from the wet O_2 concentration measured at the site, with the equation:

$$V_{CO2} = V_{CO2,sto}\left(1 - \frac{1.11V_{O2,wet}}{20.9}\right)$$

(where V_{CO2} is the dry volume fraction of carbon dioxide in the flue gas, $V_{CO2,sto}$ is the stoichiometric volume fraction of carbon dioxide based on wood fuel analysis, and $V_{O2,wet}$ is the wet volume fraction of oxygen in the flue gas)

The equations used to calculate the losses during phase 3 (steady operation) result in relative losses, rather than absolute losses. To calculate the absolute losses:

- The relative losses were calculated at one minute intervals. These short periods are pseudo-steady state
- The instantaneous output from the boiler was estimated by redistributing the total heat output for that cycle[2] according to the reduction in oxygen from 20.9% (the oxygen in air). The more the oxygen was reduced, the more heat attributed to that interval
- The absolute losses were calculated from the relative losses and instantaneous output with the equation:

$$\text{Absolute losses} = \frac{\text{Instantaneous output}}{1 - \text{Relative losses}} - \text{Instantaneous output}$$

[2] Depending on the heat meter installed and the precision of that heat meter, increases in the readings of cumulative heat delivered may have occurred many minutes or even hours apart. Therefore, a method was required for calculating far more precisely when that energy had been released.

Table 2: Efficiency calculation – calculation of losses

Phase of operation	Type of loss	Method of calculation
Phase 1: Off	Case loss	After a shutdown, there is an assumed[1] case loss in kW of: $0.01Q_{ro}$ This decays exponentially with a half-life in hours of: $0.01Q_{ro}$ lasting for a maximum time in hours of: $0.05Q_{ro}$
Phase 2: Startup	Flue loss	For the duration of the period there is an assumed[1] air flow through the boiler in kg/h of: $M_{air} = 2.5Q_{ro}$ The losses due to this air flow are calculated in kW as follows: $M_{air}\, c_{air}\, (T_{flue} - T_{air})$
	Case loss	Assumed[1] case loss in kW of: $0.01Q_{ro}$
	Unburned fuel loss	For the last quarter of the startup period, there are assumed[1] CO losses in kW of: $W_{CO}\, M_{air}\, Q_{CO}$ Values for W_{CO} are given in Table 3
Phase 3: Steady operation	Flue loss	Equations L1 and L2 from BS 845 [1], with the values from the site's fuel analysis
	Case loss	Assumed[1] case loss in kW of: $0.01Q_{ro}$
	Unburned fuel loss	Equation L3 from BS 845 [1], with K1=69.2 and a value of V_{CO} selected from Table 3 Plus an assumed[1] ash loss of 0.2%
Phase 4: Shutdown	Flue loss	For the duration of the period there is an assumed[1] air flow through the boiler in kg/h of: $M_{air} = 2.5Q_{ro}$ The losses due to this air flow are calculated in kW as follows: $M_{air}\, c_{air}\, (T_{flue} - T_{air})$
	Case loss	Assumed[1] case loss in kW of: $0.01Q_{ro}$
	Unburned fuel loss	For the first three quarters of the shutdown period, there are assumed[1] CO losses in kW of: $W_{CO}\, M_{air}\, Q_{CO}$ Values for W_{CO} are given in Table 3

Key:
Q_{ro} *is the rated output of the boiler in kW*
c_{air} *is the specific heat capacity of air in kWh/kgK*
T_{air} *is the boiler house air temperature in °C*
W_{CO} *is the weight fraction of CO in the flue*
M_{air} *is the mass flow rate of air into the boiler in kg/h*
T_{flue} *is the flue gas temperature in °C*
V_{CO} *is the volume fraction of CO in the flue*
Q_{CO} *is the calorific value of CO in kWh/kg*

Table 3: Efficiency calculation – assumed[1] values for W_{CO} *and* V_{CO}

Phase	Value[3]	Fuel type		
		Wood chip	Wood pellet	Wood log
Phase 2: Startup	W_{CO}	0.002 (~2000ppm)	0.002 (~2000ppm)	0.005 (~5000ppm)
Phase 3: Steady operation	V_{CO}	0.0002 (200ppm)	0.0001 (100ppm)	0.0001 (1000ppm)
Phase 4: Shutdown	W_{CO}	0.0005 (~5000ppm)	0.0001 (~1000ppm)	0.0005 (~5000ppm)

[3] During start and shutdown, it is assumed the molecular weight of the gases in the flue is approximately equal to the molecular weight of air. Consequently, the weight fraction of CO is approximately equal to the volume fraction of CO.

4 References

[1] "Methods for Assessing thermal performance of boilers for steam, hot water and high temperature heat transfer fluids — Part 1: Concise procedure," BS 845-1:1987 + A1.

[2] "Roomheaters fired by solid fuel — Requirements and test methods," BS EN 13240:2001 + A2:2004.

[3] "Water-tube boilers and auxiliary installations — Part 15: Acceptance tests," BS EN 12952-15:2003.

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