Determination of annual efficiency and emission factors of small-scale biomass boiler

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Abstract

In the last decades certification tests of small-scale biomass systems have impressively shown the improvement of the state of the art. Though, steady state measurements represent results only for optimal operation. In practice results differ due to varying operating conditions. Therefore, of a test stand measurement method to derive realistic annual system efficiencies and emission factors is developed. The method includes a heat loss model for thermal storages too. It can be used to test automatically fed biomass boiler, manually loaded biomass boilers and boiler / heat accumulator combinations. For the evaluation of the measurement data a calculation method based on mass flows was developed. The results of our experiments show that the newly developed method is a good tool to evaluate small-scale biomass boilers. With this method an easy and reliable instrument to determine annual system efficiencies and emission factors for realistic boiler operation is provided. The application of the method will prove that modern small-scale biomass combustion systems have the potential to significantly contribute to the reduction of air pollutants and to increase overall energy system efficiency.

1. Introduction

Annual system efficiencies and emission factors are important indicators to classify biomass boilers according to the EuP Directive (2005/32/EC) [1]. Currently used data for small-scale biomass combustion systems are older than 10 years as it is difficult and expensive to determine them under real conditions.

Small-scale (< 400 kW) wood boilers in general and – since 1996 – wood pellet boilers in particular have undergone significant technological improvements. The common assessment method is EN 303-5 [2], which determines efficiency and emissions under steady state operating conditions at full load and minimum load. Except for the introduction of flue gas condensation boilers a maturation of the technologies on a virtually high quality level can be recognized based on the type testing results according to EN 303-5 (see Figure 1).
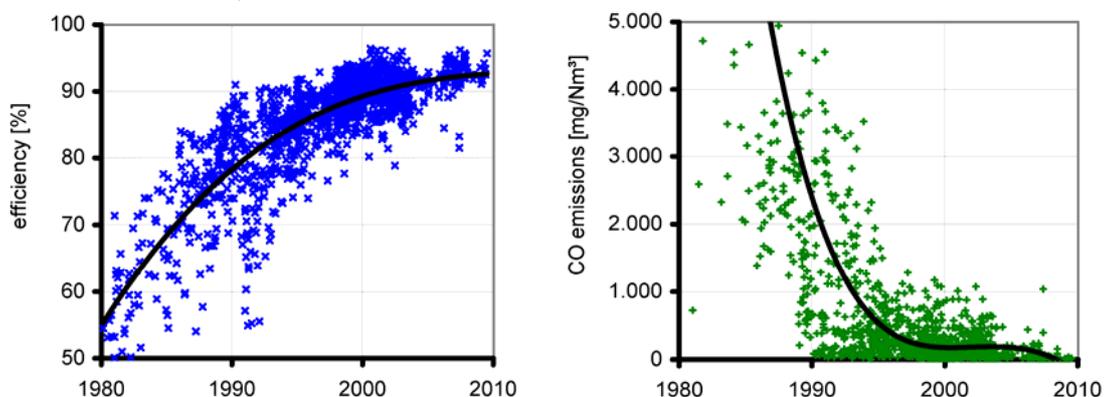

Figure 1: Efficiency and CO emissions of small-scale wood boilers (data source: FJ-BLT, compilation: BE2020+)

The weak points of the assessment according to EN 303-5 are:
• Efficiency and emissions are determined under steady state conditions. Therefore they are not representative for real life operating conditions and may raise false expectations among customers.

- Steady state comparisons do not sufficiently allow the differentiation between excellent, good and poor technologies anymore. This differentiation arises in unsteady or transient operating conditions (start-up, load change, shut down).

2. Objectives

In order to provide opportunities for an additional qualitative differentiation of small-scale wood combustion boilers, a method for the determination of annual efficiency and emission factors on the test bench is developed. The vision for such a method is to gain an equivalent of a roller bench test common in automotive industry to determine fuel consumption and CO_2 emissions. To do so, a test cycle for a reference system configuration, the respective measurement procedures and the respective analytical procedures are developed and assessed.

3. Method

Since annual efficiencies and emission factors for pollutants of biomass boilers can only be quantified in long term field tests, simplified methods for the determination are already presented in literature.
DIN 4702-8 [3] describes a method based on 6 steady state measurements at different load levels. The Concise Cycle Test [4] for combined biomass and solar heating systems uses a dynamic measurement during 12 days, each representing a month, and a simulation of the boiler controller behaviour in a second evaluation step. Many individual tests and information that is difficult to obtain are required for these tests. Therefore both methods are not widely distributed and used mainly in research.
The vision was the development of a "roller test stand" for biomass boilers, more precisely a method to determine annual efficiency and emission factors by measurement under dynamic conditions on a test bench. The procedure should require a minimum of expenses additional to the type test and has to be done with the measurement instruments and on the test bench also used for tests according to EN 303-5.
Test object of this method is the boiler only. To get comparable results it is installed in a virtual house which is emulated by the heat intake. The heat consumption is scaled linearly by the nominal heat output of the tested boiler. An optional heat storage system is taken into account as part of the evaluation.

Figure 2: System boundaries for the developed method

The interpretation of the measurement values is more extensive than in EN 303-5, as the evaluation has to take into account the amount of flue gas. Therefore a software application has been developed which calculates emission factors as sums of pollutant load. The efficiency is determined directly.

4. Test cycle

There are two common types of boiler installations. Biomass boilers which are directly connected to the room heating system have to run nearly the whole day and adjust their heat output to the actual demand. Boiler installations containing a heat accumulator are operated at nominal load whereas the operation time depends on the size of the storage tank. Therefore two test cycles are necessary, one for modulating operation and the other one for full load operation.

4.1 Modulating boiler operation

The boiler has to react on the heat demand of the building, the test cycle is a heat demand curve. To make the test results comparable, but also adaptable to different heat demands in different climate regions, a "synthetic" test cycle was created, based on typical daily load curves and on climate data. According to VDI 4655 [5] (which is based on measurements on gas furnaces) 5 reference day curves were defined. They relate to the heat demand for room-heating and hot water generation of an average modern house in the sub-alpine area equipped with a pellet boiler. A yearly operating time of 2000 full load hours and a proper hydraulic installation of the heating system are assumed.

Code	Type of day	Days per year	Room heating kWh/d	Water heating kWh/d
ÜxH	Transition period, clear	52	26,7	7,9
ÜxB	Transition period, cloudy	82	36,1	7,8
SxX	Summer	86	0,0	6,1
WxH	Winter, clear	35	90,9	10,2
WxB	Winter, cloudy	110	86,8	9,0

Table 1: Load profiles for biomass boiler, amount per year and heat demand

The 5 continuous reference day load profiles are reduced to 6 load levels according to DIN 4702-8. Weighted with the days per year (see Table 1) they are merged to a sum curve. This average day load profile for a year is further reduced to 8 hours of operation to match with the work schedule of testing institutes [6].
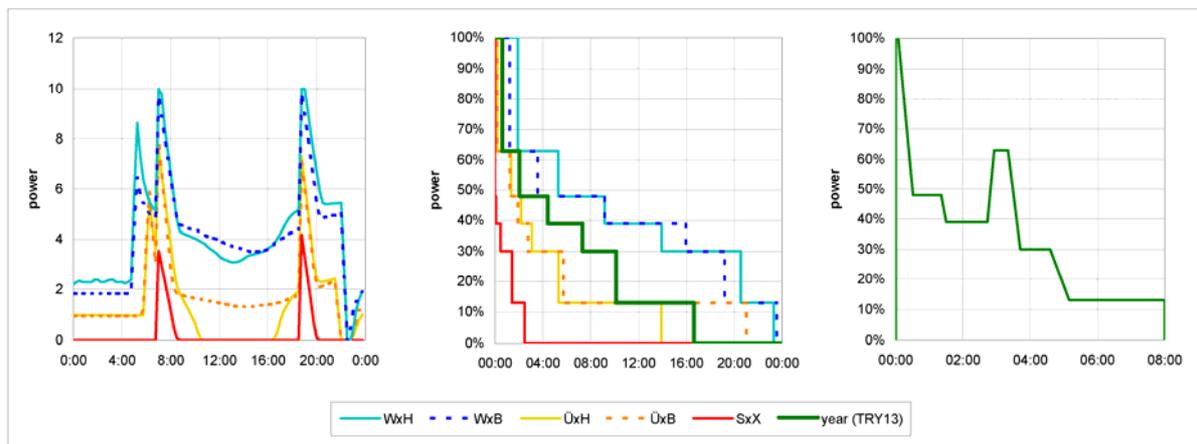
Figure 2: Conceptual design of the test cycle

The test cycle is designed for all kinds of solid fuel boilers in residential homes. In the following Table 2 specifications on the boiler load, load change and the duration of these steps is given.

	Constant load	Load change	Constant load	Load change	Constant load	Load change
Boiler load (%)	100	100 ► 48	48	48 ► 39	39	39 ► 63
Duration	00:04:52	00:26:00	00:50:15	00:09:00	01:13:44	00:12:00
Boiler load (%)	63	63 ► 30	30	30 ► 13	13	0
Duration	00:24:38	00:22:00	00:53:14	00:34:00	02:50:17	00:00:00

Table 2: Duration of all test cycle steps

4.2 Nominal power operation
In case of hydraulic systems with thermally stratified tanks the boiler is usually operated at nominal power. The storage is calculated. Test object is the boiler only. This procedure can be combined with the full load test according to EN 303-5 with only minor effort.

5. Measurement

5.1 Test bench setup
The experimental setup for this test is an advanced version of the configuration in EN 303-5. The measurement methods and the positions of measuring points are consistent to make the procedures applicable in the frame of existing accreditations of testing institutes.
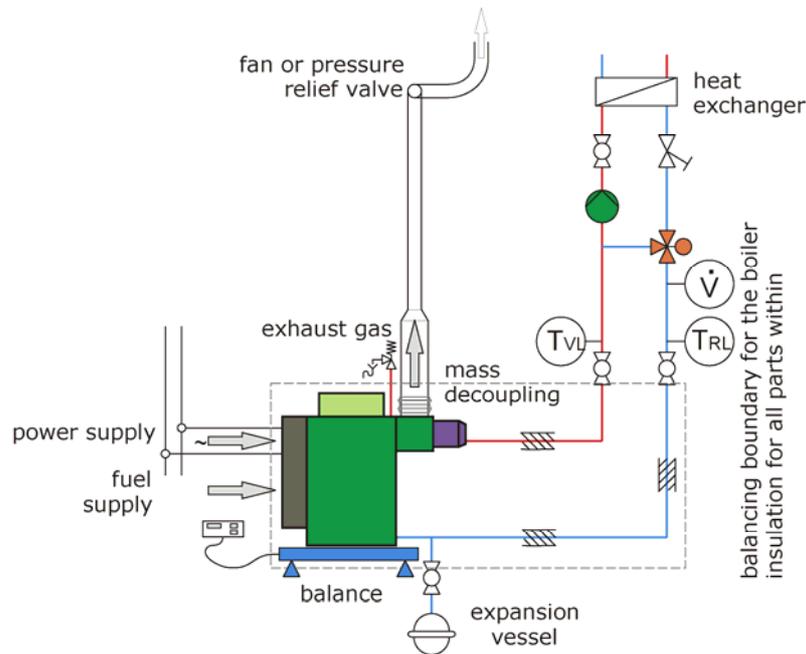
Figure 3: Experimental setup

Differences are the need for continuous determination of flue gas humidity and flow rate. Sensors for both should be available in test institutes, as they are required for dust measurement. Unlike EN 303-5 all phases of boiler operation are monitored and the data logged to file. This includes boiler start and stop, operation at constant and changing load and the cooling down at the end of the test run.
During the test cycle the flow temperature of the boiler is not stable. To control the heat demand exactly the installation of an automated heat intake on the test bench is suggested.

5.2 Test procedure
The test procedure consists of two single test runs, one at full load and the other one using the defined unsteady load cycle. In both tests the boiler set temperature should be in the range of 70 to 80 °C. If there is a return flow buster installed, it should be set to 55°C.
Start and end conditions have to be equal to allow mass and energy balance over the whole test run. Therefore the boiler is heated up to 45 °C before the test run and adjusted to the same temperature afterwards using an external heat source/sink. If the furnace is not set to 45°C directly after the standby test phase, the remaining energy is calculated using average boiler temperature and mass of water and steel of the boiler.
Detailed information on the test run and all steps is presented in Figure 4 and Table 3, the described procedures proceed between time steps.
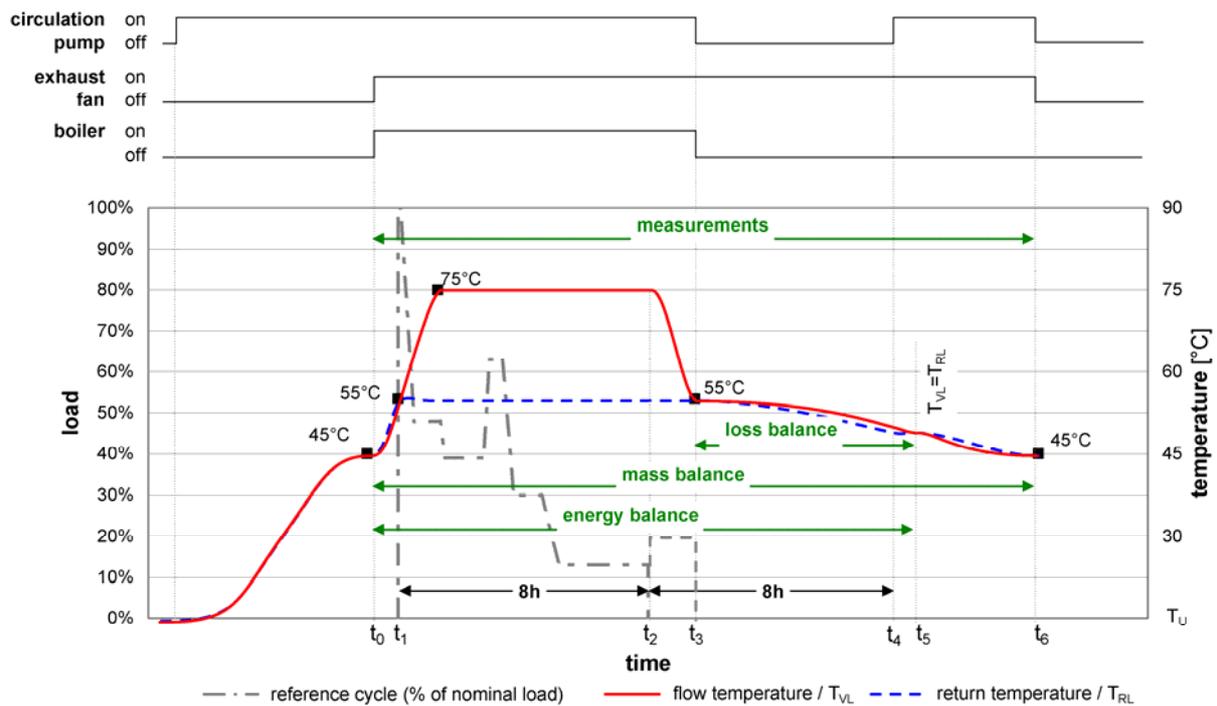
Figure 4: Operation sequence for the test run with load cycle

Time step	Point definition	Procedure
t_0	Boiler at 45°C	External warm up of boiler
		Start boiler Heat up boiler
t_1	Flow temperature > return flow temperature	
		Load cycle or full load test
t_2	Boiler operation finished	
		Remove useable heat at 20% load
t_3	Flow temperature = return flow temperature	
		Cool down for 8 hours (from t2)
t_4	Standby heat loss test finished	
		Determine remaining heat in boiler
t_5	flow temperature = return flow temperature	
		External warm up or cool down
t_6	Boiler at 45°C	
		Test finished

Table 3: Definition of steps in the test run

6. Evaluation

An automated, fast and easy to use software has been written for MS Excel to evaluate the measured data. It is specially designed for unsteady measurements and includes the interpolation of data points to allow the evaluation of exact time intervals.

The evaluation is divided in a section for the load cycle test and one for full load operation. Due to the fact that the load profile is an average over a whole year the measured efficiency in this test is the annual efficiency. The data of the test at nominal power is used to calculate the efficiency of boiler operation with a heat storage tank. Since the boiler operation depends on the storage volume, the

period of steady operation during the test is scaled linearly within the calculation. To estimate the annual efficiency the heat loss of the storage system has to be taken into account too.
After entering the necessary data for test setup, boiler and fuel into the Excel sheet the evaluation of each test run takes place in 4 steps:

- Import of measured data into file
- Calculation of energy and mass flows at each time step
- Balance of evaluation periods
- Calculation of efficiency and emission factors

The main result is the annual efficiency based on fuel and auxiliary electric energy demand. It is calculated using the direct method based on the heat output into the water by formula (1).

$$\eta = \frac{E_{heat}}{E_{fuel} + E_{electric}} \cdot 100 \quad [\%] \tag{1}$$

In case of an installation with a storage tank the heat loss off the storage is calculated according to the formula for daily heat losses in the OIB Guide [7]:

$$100 - \eta_{Puffer} = \frac{365 \cdot \left(0,5 + 0,25 \cdot V_{Puffer}^{0,4}\right)}{2000 \cdot P_N} \cdot 100 \quad [\%] \tag{2}$$

To calculate emission factors for carbon monoxide, nitrogen oxides, sulphur dioxide, organic carbon and dust the flow rate of the flue gas has to be taken into account as stated in formula (3). The result is related to the fuel energy input.

$$f_{CO} = \frac{\sum \dot{V} \cdot (1 - [H_2O]) \cdot [CO] \cdot \rho_{CO}}{E_{fuel}} \cdot 10^{12} \quad [kg/TJ] \tag{3}$$

Other important parameters, e.g. electrical energy demand for operation, are calculated too.

7. Results of experimental work
Few test runs were carried out with pellets, wood chip and log wood boiler. All systems were tested using the method described in this paper. The test at nominal power was evaluated according to EN 303-5 too. The following tables 4 and 5 show exemplary the test results from an older and a new pellet boiler. Efficiencies and emission factors were determined with both methods. In the case of heat storage the tank losses are calculated for a volume of 50 litres per kW nominal power of the boiler.

	EN 303-5	Test cycle	Heat storage	
efficiency	84,7	75,2	73,7	[%]
CO	64,8	289,1	168,1	[kg/TJ]
NO$_x$	105,8	105,2	125,4	[kg/TJ]
org. C	2,1	15,7	11,9	[kg/TJ]
PM	10	20	14	[kg/TJ]

Table 4: Results of an older, widely used pellet boiler model

	EN 303-5	Test cycle	Heat storage	
efficiency	89,7	85,6	77,6	[%]
CO	3,2	416,9	62,9	[kg/TJ]
NO$_x$	76,9	57,9	98,4	[kg/TJ]
org. C	0,3	10,6	1,1	[kg/TJ]
PM	11	10	11	[kg/TJ]

Table 5: Results of a new product on market

As expected the determined annual efficiencies are 5 to 10 % lower than values obtained by the type test. The average annual system efficiency of the tested boiler is approximately 77%, which is comparable to published results from field tests [8], [9]. Both boilers show a slightly better efficiency in modulated operation than operated with heat storage because of the additional heat loss of the buffer tank.

The measurements show that the emissions of unburned substances (carbon monoxide and organic carbon) are up to 6 times higher in modulated operation compared to the results of the full load steady state type tests, whereas nitrogen oxide emissions are at similar levels. The determined emission factors are still below the Austrian emission limits. This fact serves as proof for the high development level of Austrian biomass boilers.

The derived annual emission factors are comparable to values from field tests. There is still a difference to published emission factors [10] caused by the small amount of tested boilers.

8. Summary and conclusions

The newly developed method shall provide an easily and reliably applicable method in the short to medium term allowing an assessment of boilers under (more) realistic operating conditions additional to EN 303-5. With the method an aid for the further improvement of technologies and their integration into heating systems is given to technology providers.

The application of the method will prove that modern small-scale biomass combustion systems have the potential to contribute significantly to the reduction of air pollutants and to increase the overall energy system efficiencies. Customers benefit from a more realistic assessment of different technologies and products and potentially lower fuel consumption and respectively lower expenses. Society profits from significantly increased energy efficiencies and from significantly decreased emissions of greenhouse gases and air pollutants.

9. Acknowledgement

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