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Operational Testing of a Solid Fuel Boiler with Different Fuels

Norbert Érces * and László Kajtár

Department of Sociology and Communication, Faculty of Economic and Social Sciences, Budapest University of Technology and Economics, Műegyetem rkp 3, 1111 Budapest, Hungary; kajtar@epget.bme.hu

* Correspondence: erces@epget.bme.hu

Abstract: In the course of our investigations, we burned high-quality logs as well as wood briquettes in a conventional, manually fed mixed-fired boiler, under different operating parameters. Based on the evaluation of the measurement results, there is a significant difference in terms of recoverable energy and carbon monoxide emissions for the two fuels burned in the same device at different air supply parameters. Studies have shown that a constantly changing position of the draft control door has an adverse effect on carbon monoxide emissions as well as the energy produced. In the case of a constant draft door setting, the preset values that can be considered ideal for energy yield and CO emissions were determined for the two fuel types. The obtained results were compared with the requirements according to the MSZ EN 303-5 standard.

Keywords: biomass; CO emission; air pollutant; biomass boiler; flue gas

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1. Introduction

Solid fuel boilers play a key role in pollution across Europe. Although good quality wood burning can be considered as an environmentally conscious way of producing heat, appropriate emission indicators can only be obtained by using a combination of high-quality fuels burned in good quality boilers. As a result of the fragmentation of the economic and infrastructural development characteristics of each country, the use of modern combustion equipment characterizes heating production based on a large number of solid fuel boilers to a small extent. Outdoor air pollution causes about 400,000 premature deaths a year, as well as an even higher number of serious illnesses across Europe [1,2]. One of the major emitters of air pollution is household energy consumption. The most commonly used heating energy sources are gas burning, as well as wood burning. The distribution of fuel use without district heating is shown in Table 1.

From the 1990s to the present day, the combined use of gas and solid fuel is very common in the single-family zone. In addition to the above table, in proportions in Hungary, about 45% of dwellings use only natural gas, and 21% use solid fuel (wood, coal, or a mixture thereof). A combination of gas heating and a solid fuel boiler is used in 15% of apartments [3].

Households using solid fuel are highly concentrated in terms of territory, where it is worth mentioning that the distribution is strongly dependent on the socio–economic and infrastructural development of the given region. In 19 districts, more than 50% of the dwellings are exclusively heated by wood. In further 22 districts, 75% of the dwellings are at least partly heated by wood. Although wood burning is a CO2-neutral burn with renewable energy, it emits significant emissions under inappropriate conditions [2,4].

For each solid fuel appliance, the standard MSZ EN 303-5 defines clear requirements in terms of efficiency and emissions (among other requirements), but the fulfillment of these parameters is true when determined, specific laboratory conditions, professional operation, and last but not least, strict fuel quality requirements are provided and met. This follows from the socio–economic and infrastructural dependence mentioned above that the emissions from solid fuels mainly depend on the operating equipment and the quality of the fuel burned in the equipment. Based on Danish data from 2016, the specific particulate emissions of some heating modes are shown in Figure 1.

Table 1. Use of fuel in inhabited dwellings in Hungary (2011).

Fuel	Number of Dwellings (Thousands)	Proportion of Dwellings as a % of Total Inhabited Dwellings
Gas	2388	61.96
Coal	113	2.93
Electricity	76	1.97
Oil fuel	1	0.03
Wood	1470	38.14
Solar energy	5	0.13
Geothermal energy	3	0.08
Pellets	2	0.05
Other renewable	3	0.08
Other fuel	4	0.10
All inhabited dwellings	3854	100.00

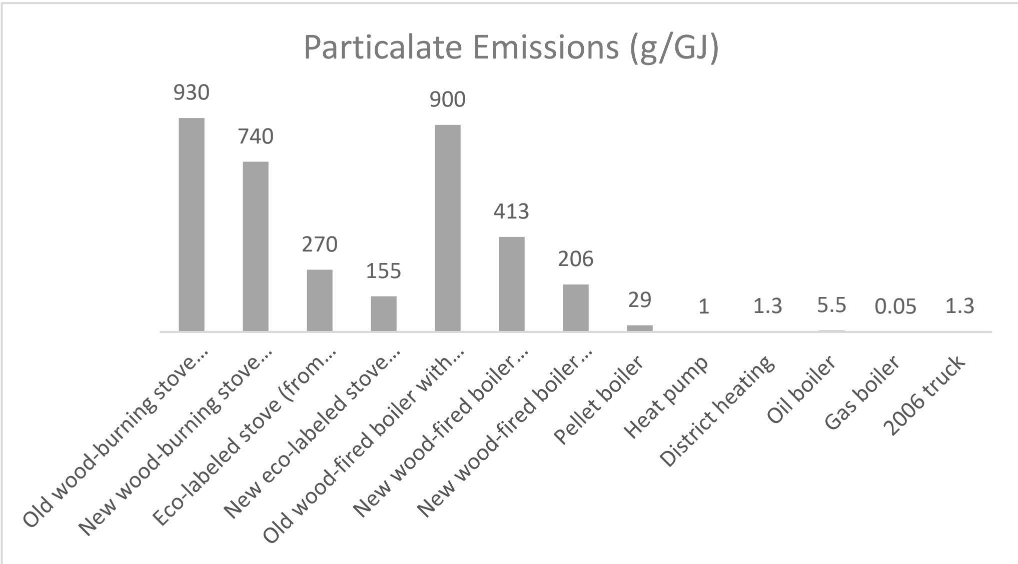

Figure 1. Particulate emissions of different heating methods in Denmark [1].

Based on Figure 1, it can be observed that solid fuel appliances, which can be considered obsolete, have outstanding emission values. By comparison, an old wood-burning stove at the end of the line emits 715 times more pollutants than the PM2.5 dust emission of a more than ten-year-old truck; however, even the environmentally conscious pellet boiler gives more than 22 times the value [1,5].

Several international studies have been conducted on the combustion of modern pellets or wood chips for boilers of household size, or with a nominal power of up to 50 kW. In the case of two types of pine-based woodchips, it was shown that increasing the excess air factor reduced the emission of pollutants, but also reduced the maximum extractable performance [6]. When using pellet fuel, the recoverable power is higher and the series of requirements according to EN 14,785 can be met [7].

Taking into account the socio–economic and infrastructural development of the Hungarian regions, as well as the reduction in the necessary environmental load, we examined a conventional, manually fed, household-sized solid-fired boiler in terms of extractable output and pollutant emissions.

2. Operational Characteristics

Even with conventional appliances, the amount of primary and secondary combustion air has a significant effect on the combustion processes in the boiler [8]. In the case of open heating appliances according to MSZ EN 303-5, the requirements according to EN 14,597 must be met:

- Equipped with a temperature controller,
- Equipped with safety temperature limiter.

The safety temperature limiter may be omitted if the device cannot be switched off and the excess heat energy can be dissipated in the form of steam due to the connection to the atmosphere. In most cases, manual dosing open heating appliances used in households are not connected to a heating buffer tank but operate with a temperature control valve [9]. The primary purpose of the temperature controller is to maximize the temperature of the heating medium produced by the boiler. During operation, a valve without auxiliary energy controls the opening angle of the draft control door, depending on the power that changes continuously during firing. Continuous intervention has a significant effect on the quality of the combustion process in the firebox, and thus on the emission of harmful substances.

In the course of our laboratory measurements, we examined the operating characteristics of a solid fuel boiler equipped with a temperature controller, as well as the operating parameters occurring during the firing of different fuel charges at specific draft control door opening angles.

3. Measurement Procedure

Prior to the actual measurements, a load was burned in the boiler to eliminate the errors from the cold start, to form suitable embers, and to warm up our system to operating temperature [10]. Our examined system operated on the basis of the arrangement shown in Figure 2. After preheating, 7.2 kg of fuel was uniformly loaded through the firebox door shown in the figure. During the tests, the total combustion period of the loaded fuel was monitored in each case. The measured parameters are shown in Table 2.

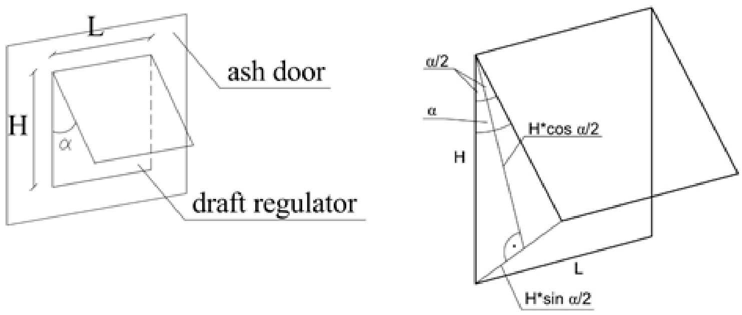

Figure 2. Geometrical parameterization of draft control door (*: multiplication).

Table 2. Measured parameters.

Sign of Measured Parameter	Unit	Name of Measured Parameter
O_2	%	Oxygen content of flue gas
CO_2	%	Carbon dioxide content of flue gas
CO	ppm	Carbon monoxide content of flue gas
NOx	ppm	Nitrogen oxide content of flue gas
SO_2	ppm	Sulfur dioxide content of flue gas
$\Delta p_{chimney}$	Pa	Chimney draft
t_{fg}	°C	Combustion product temperature
λ	-	Excess air factor
qA	%	Combustion product loss
$m_{víz}$	L/min	Heating medium mass flow
t_{fw}	°C	Flow temperature
t_r	°C	Returning medium temperature

Different operations were performed for the cases without a working draft regulator (temperature controller) and without a draft regulator with different fixed draft door settings, and the effect of different fuel loads was also measured for fixed primary air supply cases. In the various measurement studies the cases according to Table 3 were performed. In order to clearly define the opening of the draft control door of the device, a flow rate must be determined, which can be determined from the quotient of the free-flow cross section resulting from the opening of the door and the nominal free cross section, as shown in Figure 2. Figure 3 shows a schematic arrangement of the measuring station.

Table 3. Cases examined.

Fuel	Mass	Primary Air Control Door Operation	Notation
Wood	7.2 kg	with draft controller	1st case
		$C_{draft} = 0.093$ $C_{draft} = 0.275$ $C_{draft} = 0.440$	2nd case
Briquette	7 kg	$C_{draft} = 0.093$ $C_{draft} = 0.275$ $C_{draft} = 0.440$	3rd case

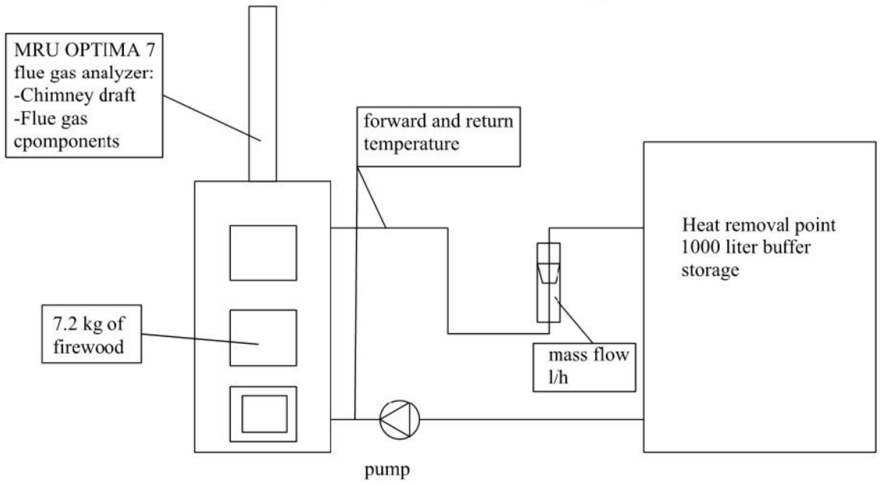

Figure 3. Schematic arrangement of measuring station.

General geometric definition of free-flow cross section:

$$A_{cs} = L \times \left(2 \times H \times \sin\frac{1}{2} \propto\right) + \left(H \times \sin\frac{1}{2} \propto\right) \times \left(H \times \cos\frac{1}{2} \propto\right)$$

From the quotient of the free-flow cross section and the nominal cross section, the flow rate for the draft control door can be determined:

$$C_{draft} = \frac{A_{cs}}{A_n}$$

where:

- C_{draft}—flow number,
- A_{cs}—the free-flow cross section,
- A_n—nominal flow cross section ($A_n = H \times L$).

In the case of the tested boiler:

- $H = 14$ cm,
- $L = 12$ cm.

4. Measurement Results

Among the measured parameters according to Table 2, the development of carbon monoxide emissions, which is of key importance according to the MSZ EN 303-5 standard, was included among the primary pollutant components to be examined. In addition to the evolution of emissions, our important goal was to be able to extract the highest possible energy yield from the device while reducing emissions.

4.1. Evaluation of Case 1

In case 1, according to Table 3, dry logs with a moisture content not exceeding 15% were burned while the primary air door of the boiler was moved by an automatic draft control device. According to the aforementioned MSZ EN 303-5 standard, a maximum permissible carbon monoxide emission of 5000 mg/m^3, which means 4000 ppm in the case of CO, is allowed for solid fuel equipment not exceeding 50 kW and equipped with an automatic dosing system. The determined volume ratio (ppm) is converted to a mass flow value (mg/m^3). The following values apply as a conversion factor for conversion from ppm to mg/m^3: f_{CO} = 1.25 [9]. Carbon monoxide emissions must be checked for the average value released during complete combustion. However, it is worth observing the evolution of CO released during the entire firing interval, as well as the recoverable power values shown in Figures 4 and 5.

In Figures 4 and 5, it can be observed that the automatic draft control door continuously reduces the flow rate in parallel with the increase in power (Q), and at the same time the CO emission also increases. As it can be observed, under the construction firing stage, Q increases, but CO decreases. At this interval, the system approaches the perfect combustion process, but at the same time, it reaches the set maximum temperature, which causes the draft regulator to close. When the load in the firebox enters the declining section, the control device begins to open the primary air door to maintain the temperature set on the draft regulator. The minimum flow rate of almost 25 min is due to the fact that, due to safe operation, a minimum amount of combustion air must be provided even in the event of a complete shutdown, which means a flow rate of 0.093 in this case. It can also be observed that in the initial, developing phase of combustion, the instantaneous CO emissions increase sharply at the same time as the draft control door is closed. For the entire firing time interval, the average CO emission was 5973 ppm, which is more than 1600 ppm higher than the limit allowed by the standard.

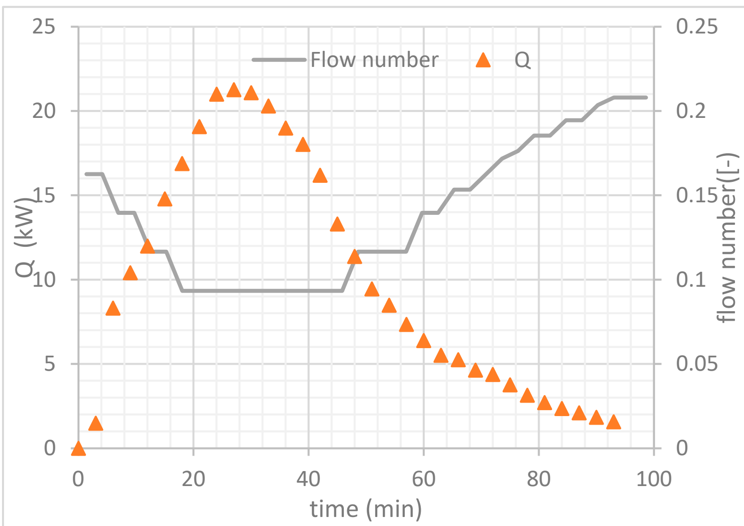

Figure 4. Development of Q at different flow rates over the whole period.

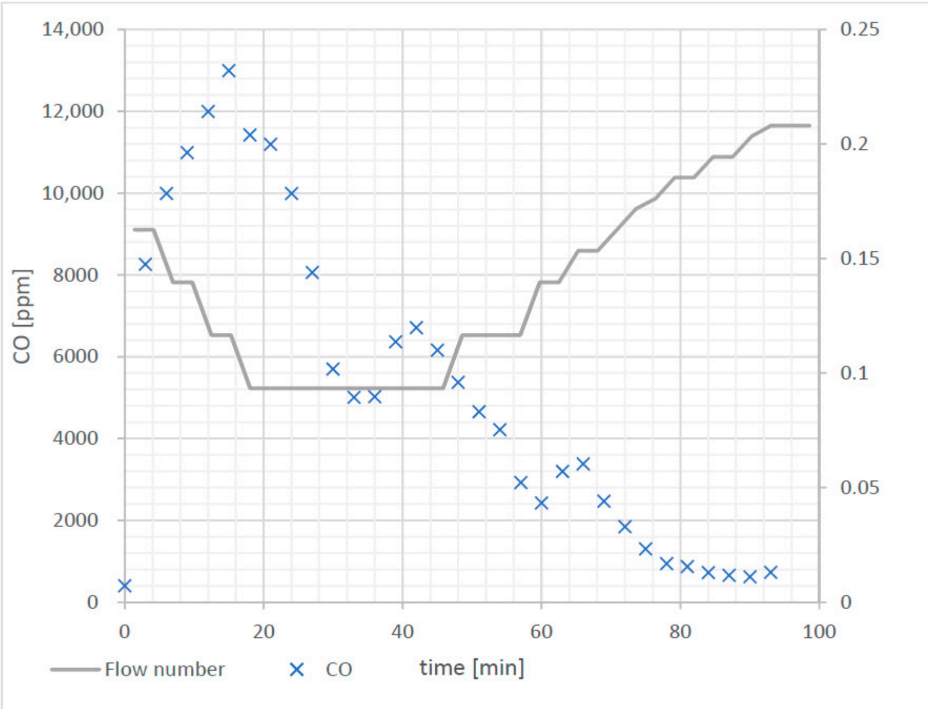

Figure 5. Development of CO at different flow rates over the whole period.

4.2. Evaluation of Case 2

It can be clearly seen from Figure 6 that with a constant high-flow rate, the firing process takes place in a short time, and the developing phase is followed by a rapid declining phase. In the case of an intermediate flow rate, the burn-out time increased by almost one hour, and the developing phase was characterized by a nearly constant peak power lasting 10 min. The declining phase was prolonged in time. With a low flow rate, the burn-out time also lengthens, but the maximum recoverable power is well below the value of the previous setting parameter. Compared to the recoverable power of Figure 4, the maximum recovered power was also higher. Figure 7 shows the carbon monoxide emission values for the entire combustion stage at the flow rates described above.

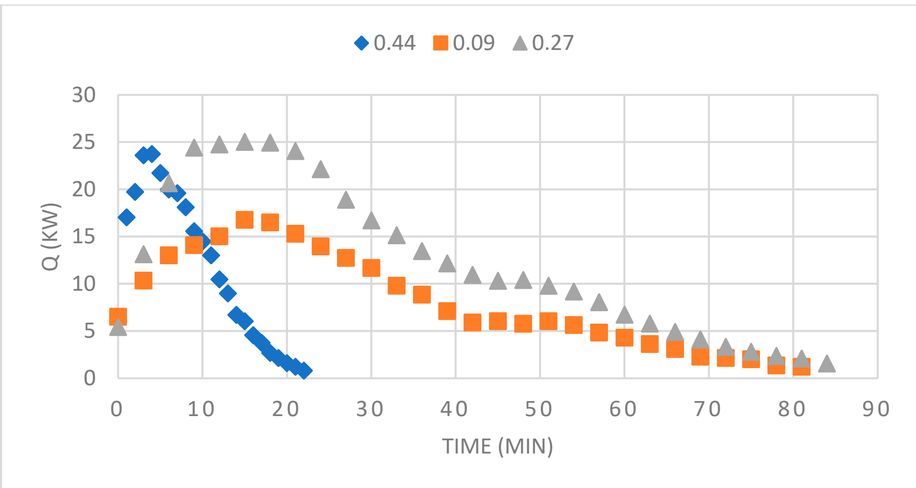

Figure 6. Evolution of the yielded power at different constant flow rates.

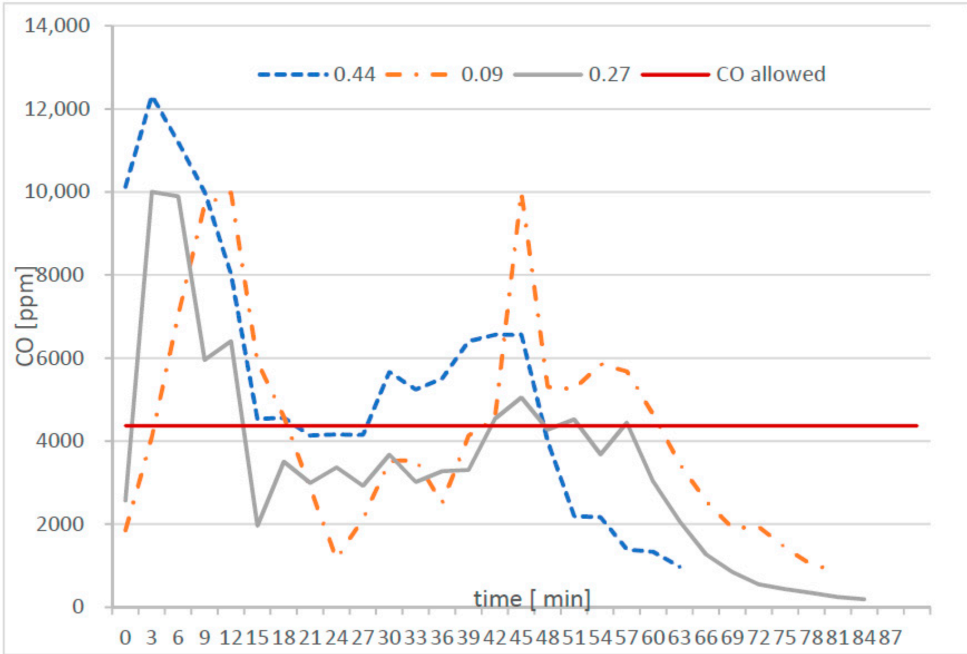

Figure 7. CO emission evolution for each flow rate.

The solid horizontal line indicates the permissible CO emission value according to the MSZ EN 303-5 standard. It can be observed that at the highest flow rate, the equipment operates above the permissible emission limit for almost the entire firing time. The air inlet resistance of the appliance is the lowest in this case, so the temperature of the flue gas, and at the same time, the draft in the chimney increase due to the rising temperature of the firebox. As a result of the combined effect of these phenomena, the amount of combustion air entering the firebox exceeds the amount required for ideal combustion, which results in poorer quality combustion and thus higher CO emissions. In the case of an intermediate draft control door position, a monotonically increasing CO evolution is observed in the developing phase of the firebox; however, after the maximum output and ideal combustion at this preset, CO formation drops drastically and briefly exceeds the standard limit in the burnout phase. At the lowest flow rate, the CO emission takes on a similar character to the previous setting value, but higher carbon monoxide emission values are typically observed over the time of total combustion.

The average CO emission values obtained for each flow rate are given in Table 4.

Table 4. Average CO emission.

Operation	CO_{avg} (ppm)	Average Difference CO_{max} (ppm)
Draft crtl.	5973.03	1606.96
C_{draft} = 0.09	4017.14	−348.93
C_{draft} = 0.27	3368.54	−997.53
C_{draft} = 0.44	4879.00	512.93

Thus, it can be stated that the automatic draft control is the most unfavorable in terms of carbon monoxide production, while the draft control door with a constant value of 0.27 flow rate is the most favorable. On average, a reduction in CO emissions of more than 2600 ppm can be achieved, which is almost half that of the permissible average CO emission limit.

In the case of Figure 8, the excess air factor can be observed under different drafts, and in the case of the draft regulator door. At 0.27 flow rates, it is experienced for the longest time, a nearly constant value, for which the control also reflects other parameters of firing.

At 0.09 and 0.44, the excess air factor values rise steeply, reflecting rapid burnout and a 21% increase in oxygen levels.

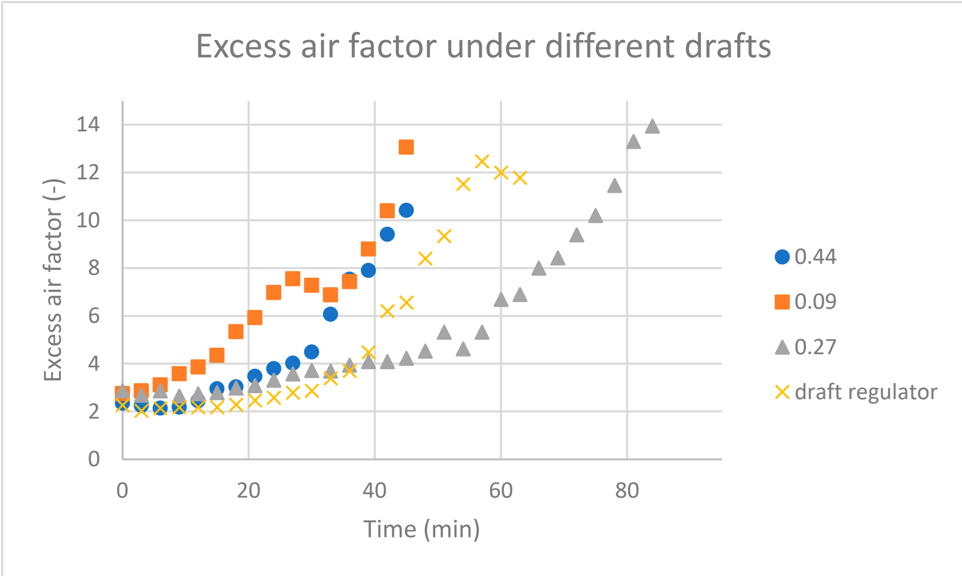

Figure 8. Excess air factor under different drafts.

4.3. Evaluation of Case 3

In case 3, the procedure was the same as before. For the three flow rates, the carbon monoxide emission and energy yield values shown in Figures 9 and 10 were obtained.

It can be observed that when burning with briquette fuel, the CO emissions can meet the maximum permissible average carbon monoxide emission limit value indicated by the dashed line at any preset value. In the case of briquettes, we obtained the lowest emission value with a flow rate of 0.27, which is almost half of the value compared to log firing. However, in the case of wood burning, the average energy yield is 17.1 kWh, compared to 14.5 kWh obtained for briquettes. However, in the case of briquettes in the operating state belonging to the maximum opening, a higher energy yield of 16.1 kWh was obtained, with a minimum increase in carbon monoxide emissions. An outstanding difference compared to log burning was that in the case of the CO emission limit value that is met even at the lowest flow rate, we achieved almost twice the energy yield in the case of briquettes.

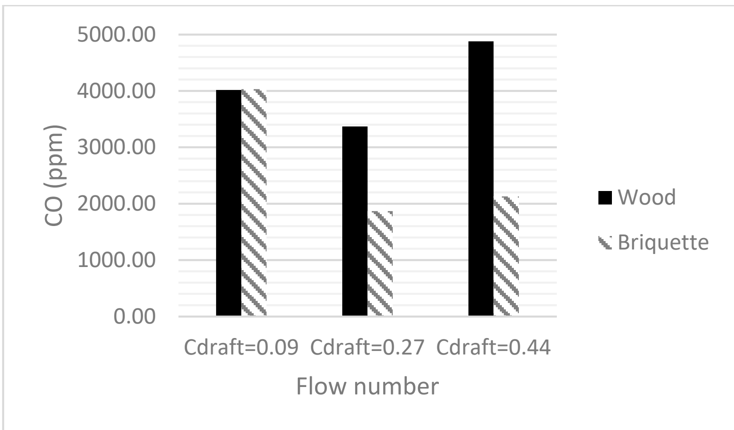

Figure 9. Average CO emissions for different fuels.

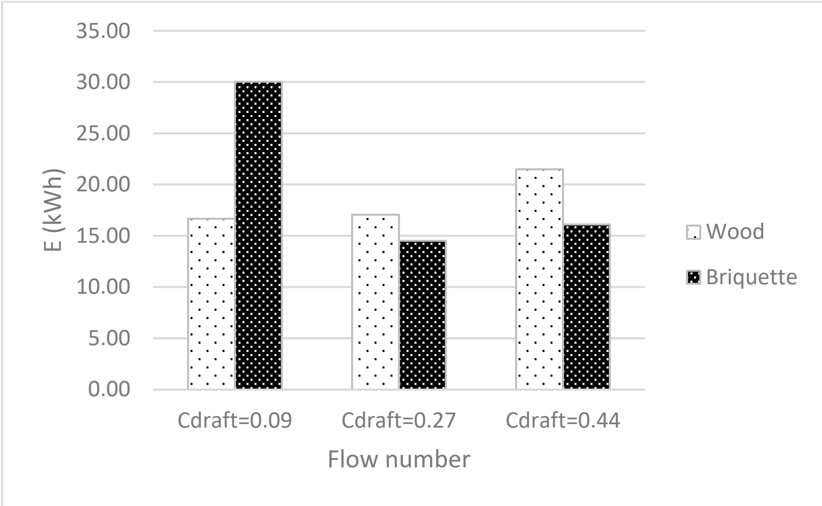

Figure 10. Average energy yields for different fuels.

5. Summary

In the course of our investigations, we performed the operational tests of a mixed-fired boiler for use in detached houses. During the tests, the flow rate characteristic of the draft control door was determined, with the help of which the operating parameters occurring during the operation of the device were measured at different presetting values. Seven separate cases were examined with two fuels. In the first case, the effect of a draft control door continuously controlled by the temperature limiter was analyzed in the case of log firing.

It can be stated from the measurement results that this type of regulation has an unfavorable effect on the carbon monoxide emission values of the device and on the recoverable energy yield, and therefore it cannot be considered as an optimal solution from the point of view of environmental protection and energy consumption.

Subsequently, in the case of logs and briquettes, the recoverable energy yield and the carbon monoxide emission were examined at three different constant flow rates. We found that, with the exception of one case, the CO emission limits specified in the relevant standard for a permanent draft control door can be met at a higher energy yield than in the case of continuous draft control.

In the case of log burning, higher CO emissions were achieved with all tested presets than in the case of briquette burning. When burning briquettes, we obtain the highest energy yield with a low flow rate and carbon monoxide emissions within the limit value. The effect of the draft regulator on dust forms a further part of our study, which is one of the main pollutants in solid fuel equipment. It is more technically complicated due to the difficult implementation of isokinetic sampling.

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