Real Operating Parameters of Bioethanol Burners in Terms of Heat Output

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ABSTRACT: The aim of this study was to determine the operating parameters of bioethanol burners used in the so-called bioethanol fireplaces, mainly in terms of their actual heat output. The method used to determine the actual heat output was designed considering procedures from the standard EN 16647 fireplaces for liquid fuel. Experiments were carried out on eight different types of burners with two different types of fuels. The measurements demonstrated a difference of up to 19% in the maximal heat output among individual fuels and a difference of up to 16% in the average heat output when comparing identical burners over approximately 60 min of operation. The average heat outputs of the burners during the measurements reached approximately 41−62% of the heat output declared by the manufacturers. The measured values were used to create graphs of the dependency of the burner opening size on its average heat output based on the fuel type. Two-chambered burners reached a higher average heat output than single-chambered burners with the same burner opening area of above ∼6000 mm². The positions of the regulation damper (75 and 50%) increased the burning time by 21 and 86%, respectively.

1. INTRODUCTION

While building or reconstructing a house or an apartment, the method of ensuring the necessary amount of heat to maintain a comfortable ambient temperature is one of the most important areas. Because the construction of low-energy and passive houses with steadily decreasing heat consumption is becoming increasingly common, customers are also becoming more aware of equipment with relatively low heat output. Of the representatives of this heat source category is the so-called bioethanol fireplaces. They are combustion appliances composed of two main parts, the fireplace body and the burner. The whole installation consists of one or more burners placed in the fireplace body. The fireplace body can be constructed as freestanding, wall-mounted, built-in (to the wall), or table. The fireplace body usually has only a decorative function; however, in the case of appropriate construction, it can accumulate part of the heat released from the combustion process.¹

The fuel used for this type of appliance is called bioethanol (renewable source of energy).

Bioethanol fireplaces have been available in the market for more than 10 years, and they have mainly been considered as design elements in houses. However, because of the non-negligible heat output of the burners (on the order of kW), which can cover a significant part of house heat losses, especially in the case of low energy demand houses, they can be classified into the category of heat sources together with conventional stoves and others.

Earlier studies regarding bioethanol fireplaces examined these appliances in terms of the safety of their operation in connection with possible accidents resulting in burns to people.²,³

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According to operating manuals, the fuel for bioethanol fireplaces is pure (denatured) ethanol. Ethanol combustion is a complicated process that can occur in different chemical reactions, as described in the research of Millán-Merino et al.\textsuperscript{4,5} Therefore, the combustion products of complete combustion are CO\textsubscript{2} and H\textsubscript{2}O. In the case of an incomplete combustion process (caused, e.g., by an inappropriate construction of the fireplace body from the amount of combustion air point of view), products from incomplete combustion (e.g., CO and OGC) can occur in the flue gas.

Substances caused by a complete combustion process (CO\textsubscript{2} and H\textsubscript{2}O) occur in home interiors naturally. The main production of CO\textsubscript{2} in homes results from the breathing of people and animals. Previous studies focused on the quality changes of unventilated indoor environments during the operation of bioethanol fireplaces in terms of volume concentration of pollutants arising from the combustion of ethanol.\textsuperscript{6,7} The results showed a significant impact, for example, increases in the volume concentrations of CO\textsubscript{2}, CO, and OGC up to values that can influence human health.\textsuperscript{8,9}

From the point of view of ethanol burning safety, there are studies describing the parameters of energy balance (e.g., mass loss rate (g/s) and heat release rate (kW)) based on pool fire testing. The methodology and equipment of these measurements are designed primarily for fire safety description and are unrelated to the possibility of heating houses by open fire from ethanol burning in small-scale bioethanol burners.\textsuperscript{10−12}

A previous study showed the possibility of a bioethanol–water mixture as a suitable fuel for cooking in developing countries such as Madagascar. For this purpose, a special stove was designed, manufactured, and tested with satisfactory results of thermal efficiency, safety, and other parameters.\textsuperscript{13} The actual operating parameters (especially the behavior of heat output over time) of the heat source for bioethanol fireplaces have not been examined yet.

Because of the principle of function, a manually filled bioethanol fireplace cannot deliver heat over a long period because it is forbidden to add fuel to a burner during its operation or to a burner that has not cooled down (the time before it is possible to refill the fuel and start a new operating cycle after the previous one is defined in the manual). This means that these fireplaces cannot be comfortably used as a primary heat source. However, they are commonly recommended by project architects as an alternative to typical solid fuel fireplaces for houses with very low heat losses (especially for houses with a recuperative air exchange unit, which can ensure sufficient air exchange in the room). For this reason, it is essential to know the mentioned operating parameters to prevent undesirable local overheating of rooms. In the case where a bioethanol fireplace is installed in a house with higher heat losses as an alternative to a local solid fuel heating appliance, it is also essential to know its operating parameters to comfortably meet the heat requirement in the given space.\textsuperscript{14}

Unlike standard combustion appliances, appliances of this kind do not require any certification (standard EN 16647 for liquid fuels\textsuperscript{15} are not harmonized in the EU), which would, for example, determine the average and maximum values of the achieved heat output during operation based on the initial dose of fuel before lighting the burner. The sales of this product on individual markets can be restricted by local laws in individual countries. For example, while introducing products of this type to the market in Czech Republic, the manufacturer has to comply with act no. 102/2001 Coll., on General Product Safety, which sets the requirement to provide products with labeling and accompanying documentation including an assessment of risks associated with the use of the product. The manufacturer is also required to abide by provisions of Section 9 of act no. 634/1992 Coll., Consumer Protection Act, which require the seller to inform the consumer about the properties of the sold products. Section 10 of this act further requires that the seller provides visible and comprehensible marking of the product, which means identification of the manufacturer, the name of the product, data on weight or size, and/or other data required about the nature of the product for its identification and use. Similar regulations are also in force in other countries of the EU.\textsuperscript{16−18}

The information provided to customers by the manufacturers of bioethanol fireplaces is mostly insufficient, incomplete, and inaccurate for the new area of focus of these appliances (i.e., heating).

Each burner should come with a manual or technical data sheet with basic information about the fuel consumption and the average heat output of the combustion appliance based on the amount of fuel dosed before lighting.

This study focused on observing the heat output of bioethanol fireplaces including different, purposely induced operating states that can occur during their normal operation in households. The novelty of our research is based on unexplored real possibilities of bioalcohol burners in terms of their usage as secondary or tertiary heat sources for house heating. The added value of the research is in changing the view of bioalcohol burners from a design element to a potential heat source. The study provides unpublished information that will lead to the appropriate bioethanol burner choice during the design of household energy systems and will also lead to the sophistication of the mentioned devices by their users.

This study does not assess the economic aspect of this heating method. This study is aimed only at manually filled burners; automatically filled burners were not included in this research.

The comparison of measured values with those of other authors is not possible because no scientific article has addressed this topic.

\section*{RESULTS AND DISCUSSION}

\subsection*{2.1. Effect of the Type of Fuel on the Heat Output of Individual Burners}

The differences in the remaining fuel weight in the burners between 1 minute intervals were used to determine the heat output of the burners according to the known lower heating values (LHVs) of the fuels. The series of heat outputs were then used to determine the maximum heat output (as the highest output achieved during the test) and the average heat output (the average value of the heat outputs over the whole period of burning the fuel). The flame temperatures were recorded as 1 minute averages of the measured values. The values in Tables 1 and 2 represent the highest achieved 1 minute averages of the temperature at the given point and the average values of measured temperatures at the given point during the whole test duration. These values are given here as accompanying data to refine the description of the performed measurement. The flame temperature changed significantly during each test because the flames were not directed strictly to any flue gas duct. The combustion took place in an open space, so the movement of the flame was quite unstable (same
Table 1. Measurement Results of All Burners While Burning "Fuel 1" (Standard Test—Approximately 60 min of Operation)\textsuperscript{a, b}

| burner designation | fuel dose [g] | LHV [MJ/kg] | actual test duration [hh:mm] | maximum heat output—highest achieved [kW] | fuel consumption* [kg/h] | average heat output in operation [kW] | average fuel consum. [kg/h] | absolute air pressure during test [hPa] | relative air humidity during test [%] | maximum flame temp. (5 cm) [°C] | average flame temp. (5 cm) [°C] | absolute air temp. during test [°C] | ambient air temp. during test [°C] |
|-------------------|--------------|------------|-----------------------------|------------------------------------------|--------------------------|--------------------------------------|---------------------------|------------------------------------------|-----------------------------|-----------------------------|-----------------------------|---------------------------------|---------------------------------|
| burner 1          | 121.0        | 24.6       | 1:07                        | 0.94 ± 0.01                              | 0.138                     | 0.73 ± 0.01                           | 0.107                     | 979.1                                    | 34.6                        | 593.5                       | 394.7                       | 330.6                           | 218.1                          | 24.0                           |
| burner 2          | 209.6        | 24.6       | 0:51                        | 2.22 ± 0.07                              | 0.324                     | 1.65 ± 0.07                           | 0.242                     | 978.0                                    | 33.7                        | 478.5                       | 323.1                       | 346.8                           | 218.2                          | 24.3                           |
| burner 3          | 302.7        | 24.6       | 1:06                        | 2.79 ± 0.07                              | 0.408                     | 1.85 ± 0.07                           | 0.271                     | 972.7                                    | 40.2                        | 362.7                       | 195.2                       | 213.6                           | 104.5                          | 24.6                           |
| burner 4          | 120.6        | 24.6       | 0:59                        | 1.15 ± 0.00                              | 0.168                     | 0.82 ± 0.01                           | 0.121                     | 980.8                                    | 37.4                        | 394.3                       | 184.0                       | 261.2                           | 160.8                          | 23.6                           |
| burner 5          | 217.5        | 24.6       | 1:04                        | 1.93 ± 0.07                              | 0.282                     | 1.37 ± 0.07                           | 0.201                     | 978.0                                    | 33.7                        | 478.5                       | 323.1                       | 346.8                           | 218.2                          | 24.3                           |
| burner 6          | 324.8        | 24.6       | 0:58                        | 2.83 ± 0.07                              | 0.414                     | 2.26 ± 0.07                           | 0.330                     | 972.7                                    | 40.2                        | 362.7                       | 195.2                       | 213.6                           | 104.5                          | 24.6                           |
| burner 7          | 501.4        | 24.6       | 1:12                        | 3.73 ± 0.15                              | 0.546                     | 2.82 ± 0.07                           | 0.412                     | 973.6                                    | 41.1                        | 538.5                       | 329.9                       | 387.8                           | 204.4                          | 25.4                           |
| burner 8          | 131.5        | 24.6       | 1:05                        | 1.27 ± 0.07                              | 0.186                     | 0.82 ± 0.07                           | 0.120                     | 981.9                                    | 36.5                        | 692.1                       | 498.5                       | 567.7                           | 367.9                          | 23.0                           |

\textsuperscript{a}The heat outputs specified by the manufacturers of individual burners are shown in Table 4. \textsuperscript{b}± indicates maximal heat output at 20 °C using density according to the manufacturer's data.

Table 2. Measurement Results of All Burners While Burning "Fuel 2" (Standard Test—Approximately 60 min of Operation)\textsuperscript{a}

| burner designation | fuel dose [g] | LHV [MJ/kg] | actual test duration [hh:mm] | maximum heat output—highest achieved [kW] | fuel consumption* [kg/h] | average heat output in operation [kW] | average fuel consum. [kg/h] | absolute air pressure during test [hPa] | relative air humidity during test [%] | maximum flame temp. (5 cm) [°C] | average flame temp. (5 cm) [°C] | maximum flame temp. (10 cm) [°C] | average flame temp. (10 cm) [°C] | ambient air temp. during test [°C] |
|-------------------|--------------|------------|-----------------------------|------------------------------------------|--------------------------|--------------------------------------|---------------------------|------------------------------------------|-----------------------------|-----------------------------|-----------------------------|---------------------------------|---------------------------------|---------------------------------|
| burner 1          | 124.3        | 26.6       | 1:04                        | 1.11 ± 0.01                              | 0.15                     | 0.85 ± 0.01                           | 0.115                     | 982.9                                    | 35.1                        | 543.2                       | 39.6                        | 491.3                           | 318.5                          | 24.1                           |
| burner 2          | 209.6        | 26.6       | 0:49                        | 2.48 ± 0.08                              | 0.336                     | 1.86 ± 0.08                           | 0.252                     | 982.7                                    | 33.8                        | 474.6                       | 338.7                       | 350.5                           | 235.6                          | 24.3                           |
| burner 3          | 303.0        | 26.6       | 1:02                        | 3.32 ± 0.08                              | 0.45                     | 2.13 ± 0.08                           | 0.289                     | 984.1                                    | 33.1                        | 390.8                       | 179.2                       | 353.5                           | 171.5                          | 24.0                           |
| burner 4          | 120.7        | 26.6       | 1:00                        | 1.37 ± 0.08                              | 0.186                     | 0.88 ± 0.01                           | 0.119                     | 982.9                                    | 35.3                        | 521.9                       | 303.3                       | 314.0                           | 179.2                          | 23.7                           |
| burner 5          | 217.3        | 26.6       | 1:02                        | 2.08 ± 0.08                              | 0.282                     | 1.53 ± 0.08                           | 0.207                     | 982.5                                    | 35.1                        | 494.1                       | 239.8                       | 371.8                           | 184.8                          | 24.0                           |
| burner 6          | 324.9        | 26.6       | 1:02                        | 3.06 ± 0.08                              | 0.414                     | 2.28 ± 0.08                           | 0.309                     | 982.1                                    | 35.4                        | 535.7                       | 285.4                       | 391.8                           | 208.7                          | 24.2                           |
| burner 7          | 502.6        | 26.6       | 1:12                        | 4.07 ± 0.16                              | 0.552                     | 3.05 ± 0.08                           | 0.413                     | 974.0                                    | 43.0                        | 542.0                       | 334.8                       | 406.5                           | 220.3                          | 25.4                           |
| burner 8          | 131.4        | 26.6       | 1:03                        | 1.37 ± 0.08                              | 0.186                     | 0.91 ± 0.01                           | 0.123                     | 982.6                                    | 34.9                        | 613.5                       | 410.3                       | 344.0                           | 205.1                          | 23.8                           |

\textsuperscript{a}The heat outputs specified by the manufacturers of individual burners are shown in Table 4. \textsuperscript{b}± indicates maximal heat output at 20 °C using density according to the manufacturer’s data.
The dosed fuel was sufficient for 40 min of operation according to the expected heat output specified by the manufacturers of individual burners and was almost always sufficient for approximately 60 min of operation. It is apparent from this initial information that the heat output specified by the burner manufacturer is significantly different from the average heat output measured over the whole test duration.

The curves (shown in Figures 1 and 2) reflecting the heat outputs of each tested burners as a function of time for different fuels are always very similar in shape (the same burner, the same fuel dose, but different fuel), with the difference being that higher average and maximum outputs were achieved with fuel 2 (higher LHV). The use of fuel with a higher LHV (fuel 2) ensured that the average heat output of the burners increased by approximately 1.5 to 16% (depending on the type of burner) and the maximum achieved heat output increased by approximately 7.5 to 19% as well. The test duration did not differ by more than 4 min in the same weight of fuel dose. The initial rapid increase of heat output in the first minutes after ignition was almost identical for both fuels.

The measured 1 minute values of heat output are shown in Figures 1 and 2. The values confirming the results are given in Tables 1 and 2.

The maximal heat output during the tests was usually reached between 20 and 40 min after ignition. In this time range, the burners showed a relatively uniform heat output. After the stable time, a decrease in heat output occurred. The decreasing trend remained until a complete burnout of the fuel during the tests with single-chambered burners. During the tests with two-chambered burners, approximately 5 min before burnout, a small peak of heat output occurred. With the increase in the burner opening area of the two-chambered burners, the mentioned peaks became less significant. For burner 4, this peak represents the highest recorded heat output for the whole testing period.

The measurement results were also used to create graphs of dependency of the burner opening size on its average heat output during the test (shown in Figure 3). It is apparent from the graphs that the average heat output of a burner increases together with the increase in the burner opening area. A closer look at the comparison of the two burner design types (single-chambered—burners 1, 2, 3, and 8 vs two-chambered—burners 4, 5, 6, and 7) makes it apparent that the trend of the above-mentioned dependency rises slowly in the case of single-chambered burners with the fuel area being completely filled with mineral wool than it does in the case of two-chambered burners. The two-chambered burners achieved a higher average heat output at higher areas of the burner opening (approximately above 6000 mm² depending on the fuel type). This trend is valid for test periods of approximately 60 min. Research on the influence of the degree of fuel filling into the burner on this trend is not part of this work.

situation as that during standard home usage of a bioethanol fireplace). For this reason, the results are not comparable with other studies strictly aimed at these values.19

Figure 1. Behavior of the heat output of individual burners while burning “fuel 1”. The heat output specified by the manufacturer is burner 1—1.5 kW; burner 2—3 kW; burner 3—3.5 kW; burner 4—2 kW; burner 5—3 kW; burner 6—4 kW; burner 7—6 kW; and burner 8—1.5 kW. The weight for each burner is the initial weight of the dosed fuel before lighting the burner.

Figure 2. Behavior of the heat output of individual burners while burning “fuel 2”. The heat output specified by the manufacturer is burner 1—1.5 kW; burner 2—3 kW; burner 3—3.5 kW; burner 4—2 kW; burner 5—3 kW; burner 6—4 kW; burner 7—6 kW; and burner 8—1.5 kW. The weight for each burner is the initial weight of the dosed fuel before lighting the burner.
2.2. Effect of Ambient Temperature on the Heat Output of Burner 1.

The main motivation for this test arises from the common usage of bioethanol burners by gamekeepers in watchtowers and by cottage owners during winter. The combustion test performed using burner 1 to simulate cold ignition and the start of heating in a cooled room, where the burner and fuel were stored in an environment with a temperature around zero degree Celsius, did not prove a noteworthy effect of the burner temperature, fuel temperature, and ambient air temperature on the overall behavior of the burner heat output. The test was performed outside the building (during a cold autumn night) to ensure such low ambient temperature. Another phenomenon was observed during the test. Despite the apparent windless conditions and the fact that the burner was sheltered by wind protection walls from three sides, the flame apparently flickered more intensely (this manifested sudden major changes in the flame height and caused the flame to move in all directions, which occurred twice during the test—at 26 and 41 min). This phenomenon results in a higher average and maximum achieved heat output and thus faster burning out of the fuel. The more intense burning was probably caused by the minimal wind coming from the unprotected front side.

The 1 minute values of heat output are shown in Figure 4. The values confirming the results are given in Table 3.

2.3. Effect of the Initial Fuel Dose and Degree of the Regulation Damper Closure on the Behavior of Burner 2 Heat Output.

The effect of the amount of initial fuel dose was observed to determine the change in the maximum and average heat output and to compare the duration of each combustion phase of the combustion process. Combustion tests with different fuel doses performed by using burner 2 showed an increase in the maximal heat output (by approximately 9%) and an increase in the average heat output (by approximately 17%) while increasing the fuel dose from 50% of the maximal fuel dose (approximately 209.6 g of fuel) to 75% of the maximal fuel dose (300.3 g of fuel) and 100% of the maximal fuel dose (400.2 g of fuel). The increase in the average heat output was caused by a more stable operation of the burner, that is, especially by the burner remaining in the vicinity of the maximum achieved heat output for a longer time. This state is shown in Figure 5 as II. phase—heating.

It is obvious from the mentioned graph that I. phase—preheating took almost the same amount of time (approximately 15 min) for all the four mentioned tests (209.6 g of fuel 1, 300.3 g of fuel 1, 400.2 g of fuel 1, and 209.6 g of fuel 2), regardless of the amount of initial fuel dose weight. II. phase—Heating is almost linear with almost the same slope for the tests with fuel 1 and with a steeper slope for the test with fuel 2. The duration of this part of the combustion test depends on the initial fuel dose weight. III. phase—Burn out was the same for the tests with fuel 1 and not dependent on the initial fuel dose weight.
The combustion tests with partial closure of the regulation damper performed with burner 2 indicated this method of heat output regulation to be applicable. When the regulation damper was closed so that the burner opening area was 75% of the fully open burner opening area, the maximum achieved heat output was 84% of the value initially measured during a combustion test with the same initial fuel dose. The average heat output during this test was 80% of the initially measured value. When the regulation damper was closed so that the burner opening area was 50% of the fully open burner opening area, the maximum achieved heat output, as well as the average heat output, was 54% of the values initially measured during a combustion test with the same initial fuel dose. This regulation may affect the actual heat output, for example, according to the current heat demand of the house and avoid overheating.

The 1 minute values of heat output are shown in Figure 6. The values confirming the above results are given in Table 3.

### 2.4. Values Specified by the Manufacturer and the Actual Parameters

The measurement results show that it is not possible to operate the burners at the heat output declared by the manufacturer during the 60 min tests with the fuels used. At ordinary interior conditions, the burners achieved approximately 57–95% of the heat output declared by the manufacturer (i.e., the maximum measured heat output, as the average value of outputs in 1 min). In terms of interior heating, the maximal achieved heat output is not crucial if the appliance can only sustain it during a fraction of the operating time, but the average heat output based on the total operating time is important. The average heat output reached approximately 41–62% of the declared heat output while considering the total test duration. Both the average and the maximal heat outputs of the burners increased during longer operation with a larger fuel dose (as ascertained by experiments with burner 2). Nonetheless, the average heat output of the burners with a completely filled fuel area would not have reached their respective declared values, even if taking this deviation into account. The burners with the lowest difference between the heat output declared by the manufacturer and the maximal measured heat output were burner 3, burner 8, and burner 2. These three burners could, with their fuel area completely filled and while using fuel 2, achieve the heat output declared by the manufacturer with their maximal heat output for a short time. This fact has not been experimentally verified.

The above-mentioned standard EN 16647 describes measuring the heat output as an average value during the test of a completely filled burner. However, in actual use, the user does not have to completely fill the fuel area with fuel, especially because premature extinguishing leads to intense evaporation of ethanol into the air. There is no mechanical measure to prevent this phenomenon. Because of the large difference between the measured values and values given by the producer, it seems that the chosen burners were not tested according to the mentioned standard.

The results of the flame temperature measurements were very unexpected, primarily because of the very irregular and unpredictable movement of the flame (even moving completely away from the thermocouples), as well as because of the very quick dispersal of flue gas into the environment.

| Burner designation | LHV [MJ/kg] | Heat output [kW] | Heat output [W] | Heat output [%] |
|---------------------|-------------|------------------|----------------|----------------|
| Burner 1 (cumulative total) | 120.6 | 24.6 | 0.58 | 62% |
| Burner 2 | 209.9 | 24.6 | 1.26 | 62% |
| Burner 3 | 300.3 | 24.6 | 1.26 | 62% |
| Burner 4 | 400.2 | 24.6 | 1.26 | 62% |

*The heat outputs specified by the manufacturers are provided in Table 1. a* indicates maximal heat output at 20°C using density according to the manufacturer’s data.
The flame from the burners was very sensible to any movement (and consequent air waves) in the surroundings.

3. CONCLUSIONS

The aim of this paper was to determine the actual behavior of the heat output of bioethanol burners.

A series of measurements were performed to meet the objective of the research. The combustion tests were performed with regard to the procedures provided by the standard EN 16647\(^{15}\) (the mentioned standard is only recommended and the manufacturer is not obligated to test or certify the appliance according to this EU standard). The situation can be changed by the legislation of individual countries.

It is possible to estimate the total burning time and the heat output of the burner beforehand while using the appropriate fuel dose. By knowing the burning time beforehand, the use can prevent undesirable fuel losses and an undesirable smell, resulting from premature extinguishing of the flame and evaporation of ethanol into the air.

The average heat outputs of the burners during the measurements (60 min tests) reached approximately 41–62% of the heat output declared by the manufacturers. The average heat output of the burners may vary depending on the quality (purity) of the fuel used, up to 16%. The combustion tests with partial closure of the regulation damper performed with burner 2 indicated this method of heat output regulation to be applicable even for standard home operation. A comparison between two burner construction types in terms of the dependence of average heat output on the burner opening area showed that two-chambered burners reached a higher average heat output than single-chambered burners with the same burner opening area above ~6000 mm\(^2\), according to the fuel type. The reduced temperature of the burner, fuel, and ambient air did not show a remarkable effect on the burner heat output. Increasing the initial fuel rate in the tests with burner 2 (from 60 min tests) to the maximum allowed value resulted in an increase of approximately 17% in the burner’s average heat output. The average measured heat output of the tested burners ranged from approximately 0.73 to 3.05 kW, which can represent a noteworthy auxiliary heat source giving low heat losses in households. However, it is necessary to keep in mind the operating safety of such a source and ensure a sufficient supply of combustion air and removal of its combustion products. It is an appliance where the combustion air from the surroundings of the appliance is used and the fuel gas also flows to the surroundings of the appliance.

Because of the necessity of air exchange in the room while using this type of combustion appliance, it is necessary to ventilate the room intensely (to completely exchange the air) according to the instructions for use, which causes significant losses of the gained thermal energy. Because of the large volume of combustion products, it is not possible to omit the intense ventilation without risking health problems in people present in the room. The available manuals for this type of appliance make no mention of the use of heat recovery.

![Figure 5](https://acrosome.org/article/acsomg/2020/5/28587-28596)

**Figure 5.** Dependency of released heat energy by burner 2 on time after ignition. The heat output specified by the manufacturer is burner 2—3 kW.

![Figure 6](https://acrosome.org/article/acsomg/2020/5/28587-28596)

**Figure 6.** Behavior of burner 2 heat outputs while burning each of the tested fuel, including tests with a partially closed regulation damper and with different fuel doses. The heat output specified by the manufacturer is burner 2—3 kW.
ventilation units, which could significantly decrease heat losses caused by ventilation and, at the same time, provide a sufficient supply of fresh air over the whole period of fuel combustion. The manufacturers of the tested burners make no recommendation to use carbon dioxide and carbon monoxide detectors to ensure increased personal safety.

Further research will focus on the operating safety of these appliances in terms of the impact of contaminants resulting from the combustion of ethanol on the quality of indoor environment.

4. MATERIALS AND METHODS

A total of eight bioethanol burners from three different manufacturers were selected to objectively determine their operating parameters. Apart from the manufacturer, the burners also differed in the fuel area volume, design type, burner opening area, and thus the expected heat output (the manufacturer does not state whether the heat output is the burner opening area, and thus the expected heat output (the current legislation does not force manufacturers to specify it). The basic information about the burners is provided in Table 4.

| Burner designation | Burner weight [g] | Burner opening area [mm²] | Expected heat output (manufacturer’s data) [kW] |
|--------------------|------------------|---------------------------|-----------------------------------------------|
| burner 1           | 1174             | 3464                      | 1.5                                           |
| burner 2           | 2524             | 7000                      | 3.0                                           |
| burner 3           | 3500             | 11200                     | 3.5                                           |
| burner 4           | 1528             | 4161                      | 2.0                                           |
| burner 5           | 2033             | 6390                      | 3.0                                           |
| burner 6           | 2524             | 8560                      | 4.0                                           |
| burner 7           | 3042             | 9950                      | 6.0                                           |
| burner 8           | 861              | 2730                      | 1.5                                           |

In terms of the design, apart from the dimensions, the burners mainly differed in the layout of the internal part of the fuel area. Burners 1, 2, 3, and 8 had their fuel area completely filled with ceramic wool (hereafter referred to as single-chambered). This type of burner is shown in Figure 7. Burners 4, 5, 6, and 7 were divided into two chambers (hereafter referred to as two-chambered). This type of burner is shown in Figure 8. The first chamber, used to dose fuel, was empty. There was a partition separating the first and second chambers. The partition contained opening areas, a 13 mm high gap along the whole width of the fuel area in the bottom part, and a series of circular orifices in the upper part (their number differed depending on the burner type). The second chamber was completely filled with ceramic wool. Because of this, the fuel is not poured directly into the ceramic wool while filling the burner, as this can cause uneven saturation by the fuel, but is poured into the first chamber, where the fuel creates a layer and subsequently gradually (along the whole width) saturates the ceramic wool in the second chamber.

The volatile combustible substance in this type of burner is then released not only from the fuel layer in the first chamber but also from the ceramic wool in the second chamber, which has the visual result of flame burning from the circular orifices in the partition. Burners 1, 2, and 3 were equipped with a double casing on the bottom of the burner to increase operating safety. Ignition of the fuel in both burner construction types takes place by the approach of a flame (by a lighter or a matchstick) to the burner opening. After ignition of ethanol vapors, the fuel burns continuously according to the several difficult processes (simplified according to eqn. 1). Part of the released heat is transported to the surroundings by convection (hot flue gases are mixed with ambient air) and part is transported by radiation. Part of the heat transported by radiation affects the temperature of the whole burner and thereby affects the intensity of ethanol evaporation. When the ethanol in the burner reaches 78.3 °C, it starts to boil (at normal pressure \( p_N = 101,325 \) Pa) and then the quantity of ethanol vapors is the highest.

Simplified combustion equation of ethanol:

\[
C_2H_5OH + 3O_2 \rightarrow 3H_2O + 2CO_2 \tag{1}
\]

4.1. Fuel. Bioethanol is ethyl alcohol (hereafter just ethanol) and its composition is identical to the composition of potable alcohol. Ethanol could be produced via the synthesis of hydrocarbons (which cannot be used for bioethanol production) or via the synthesis of biomass. All fermentable sugars (e.g., glucose and sucrose) contained in biomass can be transformed into ethanol by fermentation. Ethanol is a transparent liquid with a density of 0.7893 kg·m\(^{-3}\). According to law, ethanol not intended for drinking must be denatured by specific substances, which can vary in different countries.

Bioethanol can be bought as a fuel intended specifically for bioethanol fireplaces at different levels of purity (different levels of water contamination). Bioalcohol fuel in the form of a
gel (mixture of ethanol and xanthan gum) may also be used, if the burner permits it.\textsuperscript{21,23}

Two liquid fuels were used for the tests (fuel 1 and fuel 2).

Fuel 1 contains ethanol with a low mass fraction of water (0.025–0.04 \textendash{} according to the producer’s information) as its majority component. The LHV stated in the safety data sheet of fuel 1 is \(\text{LHV}_{\text{ethanol}} = 26.9 \text{ MJ kg}^{-1}\). This value is the LHV of pure ethanol according to the manufacturer, that is, without taking the water mass fraction in the fuel into consideration. The density of the fuel according to the safety data sheet is \(\rho_{\text{fuel}_1} = 0.80–0.82 \text{ kg dm}^{-3}\) at 20 °C.

Fuel 2 contains ethanol with almost zero mass fraction of water as its majority component. The LHV of the fuel stated in the safety data sheet is also \(\text{LHV}_{\text{ethanol}} = 26.9 \text{ MJ kg}^{-1}\). The density of the fuel according to the safety data sheet is \(\rho_{\text{fuel}_2} = 0.789 \text{ kg dm}^{-3}\) at 20 °C.

**4.2. Verifying the Heating Values of the Fuels.**

Measurements to determine the actual heating values of the fuels were performed using a calorimeter (LECO AC600). The oxidation reaction occurs in the calorimeter bomb, and heat is released and subsequently absorbed by the bomb and water. The measured values of the higher heating value (HHV) for each fuel are \(\text{HHV}_{\text{fuel}_1} = 27.423 \text{ MJ kg}^{-1}\) and \(\text{HHV}_{\text{fuel}_2} = 29.381 \text{ MJ kg}^{-1}\). The values were calculated as the average from at least five measurements.

The measurements established a difference in the HHV of the tested fuels. Because the water vaporized from the fuel and the water created from the combustion of hydrogen do not condense in the room (condensation is not desirable), it is necessary to consider the LHV, not the HHV, while calculating the heat output. The conversion from HHV to LHV was performed according to the respective standard.\textsuperscript{24}

The mass fraction of hydrogen in anhydrous fuel was determined according to the molar weight of individual chemical elements in ethanol and its value is \(H_2 = 13.1\%\). In the case of fuel 1, the mass fraction of water according to the data provided by the manufacturer was considered for the calculation.

The resulting calculated LHVs are \(\text{LHV}_{\text{fuel}_1} = 24.68 \text{ MJ kg}^{-1}\) and \(\text{LHV}_{\text{fuel}_2} = 26.68 \text{ MJ kg}^{-1}\).

**4.3. Measurement Methodology.**

Based on the measured decrease of fuel weight, the heat input of chemical energy bound in the fuel was determined taking into account the methods provided in standard EN 16647 for liquid fuel.\textsuperscript{25} Because of the flow of flue gas into the heated room and the combustion appliance being located directly in the heated room, it is possible to consider the heat input of the appliance as its heat output (the losses caused by the unburned gas residue and unburned fuel in the solid residue were disregarded; the radiative heat loss and the heat loss from the sensible heat of flue gas are considered as a gain instead of a loss).

A calibrated XS BL 6001 scale was used for the measurements. Between the scale and the tested burner (only the burner without any fireplace body), a heat insulation plate was inserted to prevent the damage. The amount of dosed fuel was for approximately 40 min of operation according to the expected heat output of the burners (according to the manufacturer’s data). The fuel dosing method was selected to ensure that the mineral wool was saturated as evenly as possible along the width of the burner opening. A funnel was used to achieve this in the case of burners 4, 5, 6, and 7. There was a 10 min time delay before lighting the burner to allow the fuel to saturate the ceramic wool.

The initial value of the fuel weight in the burner was noted down just before lighting the burner, after which the burner was ignited using a lighter supplied by the seller of the burners. The actual (remaining) weight of the fuel was recorded at every elapsed minute after igniting the burner.

Along with the heat output measurements, the maximum flame temperature was measured 5 and 10 cm above the burner level using a type K thermocouple during selected tests. The ends of these thermocouples were positioned at the center of the burner opening in terms of both the length and the width of the burner opening.

While performing the combustion tests on burner 2 with a partially closed regulation damper, the burner opening was opened to 21 mm (75% open) and 14 mm (50% open) of the 28 mm total width of the burner opening width. The other rules and the procedure were the same as in the case of other measurements.

During the combustion tests with burner 2 using different fuel doses, two volumes of fuel were used (approximately 500 mL and approximately 375 mL). The higher one was defined by the manufacturer as the maximum recommended volume.

The combustion test performed by using burner 1 to simulate heating at low ambient temperature of flue gas was done after stabilizing the temperature of the burner and the fuel at \(-11.5\) °C. The ambient temperature was 1.7 °C. The test was performed in an outdoor environment using wind protection walls from three sides.

The atmospheric pressure, the relative air humidity, and the ambient temperature during all the tests were recorded.

The uncertainties of determination of time, LHV, and fuel consumption were included in the uncertainty determination of the average and maximal heat output of the burners. The resulting uncertainty was determined according to the EA-4/02 document.
Author Contributions
This manuscript was written through contributions of all authors. All authors have approved the final version of the manuscript.

Notes
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