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Analysis of wood firing in stoves by the oxygen consumption method and the carbon dioxide generation method

T. Paloposki*, J. Saastamoinen, K. Klobut, P. Tuomaala

VTT Technical Research Centre of Finland, P.O. Box 1000, FIN-02044 VTT, Finland

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ABSTRACT

In this paper, we describe the application of two experimental methods on the determination of the heat release rate during the combustion of wood in stoves. The experimental methods are the oxygen consumption method and the carbon dioxide generation method and are adopted from the field of fire safety science. After outlining the basic ideas, we show the necessary equations and analyze the results from an actual experiment. We conclude that both methods appear to be very useful in this application.

1. Background

1.1. Wood firing in stoves

In Finland, approximately 50% of the heating energy for single family homes was provided by wood firing in 2007 [1]. The most common method for utilizing the energy content of firewood is to use modern versions of the traditional Finnish stove equipped with massive stone or brick walls for heat storage. Such stoves are capable of providing a reasonably steady heat output even if the heat input strongly varies with time, as is inevitably the case during intermittent firing of batches of firewood. In fact, a typical mode of operation is to fire 1–2 batches of wood each morning; after the burning has ceased the chimney damper is closed and the stove requires no more attention until next morning.

In order to study the performance of such stoves, we need to know the heat release rate from a batch of firewood burning inside the stove. The information can be used for optimization of the heat storage capability of the stove and also for the fine-tuning of the combustion characteristics of the stove, aiming at, e.g., reduction of emissions of harmful compounds.

1.2. Determination of heat release rate by using measurements of mass loss rate

In principle, the heat release rate could be determined indirectly from mass loss rate measurements. This technique requires that the stove be installed on a balance and the change of the combined weight of the stove and the batch of firewood burning inside the stove be recorded as a function of time. Heat release rate is then obtained by multiplying the

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* *Corresponding author.* Aalto University, PO Box 14100, FI-00076 Aalto, Finland. Tel.: +358 50 436 4610.
  E-mail address: tuomas.paloposki@aalto.fi (T. Paloposki).

mass loss rate values by the heating value of the fuel. However, this approach creates considerable theoretical and practical problems.

The theoretical problems stem from the fact that the burning process is notoriously unsteady and includes the partially overlapping phases of heating, drying, devolatilization, combustion of volatiles and combustion of char. The average heating value of volatile matter evolved from wood differs considerably from the average heating value of wood char [2,3]. Thus, one cannot really estimate heat release rate unless additional assumptions are made regarding whether the observed weight loss was due to drying, devolatilization or char combustion.

The practical problems stem from two facts. Firstly, stoves are generally very heavy when compared with the batch, so one has to be able to accurately measure small changes in the weight of a heavy object. Secondly, stoves are normally rigidly connected to a chimney, which not only is another heavy object, but may also transmit loads from other parts of the building structure to the stove. Thus, accurate weighing becomes quite difficult.

In view of the difficulties described above, we decided to search for other options for the analysis of heat release rate during wood firing in stoves. Promising candidates were found in the field of fire safety science and are described in the next section.

2. Oxygen consumption method and carbon dioxide generation method

2.1. Fundamental ideas

The ideas behind the oxygen consumption method and the carbon dioxide generation method are illustrated in the following. Let $C_aH_bO_c$ be the generic chemical formula for any fuel consisting of carbon, hydrogen and oxygen. Assuming complete combustion of the fuel to carbon dioxide CO_2 and water vapor H_2O, the combustion reaction can be expressed as

$$C_aH_bO_c + dO_2 \rightarrow aCO_2 + \frac{1}{2}bH_2O \qquad (1)$$
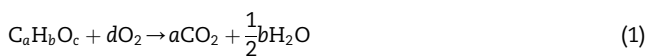
where

$$d = a + \frac{1}{4}b - \frac{1}{2}c. \qquad (2)$$

Now consider the amount of chemical energy being released as heat due to the combustion reaction. Define the following heating values:

$$Q' = -\Delta H_r \qquad (3)$$

$$Q'' = -\frac{\Delta H_r}{d} \qquad (4)$$

$$Q''' = -\frac{\Delta H_r}{a} \qquad (5)$$

where ΔH_r is the heat of reaction for the reaction expressed in Equation (1). Thus, Q' is the heating value of the fuel per 1 mol of fuel consumed in the reaction; Q'' is the heating value of the

Table 1 — Combustion reactions of selected fuels. The heats of reaction are for the case where H_2O in the products is assumed to be in vapor state.

Code	Fuel	Combustion reaction	ΔH_r [kJ/mol]
(R1)	Carbon	$C + O_2 \rightarrow CO_2$	−394
(R2)	Methane	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	−800
(R3)	Propane	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$	−2044
(R4)	Benzene	$C_6H_6 + 7\frac{1}{2}O_2 \rightarrow 6CO_2 + 3H_2O$	−3128
(R5)	Methanol	$CH_3OH + 1\frac{1}{2}O_2 \rightarrow CO_2 + 2H_2O$	−635
(R6)	Acetic acid	$CH_3COOH + 2O_2 \rightarrow 2CO_2 + 2H_2O$	−876
(R7)	D-glucose	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$	−2772

fuel per 1 mol of oxygen consumed in the reaction; and Q''' is the heating value of the fuel per 1 mol of carbon dioxide generated in the reaction. The latter two heating values will be used in the analysis of the heat release rate by the oxygen consumption method and by the carbon dioxide generation method, respectively.

The value of the heat of reaction depends on whether the water vapor in the products is assumed to be in liquid form or in gaseous form. In this study, the water vapor is assumed to be in gaseous form; thus the lower value of the heat of reaction is employed in all calculations, and, consequently, lower heating values (LHV) are obtained from Equations (3)—(5).

Now consider the combustion reactions presented in Table 1. Here the fuels were chosen to represent a wide variety of organic compounds. The heats of reaction were taken from [4], except for reactions (R4) and (R6) which are not presented in [4]. For these two reactions, the heats of reaction were taken from [5]. The data listed in [5] are actually heating values per unit mass of the fuel; thus, the heating values were first multiplied by the molar masses of the respective fuels to obtain heating values per 1 mol of the fuel, and the heats of reaction were then computed using Equation (3).

The next step is to apply Equations (3)—(5) to the reactions presented in Table 1. The results are compiled in Table 2.

It can be seen that the value of Q'' is approximately constant regardless of the fuel. The average value for all seven fuels listed in Table 2 is 420 kJ/mol, and all values are seen to be within ±10% of the average value. There seems to be a slight increasing trend as we move from pure carbon to hydrocarbons and from hydrocarbons to oxygenated

Table 2 — Heating values of the fuels listed in Table 1. The heating values are for the case where H_2O in the products is assumed to be in vapor state.

Code	Fuel	Q' [kJ/mol]	d [ ]	Q'' [kJ/mol]	a [ ]	Q''' [kJ/mol]
(R1)	Carbon	394	1	394	1	394
(R2)	Methane	800	2	400	1	800
(R3)	Propane	2044	5	409	3	681
(R4)	Benzene	3128	$7\frac{1}{2}$	417	6	521
(R5)	Methanol	635	$1\frac{1}{2}$	423	1	635
(R6)	Acetic acid	876	2	438	2	438
(R7)	D-glucose	2772	6	462	6	462
Average:				420		562