# Energy performance of Portuguese and Danish wood-burning stoves

Ricardo L. T. Carvalho[1,*], Ole M. Jensen[1], Luís A. C. Tarelho[2], Alireza Afshari[1], Niels C. Bergsøe[1], Jes S. Andersen[3]

[1] *Danish Building Research Institute, Aalborg University, Hørsholm, Denmark*
[2] *Department of Environment and Planning, University of Aveiro, Aveiro, Portugal*
[3] *Centre for Renewable Energy and Transportation, Technological Institute, Aarhus, Denmark*
**Corresponding author. Tel: +45 99402373, Fax: +45 45867535, E-mail: rlc@sbi.dk*

**Abstract:** In Europe, considerable amounts of renewable energy resources are used for residential heating with wood-burning stoves, which can cause considerable energy losses and environmental impacts. A better understanding of its operating characteristics will permit to improve the buildings energy efficiency and indoor climate, and to reduce the emission of air pollutants to the environment.

This study aimed to analyze the operating conditions of a Portuguese made stove and compare it with the most efficient Danish made stoves tested at the Technological Institute.

The combustion experiments were carried out through the measurement of the main operating parameters: flue gas temperature and composition, combustion air flow rate, and fuel consumption rate. The results showed that the appliances emitted energy intermittently, with a mean heat flow rate into the indoors of 5 $kW_{th}$, representing mean thermal energy efficiencies of 70% and 76%, respectively for the Portuguese and Danish stoves. The Carbon Monoxide concentration in the flue gas was lower than 0.4 % (v/v; 13% $O_2$) for all stoves.

There is still a need for more accurate knowledge the relationship between the energy and the environmental performance of the appliances. A dynamic analysis of the problem will permit to increase the households energy savings.

***Keywords:*** *Wood-burning stoves, thermal energy efficiency, heat flow rate, flue gas composition.*

## Nomenclature

| | | |
|---|---|---|
| $\eta$ | *energy efficiency* | % |
| $h_a$ | *ambient air specific enthalpy* | $kJ\ kg^{-1}$ |
| $m_b$ | *fuel consumption rate* | $kg\ h^{-1}$ |
| $n_i$ | *molar flow rate* | $mol\ s^{-1}$ |
| $Q_g$ | *thermal energy gains* | $kW$ |
| $T_{EG}$ | *flue gas temperature* | $K$ |
| $w_{wF}$ | *fuel moisture* | $kg_{H2O}\ kg^{-1}$ |
| $c_{pi}$ | *mean calorific capacity* | $kJ\ mol^{-1}K^{-1}$ |
| $h_{fg}$ | *latent heat of H2O* | $kJ\ kg^{-1}$ |
| $m_{ca}$ | *combustion air flow rate* | $kg\ h^{-1}$ |
| $PCI$ | *lower heating value* | $kJ\ kg^{-1}$ |
| $Q_l$ | *thermal energy losses* | $kW$ |
| $T^0$ | *reference temperature* | $K$ |

## 1. Introduction

Nowadays, a great amount of energy is used for residential heating and even in the European modern houses is possible to save considerable amounts of thermal renewable energy. Among the existing sustainable energy systems are the wood-burning stoves that are still commonly used for space and sanitary water heating.

In Portugal, it is estimated that 32% of the houses are using either wood-burning stoves or open fireplaces for space heating, whereas in Denmark 26% of the households are using wood-burning stoves being estimated that wood share is estimated to 18% of the total amount of fuel used for heating in single family houses, and amounts to 60 % of renewable energy contribution in this category of houses [1;2].

However, these equipments can reveal low thermal energy efficiency when operated under deficient conditions also causing considerable impacts in the environment. During the last few years there was an effort to improve both the energy and environmental performance of such equipments, through the establishment of national and international guidelines and standards.

The international standard EN 13240 for “room heaters” and EN 13229 for “insert appliances and open fire places” establish requirements concerning the thermal energy efficiency and operating conditions of the equipments [3;4]. The standards determine the laboratory test procedures and required emission factors concerning the appliances certification. At the same time the new version of the Energy Performance Building Directive (EPBD 2010) is asking the member states to implement an integrated building certification system and that means the energy analysis must consider both the thermal efficiency of the households and its elements, through the establishment of labeling systems for the building equipments. Moreover, the certification of energy systems should take into account its impacts on thermal comfort and indoor air quality [5].

Some countries have been developing national standards for wood-burning stoves, namely the Swan Labeling created in the Nordic countries that present tighter requirements concerning for example the emission factors of total particle matter (PME). In Denmark, most stove manufactures are applying this labeling system through tests in certified laboratories such as the testing laboratory of the Technological Institute [6]. During the last decades, these regulations have been adopted by European stove manufacturers and sellers and this has contributed to the improvement of the energy performance of the marketed wood-burning stoves. The problem and hypothesis is that the increase of the equipments thermal efficiency can in certain extend be related to a decrease in the environmental performance of the biomass stoves, namely concerning its impacts in both the ambient and indoor air quality [7;8].

There is still a lack of knowledge about the relation between the wood-burning efficiency, the heat transfer processes from the combustion chamber to the indoors and the emission of pollutants to the environment. In this context, the aim of this study was to analyze and compare the operating conditions of wood-burning stoves made in two different European countries with distinct energy demands but where the use of wood-burning stoves are still a solution for residential heating. The objective is to contribute to the increase of knowledge about processes involving wood-burning stoves in order to identify practices that can promote higher energy savings in buildings and a cleaner wood-burning process, as well as the creation of guidelines for manufactures, sales men and stove users.

## 2. Methodology

The present study was carried out in a laboratory test installation at the University of Aveiro (Portugal) projected and implemented for monitoring several operating parameters of the typical Portuguese made wood-burning stove. The project carried out at the Portuguese university aims to increase the knowledge about the test methods used to evaluate the energy and environmental performance of such appliances. The experimental results obtained were compared with the data acquired during similar tests carried out for a Danish made stove - tested at the testing laboratories at the Technological Institute (Denmark), following the European standard EN13240. In both cases, it was considered that the studied equipments are representative of the commonly used wood-burning stoves in Portugal and in Denmark, respectively. The biomass used in this comparative study was wood commonly collected in the Portuguese forest (used for residential wood-burning), for example the ash tree (*Fraxinus Angustifolia*) and for the Danish stove birch wood following the requirements of the EN

13240. The general information about the experimental conditions used are presented in the Table 1.

### *2.1. Experimental installation and test conditions*

In Portugal, the experimental installation integrated a wood-stove (insert appliance) with a mechanical ventilation system used for forced convection, a set of on-line gas analyzers, temperature sensors, a combustion air flow meter, a weight sensor and an automatic control and data acquisition system operated by a computer. During the experiments the following parameters were monitored continuously: the temperature in the combustion chamber and on the stove walls, the flue gas temperature at several locations along the reactive system (at the chimney entrance and exit), the flue gas composition, the combustion air flow rate and the rate of biomass combustion.

The temperature in the different points along the experimental installation was measured with K-type thermocouples while the flue gas composition was determined applying the following continuous measurement methods: a paramagnetic analyzer (ADC model $O_2$-700 with a Servomex Module) for $O_2$, and a non-dispersive infrared analyzer (Environnement, MIR 9000) CO and $CO_2$. The composition of the combustion gas was measured in the chimney at 2.8 meters above the combustion chamber exit. The combustion air flow rate was determined using a mass flow rate meter (Kurz, series 155) while the biomass consumption was monitored through a weight sensor (DS Europe 535 QD – A5) [9].

In Denmark, the stove was tested under the operating conditions established by the European standard, through the determination of the CO and $CO_2$ concentrations by means of IR spectroscopy using an ABB AO 2020 gas-analyzer. The flue gas temperature and other temperatures were measured with K-type thermocouples. The test laboratory is accredited by the European standard EN 17025 by DANAK (with accreditation number 300 and notified body with notification number 1235). The measurements in the flue gas of both the CO and $CO_2$ concentrations were carried out at 1.43 meters above the combustion chamber using the test section specified by the EN 13240 Fig. A.9.

*Table 1. Operating conditions during the wood-burning stoves monitoring (mean values for the 60 minutes period).*

| Appliance (country) | Type of appliance | Fuel consumption (kg $h^{-1}$) | Combustion air flow rate ($Nm^3$ $h^{-1}$) | Forced convection rate ($Nm^3$ $h^{-1}$) |
|---|---|---|---|---|
| Portuguese | Insert | 1.7 | 29.97 | 40.00 |
| Danish | room heater | 1.6 | 27.30 | N.A. |

The laboratory experiments were carried during the heating season of 2010 using typical operating conditions for the studied wood-burning stoves. The duration of each laboratory experiment (wood-burning cycle) was 60 minutes, according to the European standards EN 13240 and EN 13229, respectively for the Danish (wood stove) and Portuguese (wood stove, insert appliance) equipments.

The experimental results obtained were considered in both the mass and energy balance to the wood-burning stoves in order to calculate the thermal energy efficiency of the appliances during a typical wood combustion cycle.

## 3. Results

The behavior of the monitored operating variables (flue gas temperature in the combustion chamber, both the CO and $CO_2$ concentrations in flue gases, and mass of fuel in the grate of the stove) during the combustion of biomass is shown in the Figures 1 and 2, respectively for the Portuguese stove and Danish stoves.

The combustion of wood in both equipments shows some major differences. For example, in the Danish stove both the flue gas $CO_2$ concentration and temperature increased in the initial stages of the combustion cycle, whereas in the Portuguese stove those variables achieve maximum values only after 20 minutes after to the fire lightning (Figures 1 and 2).

An increase in the flue gas CO concentration at the initial stages of combustion was observed for both stoves, although in the case of the Portuguese insert appliance the CO concentration value is higher than for the Danish stove, and lasts for a longer time period. For both cases it is possible to observe an increase in the concentration of CO in combustion gases during the final stages of wood combustion (Figures 1 and 2).

The temperature in the combustion chamber varied between 200 and 600 $^{o}$C in the Portuguese wood stove – similar to the temperatures expected for the Danish stove based on thermal calculations.

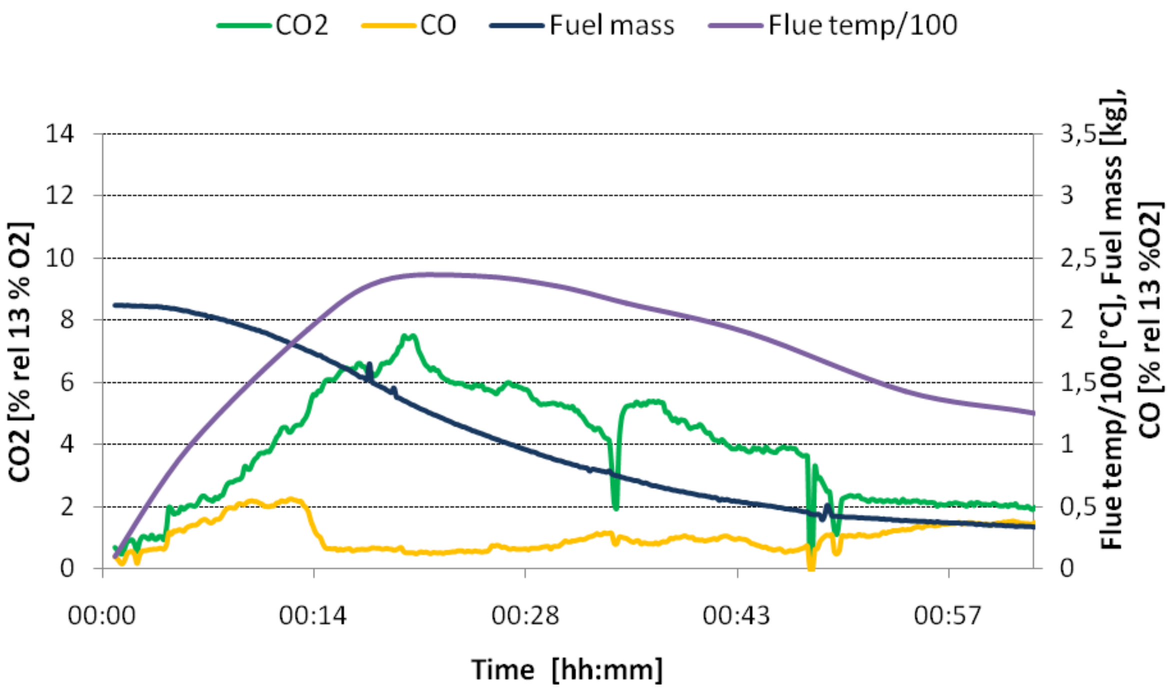


*Figure 1. Fuel consumption, CO and $CO_2$ concentration (13% $O_2$, dry gases) in the exit flue gas, and temperature of the flue gas over the test period in the Portuguese stove.*

The Figure 1 shows that there was a rapid decrease in both the flue gas CO concentration and temperature, respectively 35 and 48 minutes after to light the fire in the stove. The first case is associated to the door opening after 35 minutes of sampling, due the verified problems with the combustion bed. The second situation is related to the automatism of the software sampling systems, since it was programmed for a certain period of measurements and as a consequence it was not registering any values at the 48 minutes time instant.

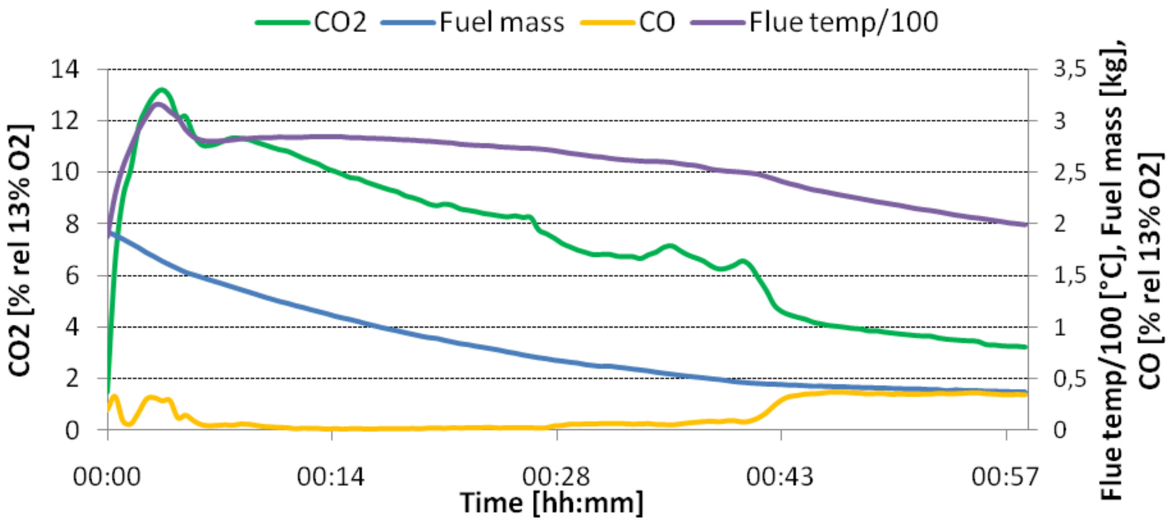


*Figure 2. Fuel consumption, CO and $CO_2$ concentration (13% $O_2$,* dry gases*) in the flue gas and temperature of the flue gas over the test period in the Danish stove.*

For the Portuguese stove, the mean CO concentration in the combustion flue gas over the test period was 0.27% (v/v, dry gases), while the mean $CO_2$ concentration was 3.6% (v/v, dry gases), and the mean flue gas temperature was 173 ºC. The biomass combustion rate was around 1.7 kg/h. Important is to point out that during the wood combustion experiment it was necessary to handle one of the wood logs in the stove grate in order to maintain the combustion process under satisfactory conditions; this handling interventions are reflected in Figure 1 by the decrease in both the flue gas $CO_2$ concentration and temperature around 35 minutes after the beginning of the wood combustion cycle.

For the Danish stove, the mean CO concentration in the flue gas was 0.10 % (v/v, dry gases) while the mean $CO_2$ concentration was 7.3 % (v/v, dry gases), and the mean flue gas temperature was 250 ºC. The biomass combustion rate was around 1.6 kg/h.
Important is to point out that, the gas flow rate throughout both of the stoves is varying in same range (25 to 30 $m^3 h^{-1}$).

The mean thermal efficiency of both wood-burning stoves was determined for each testing period (60 minutes) in order to compare the energy performance of the studied equipments.

The thermal efficiency was calculated considering two European standards, namely the EN 13240 (insert appliances) and EN 13299 (room heaters) that establish a minimum testing period of 45 minutes [3;4]. The calculation of the energy efficiency of each stove was carried out through an energy balance to the equipments. The system boundary considered for the calculation of the energy loss from the stove to the outdoors was the top of the chimney in both equipments.

The amount of energy losses was exclusively associated to the sensible and latent heat of combustion gases leaving the chimney.

The Equations 1 to 3 were used for the calculation of the thermal efficiency of the two stoves. The obtained results are presented in Table 2.

$$\eta = \frac{\dot{Q}_g - \dot{Q}_l}{\dot{Q}_g} \cdot 100 \quad (1)$$

$$\dot{Q}_g = \dot{m}_b \cdot PCI_b + \dot{m}_{ca} \cdot h_a \quad (2)$$

$$\dot{Q}_l = \sum_{i=1}^{i=n} \dot{n}_i \cdot \bar{c}_{p_i} \cdot \left(T_{EG} - T^0\right) + m_b \cdot w_{wF} \cdot h_{fg} \quad (3)$$

*Table 2. Nominal heat output and energy efficiency of the Danish and Portuguese tested wood stoves.*

| | Danish * | Portuguese ** |
|---|---|---|
| Nominal heat output (kW) | 5.2 | 5,2 |
| Nominal burn time (min.) | 60 | 60 |
| Efficiency (%) | 76 | 70 |
| Mean flue gas temperature (ºC at 20ºC ambient temp.) | 250 | 180 |

**) Claimed values from the CE-dataplate – Tecnological Institute.*
***) Experimental values obtained at the University of Aveiro laboratory.*

## 4. Discussion and conclusions

The knowledge about the energy and environmental performance of wood-burning stoves is still insufficient and there is a need to improve them concerning the sustainability of the integration of such a kind of energy conversion systems in the modern energy efficient households.

The development and implementation of testing methods and laboratories is a step stone towards a better knowledge about the operating conditions of such equipments, and the consequent improvements on both its energy efficiency and environmental performance all over Europe.

During the last few years, there was an effort to improve the thermal efficiency of the wood combustion appliances from 50% to more than 80%, however, it is well known that the use of such energy systems continue to cause considerable impacts on the environment.
The presented work revealed that the thermal efficiency of the studied stoves varied between 70% and 76%, respectively for both the Portuguese insert appliance and Danish stove; the nominal thermal heat output considered was around 5 $kW_{th}$. Regarding the energy efficiency, it can be concluded that the two equipments have efficiencies in the same range, even though the combustion characteristics are pretty uneven, as indicated by the behavior of the operating variables along the time and its mean values. The background is that the energy efficiency is

derived from the ratio $CO_2$ concentration / Flue gas temperature. So offsetting the two parameters in parallel upwards or downwards will return no change in the actual efficiency.

Normally, one cannot avoid a CO peak in the beginning of the burn cycle (devolatilization), and neither a moderate increase of CO concentration at the end of the burn cycle, due to incomplete combustion (associated to low temperatures) once the flame did extinguish.

However, the presence of CO concentrations varying from 0.2 to 0.4 % (Portuguese insert appliance) in between the peaks at the beginning and at the end of the combustion cycle indicates incomplete combustion conditions, also indicated by the relatively low $CO_2$ concentration (inserts having an air excess rate of approximately 250% indicates that theoretical mean $CO_2$ concentrations of up to 8.3 % are achievable).

Thus it ought to be possible to improve the combustion conditions, leading to higher $CO_2$ concentrations, higher flue gas temperature (and consequently more or less unaffected thermal efficiency), and lower CO concentrations, for benefit of the external environment, as the stove would emit less organic carbon residuals in the flue gas.

However, in comparing the two appliances one should bear in mind that the Danish stove was tested at ideal test conditions and settings during a type test, whereas the Portuguese insert appliance was tested in a university environment (testing conditions similar to that established by the European standard), and considering normal user operating conditions.

As a consequence, there is still a demand for improving the test methods and developed a mathematical tools (numerical models) that will integrate and describe both the combustion and heat transfer processes involved. The use of numerical models will permit to identify solutions to save considerable amounts of energy in households, for example through both a more efficient energy utilization and storage.

The develpment of a new energy simulation computerized tool will help the manufactures and technical consultants to design more efficient wood-burning stoves adapted to different types of building constructions and wood fuels all over the world.

**Aknowlegements**

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