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Effect of excess air on the optimization of heating appliances for biomass combustion

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Abstract

The performance of a domestic appliance for wood logs combustion is a function of several variables, such as the geometric design of the appliance and its operating parameters. Among them, air feeding conditions are really decisive if the objective function is the maximization of the heat recovered from flue gases. Therefore, even if pollutant emissions have to be ever considered, the amount of excess air can be seen as a fundamental parameter in the definition of thermal efficiency of the appliance.

In this paper the role of this parameter is analysed. The analysis is conducted by linking the results obtained from experimental data, detailed CFD simulations and a simplified mathematical model based on a network of CSTR. The derivation of an idealized schematization of the appliance was essential to realize the role of excess air variations, with more generality than with respect to a specific appliance configuration. Conversely, while the experimental data and CFD results were necessary to derive the simplified model, the indications given by this simplified model were useful to analyze results coming from both experiments and detailed numerical simulations.

It has been evidenced the need to distinguish between the role of excess air in the chemical combustion and in the heat recovery in the appliance as well as to quantify the feedback between these two processes.

Keywords: Renewable energy; Biomass combustion; CFD; Optimization

1. Introduction

Biomass fuels and their derived products can contribute significantly to the global energy supply, sharing in the pursuit of a sustainable development. The use of energy from biomass has many unique qualities that provide environmental benefits: it can help to mitigate climate change, to reduce CO_2 emissions and acid rains, to provide wildlife habitat, and to maintain forest health through better management. Among biomass species, wood and its wastes are the most common fuels (64%) and their direct combustion is the most important and mature technology nowadays available for their utilization [1]. Nevertheless, wide margins for improvements with respect to efficiency, emissions, and cost can be still further exploited for both domestic and industrial appliances. So, a wider adoption of suitable biomass combustion systems has a potential for a better economy while reducing the environmental impact [2].

Various approaches are suggested in literature aimed at increasing the efficiency of the appliances, or focused on the reduction of pollutant emissions varying both geometric variables and operating parameters. All these studies show a strong influence of the analyzed variables on the performance of the appliance, so they allow the determination of more suitable configurations. In the great number of activities and studies involved in the optimization of appliances for wood combustion, computational fluid dynamic (CFD) can be a very useful tool. Focusing on the improvement of thermal efficiency through the optimization of geometric parameters, Ravi et al. [3] presented an approach in which detailed CFD simulations of the flow,

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Nomenclature

$A_{M,N}$	surface extension (m^2)
C	carbon content of test fuel (% wt)
$c_{p,i}$	specific heat of species i (kJ/(kg K))
Cr	carbon content of the residue passing through the grate, referred to the quantity of test fuel fired (%wt)
CO	CO in the dry flue gases (% vol.)
CO_2	CO_2 in the dry flue gases (% vol.)
H	hydrogen content of the test fuel (% wt)
$\dot{M}_i$	mass flow of species i (kg/s)
Q	thermal power (kW)
T	temperature (K)
U_N	coefficient for conductive more convective flux (kW/(m^2 K))
κ_N	model coefficient for radiative flux (kW/(m^2K^4))
λ	excess air (%)
W	moisture content of the test fuel (% wt)

Subscripts

1	first reactor
2	second reactor
CC	conductive plus convective
G	total heat
RAD	radiative
St	stoichiometric
W	heat to water
Wall	relative to surface.

heat transfer, and chemical processes are conducted for a simple sawdust stove, attaining a better configuration for the stove geometry. Bryden et al. [4] used CFD analysis coupled to a graph based evolutionary algorithm to upgrade the heat transfer in a cook stove. The optimization variables were the position and size of some baffles that influence the swirl of the gas flow. Also Scharler et al. [5] studied the influence of the geometric characteristics of the appliance by means of CFD simulations with a simplified model for the chemical process. Two different combustion chambers and grate systems were simulated to determine the effect of the gas flow recirculation and the air staging on efficiency and pollutant emissions.

All these studies, apart from the work of Scharler et al. [5], even if successful in the proposition of modifications of the initial design able to improve the efficiency of the appliance, lack a general analysis that can be easily extended to different configurations.

A reason is that the optimization analysis of such systems with the help of CFD simulation is quite complex, due to the great number of variables involved and to the high computational cost of detailed CFD models, while the study of the effects of variations of each optimization variable requires a large number of tests for different configurations of the appliance. Furthermore, the geometry of the appliance is one of the main design variables and the creation of the computational mesh is a complex and time consuming step that cannot be automated for large geometry variations. Even if optimization algorithms can be invoked to reduce the computational effort [4,6], this approach can hide all the possibilities if a preliminary estimate of the performance theoretically achievable is not evident.

This work was promoted by the consideration that, if we assume reasonable to perform a large number of optimization tests, we obtain an enormous number of data and it becomes very difficult to manage and analyze them without a proper framework. This helps both to improve the optimization process of a single appliance but also to identify the beneficial mechanisms that can be adopted in other configurations. We approached the optimization problem firstly in a simplified way, establishing whether it is possible to determine simple and general guide-lines to be followed during the study.

Another important reason comes from having recognized that a preliminary analysis of the influence of the main parameters is necessary to identify the margins available for the optimization and how much this margins can be increased by acting on the several parameters that can be varied.

This approach was for instance followed by Wiinikka and Gebart [7]. They, coupling CFD analyses with experimental measurements of a laboratory small-scale combustor, investigated the effect of primary air factor, total air factor and magnitude of the swirl in the combustion chamber on the level of particulate emissions, providing insights that can be used for the optimization of emissions from wood combustion systems.

Apart from the role on pollutant emissions, excess air is the most important parameter also in the definition of the efficiency of the combustion process. Tillman underlined that this parameter, together with wood composition and its heating value and moisture content, is an important factor for both the combustion efficiency and the flame temperature that are, respectively, a measure of the quantity of heat released and of the quality of heat available [8]. Therefore, in this paper we focus on the effect of excess air on efficiency.

A theoretical calculation of the total efficiency with respect to the excess air fed, parametrically with respect to flue gas temperature and in the hypothesis of complete fuel oxidation, can be obtained assuming the appliance as a black box where the complete combustion of wood is realized and all the heat generated is recovered or lost with the flue gas (a similar calculation is proposed in [8]). Results are reported in Fig. 1 and they represent the