Preliminary CFD analysis of a ventilated chamber for candles testing

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Abstract

As candles have grown in popularity with consumers over the last few years, so has the potential safety concern with their use in indoor environments. Carbon monoxide, particulate matter and different volatile and semi-volatile species can be found in candles emissions. Currently it is not possible to predict theoretically which emissions will be produced by a specific candle and in order to quantify real emissions is still necessary to proceed with experimental tests. A common way to quantify released pollutants is to burn candles in a well-controlled environment, such as a laboratory-scale test chambers. Obviously, it is required that these chambers are able to reproduce the environmental combustion regime of the candles, so as to guarantee that an equal level of emissions is produced and measured. Another crucial point is related to the measurements themselves: generally, air quality is measured in a single point inside the chamber with the assumption that the air and the exhausts in that point are representative of the whole ambient. This work aims to reproduce one of these chambers by means of a CFD (Computational Fluid Dynamics) model, with the purpose of obtaining an adequate tool to analyze and design more efficient test chambers. A comparison with an ad hoc experiment is performed to validate the CFD model.

Introduction

Both indoor and outdoor sources affect the concentration and composition of pollutants in indoor air. There is usually more information available on emission characteristics, such as emission factors or emission rates, of outdoor pollutants sources than of indoor ones. However, the assessment and quantification of emissions from indoor sources is very important for assessing the human exposure to pollutants; it allows to relate measured values with recommended guidelines for indoor air quality and, eventually, to identify the possible scenarios and limitation of use that still guarantee healthy air conditions. Combustion processes are the main indoor sources of smaller particles. Gaseous pollutants from combustion play also an important role because they can affect directly the human health or they can act as precursors of secondary particles in the indoor environment, through the process of gas-to-particle conversion.

Over the years many experiments have been made to improve knowledge of the candles burning mechanism. Probably the first modern study on the candles burning was presented by Faraday [1] who has been followed by studies on various aspects such as burning candles in microgravity conditions [2]. Following in particular the development of the scented candles market, a part of the available literature had focused on the possible harmful emissions produced by candles and air quality standards, since the preliminary studies of Lau et al. in the 1997 [3]. More recent papers have been published where the use of a test combustion chamber has been adopted. Previous works of Derudi et al. should be collected in this vein [4] [5] and the present work refers to the same test chamber. Surprisingly, there is not a corresponding development in CFD modeling of candles, with only a few contributions. One interested in CFD modeling can refer at the Abbasi's work [6] on the reproduction of a candle with focus on soot emissions, and the recent studies of Gritter et al. [7], but nothing seems to has been written about the possible influence or interaction between the test chamber and the candles utilized during the tests. Therefore, this study has been focused on the development of a CFD method that can reproduce correctly, with reduced calculation times, the effects of the combustion of a candle inside a ventilated chamber with the aim to evaluate the capability of the test chamber both to reproduce realistic burning conditions and to ensure proper sampling and characterization of the candle exhausts.

Experimental setup

As a crucial point in the determination of the emissions concentration is the simulation of realistic conditions for burning candles, a special enclosed chamber has been developed to ensure defined burning conditions and the possibility to perform a gas sampling of the exhausts without turbulences. The test chamber exhibit a volume of about 170 l, and it is equipped with an air sparger, set on the bottom of the equipment, to supply the inlet-air to the chamber with minimum turbulence and spatial velocity. For all experiments pre-cleaned air, passed through a charcoal trap, has been used; moreover, to ensure the filter effectiveness during each run a blank measure has been also made on the air fed to the chamber. The air flow rate in the test chamber was adjusted in order to reach realistic burning conditions. Furthermore, equipment to monitor temperatures as well as a system for the sampling and characterization of the main combustion products (O_2, NOx, CO and CO_2) within the test chamber at different positions completes the experimental apparatus (Fig. 1). To determine the wax consumption every candle is weighted before and after the burning experiment and the corresponding burning time is recorded.

CFD model

As previously mentioned, one of the aims of this work was to obtain a fast tool to evaluate the performances of a ventilated chamber for combustion tests. The experimental layout has been thought to guarantee the possibility to take advantage of an axial symmetry and consequently, the computational grid was constructed as a radial slice of the chamber, with a particular refinement zone in the combustion area. Where it was possible a quad mesh was implemented to speed up calculations, as evidenced by Fig. 2.

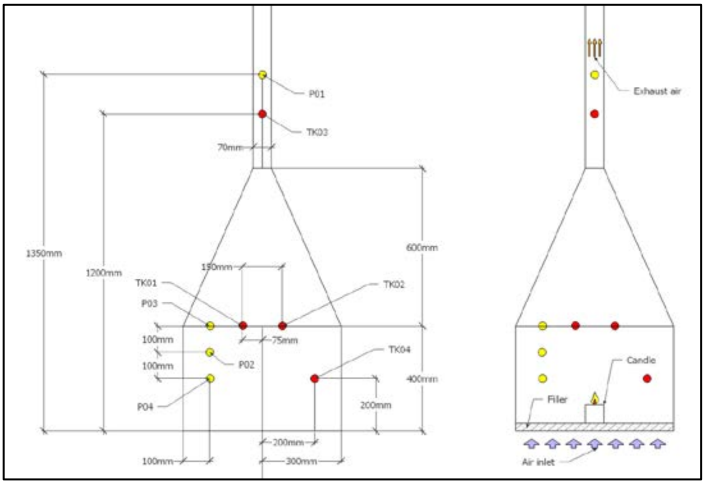

Figure 1. Schematic of the combustion chamber with sensors positions (TK = thermocouple type K; P = gas probe)

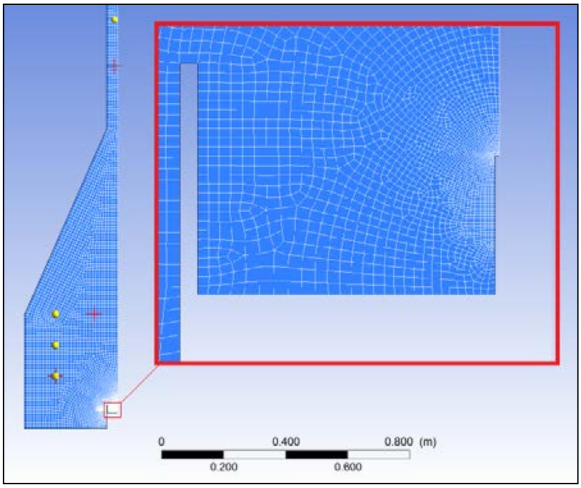

Figure 2. Global mesh with sensors positions highlighted (red crosses – thermocouples, yellow dots – gas probes) and detail of mesh refinement in the candle region.

In this work the commercial package Ansys Fluent® [8] has been used with standard k-ϵ model for turbulence, and eddy dissipation model to describe the combustion reaction. It has been chosen to utilize a simple volumetric reaction because, not being interested in accurate reaction description, this was the fastest and easiest way to describe the wax combustion process. Following this simplified approach, the candle was assumed to be completely made by n-eicosane, a medium length paraffin wax which stoichiometric combustion reaction is:

$$C_{20}H_{42} + 30.5\, O_2 \rightarrow 20CO_2 + 21H_2O \qquad [1]$$

Fuel was introduced in the computational domain as a mass flow rate of gaseous specie, at n-eicosane boiling temperature (617 K) and equal to the measured mass loss rate of the candle, about 2.3 g/h. A fundamental aspect of this CFD analysis is related to boundary and initial conditions. In fact, the low heat released by a single candle leads only to minor alterations inside the chamber, events which make difficult to separate the net contribution of the candle from possible fluctuations of the environmental conditions. In Table 1 air composition of the admission flow is reported both for CFD simulation and experimental test (CFD values were selected accordingly with experimental measurements when data were available and on reasonable hypothesis for the other species). Thermal boundary conditions were assumed to be uniform, equal to 297 K, with the exception of the chamber walls, which were supposed to be at a constant temperature of 300 K.

Table 1. Air composition referring to 15 NL/min of inlet flow

	N_2 [%]	O_2 [%]	CO_2 [%]	H_2O [%]
Experimental	n.a.	20.20	0.20	n.a.
CFD	78.50	20.20	0.20	0.50

Results

Several experimental runs, with a single paraffin jar candle, were performed and the results highlighted that steady state conditions are reached after about 3000 s, with low temperature rise and small variations of measured concentration, as shown in the example of Fig. 3 and Fig. 4.

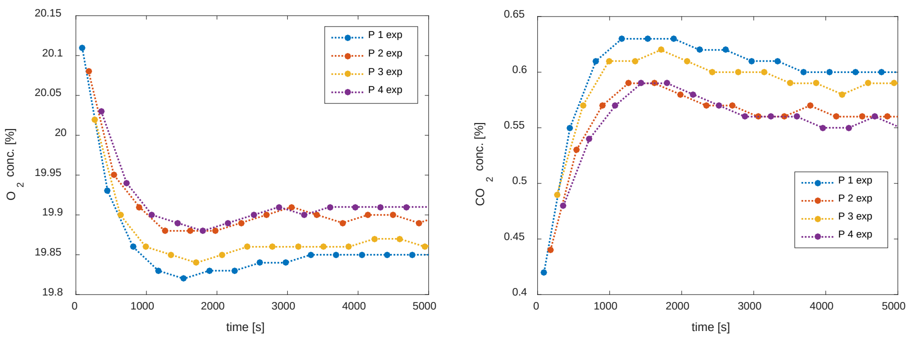

Figure 3. Experimental trends of CO_2 and O_2 measured within the test chamber

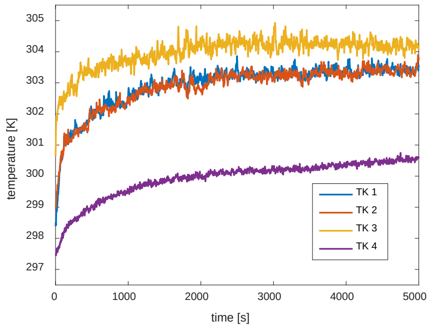

Figure 4. Temperature evolution in the test chamber

From these results, that highlight also a slight stratification of the measured species along the vertical coordinate of the ventilated test chamber, some reference values have been extracted (Tab. 2), to perform a preliminary comparison with CFD results obtained from steady state simulations, reported in Fig. 5.

Table 2. Experimental measured concentrations and temperature at steady state

	P01	P02	P03	P04
O_2 [%]	19.85	19.89 – 19.90	19.86 – 19.87	19.91
CO_2 [%]	0.59 – 0.60	0.56	0.59	0.55 – 0.56
	TK01	TK02[1]	TK03	TK04
T [K]	303.3	303.3	304.2	300.1

[1]TK02 is symmetric to TK01, consequently it is not represented in the CFD plots.

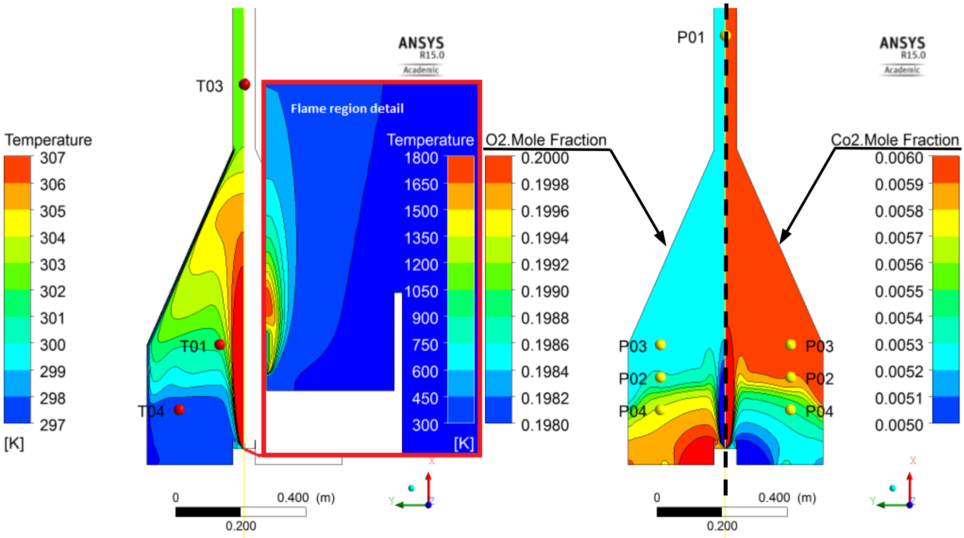

Figure 5. CFD results for temperature, CO_2 and O_2 concentrations

The contour plots of Fig. 5 evidence a reasonable agreement between CFD and experimental results; a comparison between CFD data and average values of temperature highlights that probably the thermal stratification in the real chamber is not so well defined as in the CFD model. On the other hand, it is worth to be notice that good mixing conditions can be obtained in the conical section of the test chamber, thus creating homogeneous and steady distribution of oxygen, main combustion products and possible micro-pollutants within the exhausts; this is of paramount importance because the characterization and quantification of the candle emissions is based on the gas sampled from the chamber exit section and any negative effect due to fluctuations and inhomogeneity of the flow field must be limited.

Conclusions and further developments

The use of CFD to reproduce the interactions between a burning candle and a test chamber looks like to provide reliable results, although further tests are necessary to obtain a final validation of the model. Also the speed of the simulations is currently guaranteed by the mesh axial symmetry, so further analysis is required to find a method which allows to study different configurations in a short time.

References

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