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CHIMNEYS IN WOODEN ROOFS: A 3D STEADY NUMERICAL MODEL FOR THE PREDICTION OF THE TEMPERATURES

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ABSTRACT

Chimneys convey exhaust gas produced in domestic heat appliances to the external environment and to do this they have to pass through floors and roofs: if these elements are made up of flammable materials, the fire hazard may occur. This article presents the verification of a 3D numerical model set for the determination of the stationary temperatures reached on the flammable materials in the vicinity of chimneys. The verification has been done comparing the temperatures measured in experimental tests with those estimated by means of the numerical model. Results show that the 3D numerical model is a valid tool for the analysis of heat transfer between chimney and roof. Since in the experimental tests it is not always possible to reach stationary temperatures, a lumped element model to estimate them is also proposed and it could support the chimney certification.

Keywords: *Flammable material, Chimney, Numerical model.*

1 INTRODUCTION

The increasingly attention to sustainability and energy saving has lead to the use of materials such as wood, straw and wood fiber, that are insulating but at the same time flammable, that is, if exposed to a heat source they can ignite. For this, a critical point is represented by the passage of chimneys through elements made up of these materials, such as roofs and floors.

The heating of flammable materials exposed to chimneys was widely investigated in the past [1], and the majority of the studies focused on the heating of wood [2–5]. Since the problem of roof fires due to the passage of chimneys has been highlighted in Italy and in others European countries [6–8], recently studies focus on the UNI EN ISO 1859 standard [9]. The standard [9] prescribes two heat tests by means of which the distance to be respected between chimneys and flammable materials is determined. Deficiencies related to the smoke temperature measurement were highlighted by [10]. Testing chimneys in all the possible conditions would make safe installations, but, at the same time, it would result in cost not affordable by chimney producers. However, an accurate numerical model can substitute the real case [11].

The aim of this study is the verification of a 3D numerical model designed for the estimation of the stationary temperature on flammable materials in the vicinity of a chimney. To do this, temperatures estimated with the numerical model have been compared with those measured in experimental tests and then elaborated by means of a lumped element model. The achievement of the stationary condition is not always possible and the prescriptions of the standard [9] imply to stop the tests before the achievement of it. However, the lumped element model allows to estimate the stationary temperature from measured data.

2 Materials and Methods

2.1 Experimental test

The UNI EN ISO 1859 standard [9] prescribes two tests by means of which the distance to be respected between chimney and flammable materials is determined: the thermal stress test that reproduces the functioning of chimneys in stationary conditions, and the thermal shock test that reproduces the soot fire conditions. To perform the heat stress test, the one analyzed in this article, chimneys have to be installed in a test structure following the manufacturer prescriptions and to be connected to

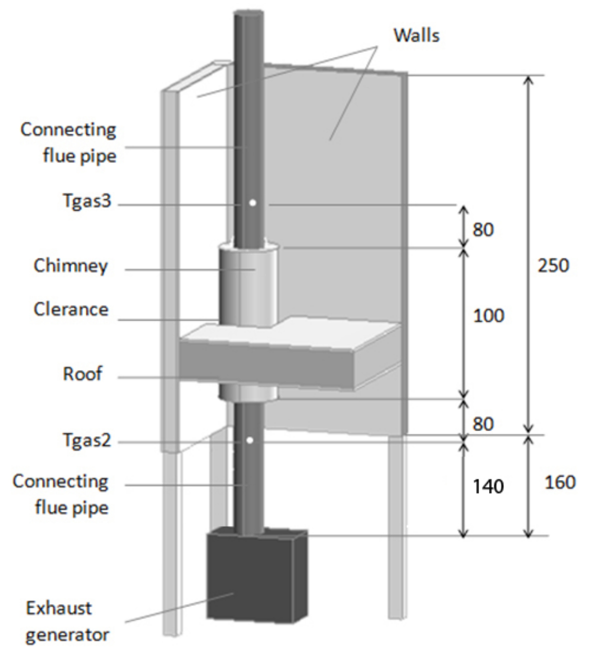

Figure 1. Test structure scheme. Dimensions are in centimeters.

Table 1. Summary of the tests and their characteristics. The acronymus a.a.t. means aluminum adhesive tape.

ROOF	CLEARANCE SEALING MODE	TEST	CLEREANCE SEALING MATERIAL	T_{ch} [°C]	T_{env} [°C]
Roof 1	Sealed	$R1_{ms}$	Sheet of lead and a.a.t	547.8	22.2
	Sealed	$R1_{ad}$	Mineral wool panels 5 cm thick and a.a.t	587.2	30.3
	Filled	$R1_{fi}$	Super wool 96 Kg/m^3	570	29.6
Roof 2	Sealed	$R2_{ms}$	Aluminum sheets 0.1 mm thick and a.a.t	499.9	21.5
	Sealed	$R2_{ad}$	Wood fiber panels 6 cm thick and a.a.t	504.9	21.3
	Filled	$R2_{fi}$	Super wool 96 Kg/m^3	501.4	20.8
Roof 3	Sealed	$R3_{ms}$	Aluminum sheets 0.1 mm thick and a.a.t	499.8	21.7
	Sealed	$R3_{ad}$	Wood fiber panels 6 cm thick and a.a.t	503.3	19.2
	Filled	$R3_{fi}$	Super wool 96 Kg/m^3 and a.a.t	495.8	21.4

an exhaust gas generator. The test consists in producing exhaust gas at a chosen temperature and in measuring temperatures on the test structure until the achievement of the final test condition, i.e., when the increase in temperature on the test structure is less than 2 °C in 30 minutes. If the flammable materials temperatures are lower than 85 °C, the chimney is certified. The experimental tests in which the temperatures reported in this paper were measured, were performed installing a chimney in the test structure shown in Figures 1 and 2. The test structure is made up of two walls at right angle and an interchangeable roof, and it is supported by three pillars, one of which is placed between the two walls and it extends for their full height. A cylindrical double metal walls chimney was installed 20 mm far

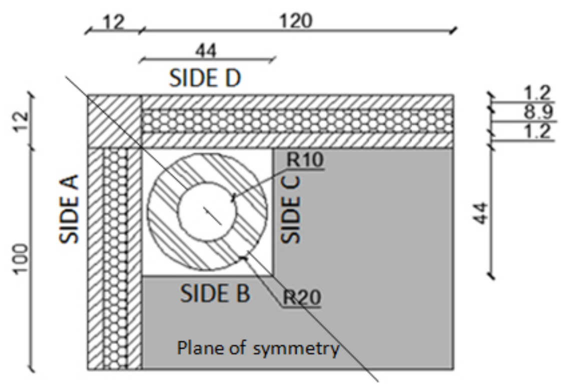

Figure 2. Top view of the structure. Dimensions are in centimeters.

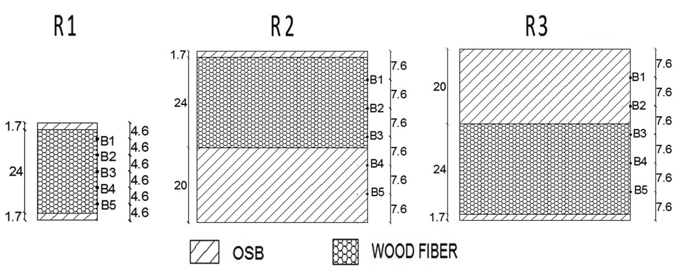

Figure 3. Roofs tested in the experiments. The thermocouples position is indicated with letter B. Dimensions are in centimeters.

from flammable materials, so a clearance was formed between the chimney and the structure. In the experimental campaign three roofs and three clearance sealing modes were tested: each roof was tested with each clearance sealing mode for a total of nine tests whose characteristics are summarized in Table 1. Each test is identified by an acronym: the first two letters indicate the roof on which the test was performed and the subscript indicates the clearance sealing mode. The roofs are shown in Figure 3: roof R1 is similar to the thicker roof prescribed by the standard [9], roofs R2 and R3 are representative of roofs in energy saving buildings and they have same thickness and thermal resistance but different layers position. The tested clearance sealing modes are: sealed by means of metal sheets (*ms*), sealed by insulating material (*ad*) and filled with insulating material (*fi*). The sealing with metal sheets allowed air movement in the clearance and heat transfer through the sealing, the sealing with insulating material allowed air movement in the clearance but prevented heat transfer through the sealing, approaching an adiabatic condition, and the filling prevented any air movement in the clearance.

During the tests, every 10 seconds, the exhaust gas temperature (T_{gas2}, T_{gas3}), the environment temperature (T_{env}) and the flammable materials temperature were measured. The exhaust gas temperature in the chimney T_{ch} was calculated as average of T_{gas2} and T_{gas3} that were measured at the chimney inlet and outlet respectively, as shown in Figure 1. The flammable materials temperatures were measured by means of 20 thermocouples positioned in the clearance as shown in Figure 4: on each side of the clearance, five thermocouples were attached and each thermocouple was identify by means of the side letter followed by a

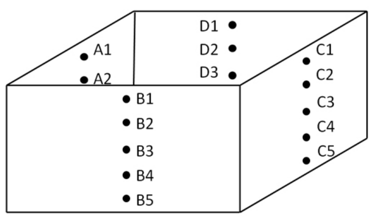

Figure 4. Thermocouples position in the clearance between chimney and test structure.

number ranging between 1 and 5 (number 1 indicates the upper thermocouple and number 5 the lowest). Since the conditions on the wall sides (A and D), and the roof sides (B and C) are the same for symmetry reasons, one unique temperature value (calculated as average of them) was determined for each pair of corresponding thermocouples (i.e. positioned at the same height). Five temperatures were calculated for the walls and five temperatures were calculated for the roofs.

K thermocouples have an uncertainty of $\pm 2.8\,^{\circ}$C for temperatures ranging between $0\,^{\circ}$C and $350\,^{\circ}$C and of 0.75 % for temperatures ranging between $350\,^{\circ}$C and $1260\,^{\circ}$C. The uncertainty of the DaQ is $\pm\ 0.02\,^{\circ}$C. Uncertainty of temperatures was determined as the sum of the uncertainty related to the measuring instruments and that related to the data elaboration, indeed final temperatures were determined as average of temperatures measured in the last five minutes of the tests. The uncertainty is $\pm 2.8\,^{\circ}$C for environment temperatures and $\pm 2.9\,^{\circ}$C for measured gas temperatures (T_{gas2}, T_{gas3}). Final flammable materials temperatures have been determined as average of two values and the related variability as been determined as their difference.

2.2 Lumped element model

A body of volume V, surface A, immersed in an environment at a uniform temperature T_f with coefficient of convection h, heats (or cools) following an exponential trend

$$\frac{T_i - T_f}{T_s - T_f} = e^{-lt} \tag{1}$$

where

$$-l = \frac{hA}{V c_p \rho} \tag{2}$$

if the temperature of the body T (Bi$\ll$1) and the initial temperature T_S are uniform, and the environment temperature T_f is constant.

It has been assumed that the thermocouples in their heating follow an exponential trend and, being very small, it can be assumed that their temperature is uniform. Given that in addition to convection, conduction occurs, or even in the case of filling there is only conduction, the meaning of T_f and l terms are different and must be determined from measured data.

A lumped element model has been designed so as to estimate the stationary temperature determining the interpolating function that makes the determination coefficient R^2 the highest as possible. The determination coefficient is a measure of how well the interpolating function approximates the real data and R^2 equal to 1 indicates that the regression line perfectly fits the data.

The step for estimating the stationary temperatures are:

1. Detemination of the dimensionless temperatures T_{a_i} from measured temperatures T_i

$$T_{a_i} = ln\left(\frac{T_i - T_f}{T_s - T_f}\right) \tag{3}$$

   where Ts is the initial temperature and T_f is the stationary temperature that initially has to be hypothesized on the basis of the temperatures time traces.

2. Linearization of the temperature time trace by means of the following equation

$$T_{c_i} = n + m \cdot (t_i) \tag{4}$$

   where T_{c_i} is the temperature calculated at the time step t_i, n is the intercept on the y-axis and m is the slope of the function and they are calculated as

$$m = \frac{\sum[(T_{a_i} - \bar{T}_a)\cdot(t_i - \bar{t})]}{\sum(t_i - \bar{t})} \tag{5}$$

$$n = \bar{T}_a + \bar{t}\cdot(m) \tag{6}$$

   where $\bar{T}_a$ is the means of the dimensionless temperatures, $\bar{t}$ is the means of the time intervals.

3. Estimation of the stationary temperature T_f that corresponds to the highest determination coefficient R^2 that is calculated as

$$R^2 = \left[\frac{N\cdot\sum(T_{a_i}\cdot T_{c_i}) - \sum T_{a_i}\cdot\sum T_{c_i}}{\sqrt{(N\cdot\sum T_{a_i}^2 - (\sum T_{a_i})^2)(N\cdot\sum T_{c_i}^2 - (\sum T_{c_i})^2)}}\right]^2 \tag{7}$$

   where N is the number of considered values.

In the following, with *measured data* are intended the temperatures measured and then elaborated by means of the lumped element model.

2.3 The 3D numerical model

To reproduce the conditions occurred in the experimental tests, a 3D numerical model has been designed. To reduce the number of cells and then to facilitate the simulations, only half of the test structure has been simulated and a symmetry condition has been imposed on the symmetry plane as shown in Figure 5. The vertical extension of the chimney has been limited at 200 mm beyond the upper and lower part of the roof for the roof R1, 100 mm for R2 and R3. Only a part of the walls has been represented in the model and their extension has been

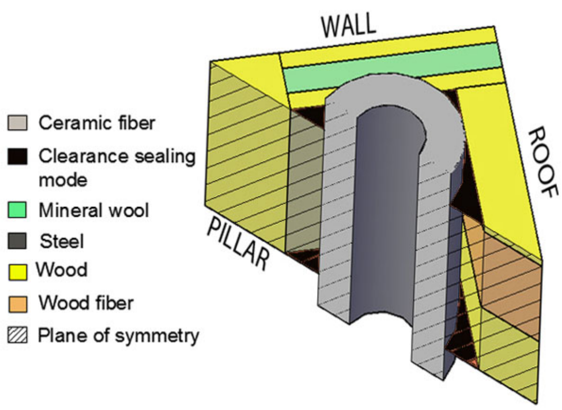

Figure 5. Rappresentation of the 3D model.

Table 2. Thermal conductivity λ [W/mK] of the materials as a function of the exposure temperature T [$^\circ$C].

T [°C] / MATERIAL	20	50	100	200	300	400	600	700	800	1000
Ceramic fiber	_	_	_	0.06	_	0.1	0.15	_	0.2	0.27
Mineral wool	_	0.035	0.043	0.069	0.079	0.104	_	0.22	_	_
OSB	0.12	_	_	0.15	_	_	_	_	_	_
Steel	15	_	_	_	_	_	_	_	_	_
Super wool	_	_	_	0.05	_	0.09	0.14	_	0.21	0.29
Wood fiber	0.037	_	_	_	_	_	_	_	_	_

chosen equal to the thickness of the considered roof. The grids have been created with the preprocessor Gambit and they are characterized by hexahedrical cells of dimension 3 mm in the clearance and of greater dimension into the roofs. The cells were more dense near the clearance in order to allow the software to perform an accurate computing in the areas of transition from conduction to convection. For the simulations in Fluent, in the clearance both free convection and radiation have been considered when it was sealed, but only conduction in the cases in which it was filled. For free convection contribution, the Boussinesq model has been used, with air considered as a fluid with thermal conductivity 0.0242 W/(mK), density 1.225 kg/m^3 and coefficient of thermal expansion 0.00268 K^{-1}. For the radiation contribution the Discrete Ordinates (DO model) has been chosen. Moreover the default laminar model has been set up because the Grashof number is always in the range of laminar regime.

The boundary conditions set in the model are:

- heat transfer coefficient h_{e1}=15 W/m^{2}K on the upper horizontal surface of the roof and on the external vertical surface of the chimney;
- heat transfer coefficient h_{e2}=5 W/m^{2}K on the bottom horizontal surface and on the lateral vertical surfaces of the roof;
- heat transfer coefficient h_i=10 W/m^{2}K on the internal surface of the chimney;
- adiabatic condition on the extremities of the chimney.

The filling of the clearance has been simulated by an homogeneous solid, while the sealing has been simulated by acting on the upper and the lower surfaces of the clearance indicated in black color in Figure 5. In particular, the sealing with insulating material has been simulated imposing the adiabatic condition, while in the sealing with metal sheets the convective heat transfer coefficients on the sealing have been set.

For all the other solids and lines, the thermal conductivity λ has been expressed as piecewise-linear function of the exposure temperature and the values are indicated in Table 2. The model requires to set the environment temperature T_{env} and the exhaust gas temperature T_{ch} that for the tests here analyzed are reported in Table 1.

3 Results and discussion

The first step of the analysis has been the determination of which measured data has to be used for estimating the stationary temperature by means of the lumped element model. Then, the verification of the numerical model has been done comparing the temperature distribution and the maximum temperature values obtained by means of simulations with those measured in the tests.

3.1 Stationary temperature estimation

To estimate the stationary temperature T_f by means of the lumped model presented in the previous section, it is necessary to enter the temperatures T_{ai} measured during the heat stress test. The analysis proposed in this section is intended to check what data to enter and to understand if the final test condition proposed by the standard [9] allows to collect enough data for the computing of the stationary temperature T_f

The verification has been done considering the temperature time traces shown in Figures 6 and 9. In both cases the stationary temperature has been approached; the temperature time traces are characterized by a segment concave up, a next segment concave down and a final flat segment, while the time traces related to tests in which the stationary temperature has not been approached do not present the final flat segment. The main difference between these two time traces is that the time trace in Figure 9 presents less oscillations than that in Figure 6.

The standard [9] defines the final test condition achieved when the increase in temperature on flammable materials is less than 2 $^\circ$C in 30 minutes. The temperatures from the beginning of the tests until the achievement of the test final condition have been considered, and the temperatures succeeding this instant have been excluded from the analysis and used for verification. In particular, the research of the most suitable initial instant t_s has been done considering several time frames whose final instant t_f is that of the achievement of the final test condition defined by the standard [9]. Considering time lapses starting from the initial instant t_s so identified, the final instant t_f has then been researched. The instants that have allowed to estimate a temperature more close to the stationary temperature have been considered the most suitable.

The time trace in Figure 6 is related to thermocouple C2 in the test R3$_{ms}$, in which the final test condition was achieved after 4 hours when the temperature was 63.40 $^\circ$C, but the time trace suggests that the stationary temperature is approximately 65 $^\circ$C. The stationary temperatures estimated considering different initial instants t_s are reported in Figure 7. It can be seen that, by choosing an initial instant t_s in the concave up part of the function leads to an erroneous stationary temperature, while by choosing an initial instant in the zone where the time trace is concave down allows to estimates temperatures closer to the identified value. The research of the final instant t_f has been done considering the initial instant t_s equal to 1.5 hours and the results are reported in Figure 8. It can be seen that considering the four first values, that is 2, 2.5, 3 and 3.5 hours, does not allow to estimate a correct stationary temperature T_f: this is probably due to the fact that in these points the temperature time trace shows oscillations. For the next instants, that is 4, 4.5 and 5 hours, the estimation is more correct. By considering a longer time frame, the lumped element model can detect the exponential trend easily. Then, it seems that the achievement of the final test condition allows to estimate the stationary temperature also if the time trace is affected by fluctuations. The time trace in Figure 9 is related to thermocouple A5 in the test R2$_{ms}$. The measured temperature time trace suggests that the stationary temperature is approximately 63 $^\circ$C. The final test condition defined by the standard [9] was achieved after 3.75 when the temperature was about 57 $^\circ$C. In Figure 10, the temperatures estimated considering several initial instants t_s are reported. It can

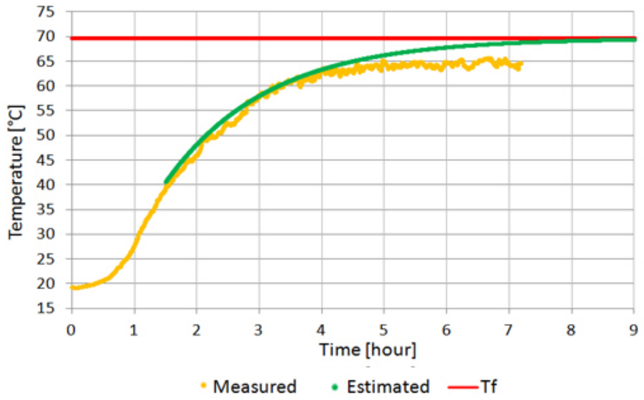

Figure 6. Temperature time traces measured and estimated for thermocouple C2 in the test R3$_{ms}$. T$_f$ is the estimated stationary temperature.

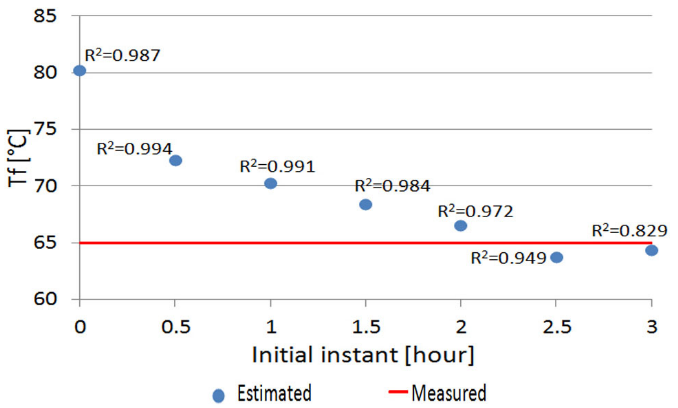

Figure 7. Stationary temperatures and determination coefficient R^2 estimated for different initial instant (t$_s$) for thermocouple C2 in the test R3$_{ms}$. The final instant (t$_f$) has been chosen equal to 4 hours.

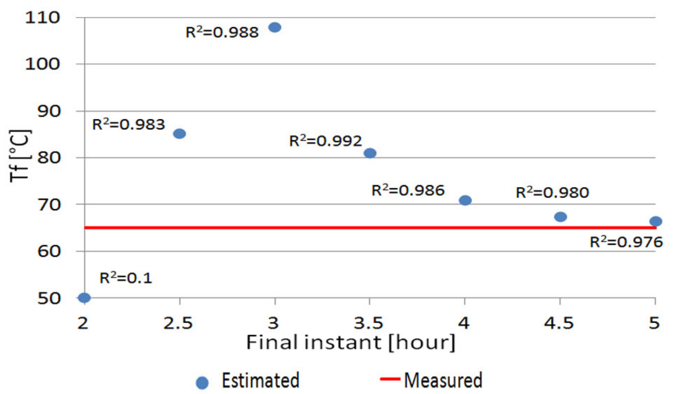

Figure 8. Stationary temperatures and determination coefficient R^2 estimated for different final instant (t$_f$) for thermocouple C2 in the test R3$_{ms}$. The initial instant (t$_s$) has been chosen equal to 1.5 hours.

be seen that the choice of the initial instant t$_s$ does not strongly affect the computing of the stationary temperature, because the estimated values are within a range of six degrees. However, the most suitable initial instant t$_s$ seems to be 2 hours, that is the instant just outside the zone where the function is concave up. Then, this instant has been considered as the initial instant in the research of the most suitable final instant and the results

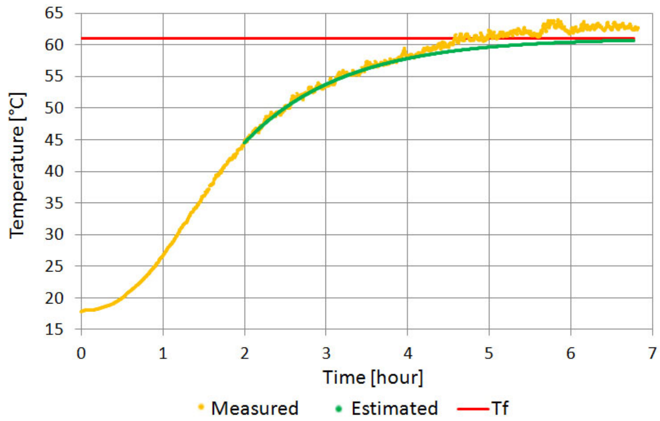

Figure 9. Temperature time traces measured and estimated for thermocouple A5 in the test R2$_{ms}$. T$_f$ is the estimated stationary temperature.

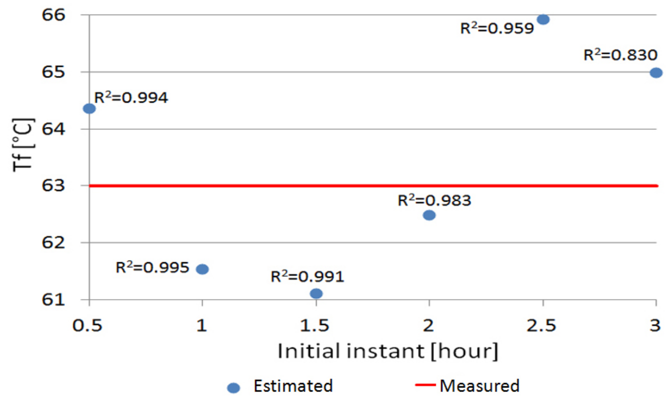

Figure 10. Stationary temperatures and determination coefficient R^2 estimated for different initial instant (t$_s$) for thermocouple A5 in the test R2$_{ms}$. The final instant (t$_f$) has been chosen equal to 3.75 hours.

are reported in Figure 11. Choosing the final instant equal to 2.5 hours lead to an erroneous computing because the estimated value is very low with respect to the identified value and the determination coefficient R^2 is very low: this is probably due to the fact that considering a time frame ranging between 2 hours and 2.5 hours, that is, only 30 minutes, the trend of temperature seems linear. However, the computing is not affected by considering longer time frames.

As a results of these considerations, the estimated temperature time trace reported in Figure 6 has been determined considering the time frame from 1.5 hours to 4 hours. The estimated stationary temperature T$_f$ is 69°C; this leads to a deviation of 3%. The estimated temperature time frame shown in Figure 9 has been calculated considering the time frame from 2 hours until 3 hours: it can be seen that the estimated temperature time trace well represents the measured time trace and the deviation is about 3%. Despite the test final condition defined by the standard [9] allows to obtain a good estimation of the stationary temperature, the lumped element model determines higher temperatures and therefore in favor of safety.

The lumped element model describes the heating of a body by means of a concave down function: for this, part of the temperature measured at the beginning (where the temperature time trace is concave up) has to be excluded, because it does not

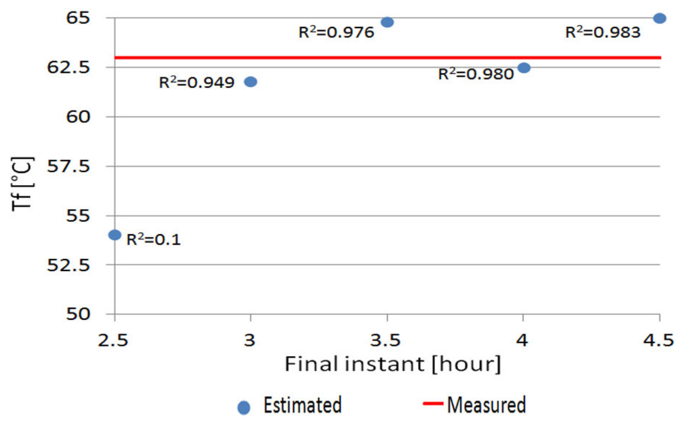

Figure 11. Stationary temperatures and determination coefficient R^2 estimated for different final instant (t_f) for thermocouple A5 in the test $R2_{ms}$. The initial instant (t_s) has been chosen equal to 2 hours.

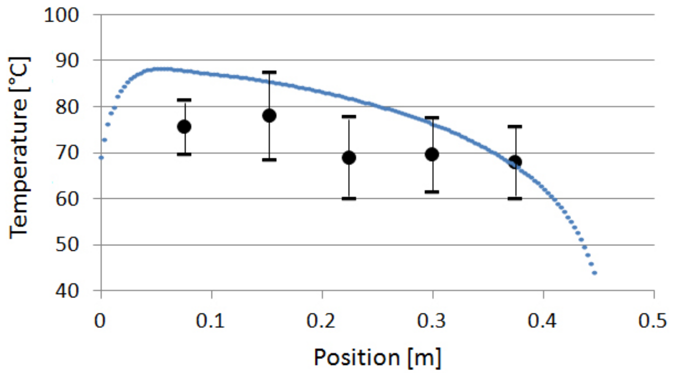

Figure 12. Comparison between simulated and measured temperatures on the walls for $R2_{ms}$.

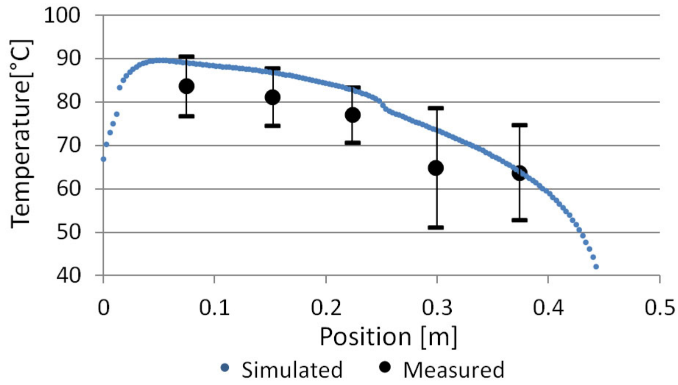

Figure 13. Comparison between simulated and measured temperatures on the roof for $R2_{ms}$.

follow the theoretical time trace of the lumped element model. Indeed, at the beginning of the tests, the exhaust gas temperature was not constant because a certain time laps was necessary to achieve the predetermined temperature T_{ch}. Then, it can be stated that in order to estimate the stationary temperature correctly, the initial instant t_s has to be chosen in a zone where the exhaust gas temperature T_{ch} has stabilized on the predetermined temperature, while the final instant t_f has to be chosen in a zone where the temperature tends to stabilize and does not present strong oscillations. The heat stress test should be stopped when the final test condition is achieved in order to collect enough data to be entered in the model. Nevertheless, even if the final test condition can not be achieved, in order to estimate the stationary temperature correctly, it is necessary to collect data until the instant in which the temperature time trace flattens, so to avoid to enter into the model temperature whose trend can be considered almost linear.

3.2 Comparison between measured and estimated temperature

The 3D numerical model estimates the stationary temperature on flammable materials in the vicinity of a chimney and, to verify it, temperatures estimated by means of it have been compared with those measured experimentally and then elaborated by means of the lumped element model (*measured temperature*). In particular, the comparison has focused on the temperature profiles and on the maximum temperature values.

Temperatures profiles are reported in Figures 12, 13, 14, 15, 16, 17, 18 and 19. Although only five measured temperatures are available, it can be stated that the position of the maximum temperature is detected by the numerical model. The estimated temperatures are higher than those measured: this result was expected because in the experimental tests it was not possible to completely avoid air infiltration in the clearance and this caused a cooling of the flammable materials. For the cases with clearance sealed by means of metal sheet (Figures 12 and 13), the conditions that occurred in the experimental tests were very similar to those reproduced by the numerical model. Since the estimated profiles are intercepted by the measured data, it can be stated that for this configuration the numerical model allows to correctly estimates the temperature on flammable materials. For the cases with adiabatic sealing and filled clearance, the experimental conditions were more far from those reproduced by the numerical model: the sealing by means of insulating panels (Figures 14 and 15) did not allow to approach a real adiabatic condition, and the filling of the clearance (Figures 16, 17, 18 and 19) probably was not homogeneous. Profiles in Figures 18 and 19 show measured temperatures closer to the estimated ones, than the profiles in Figures 16 and 17. In the first case ($R3_{fi}$) aluminum adhesive tape was attached to the filling in the clearance in order to avoid air infiltration through the insulating material. Then, it can be stated that also small air seepage affects the temperature of the roof. Comparing the profiles in Figures 17 and 19 it can be noted that the model well detects the temperature distribution in roofs having same thickness and thermal resistance, but different layers position.

Since the certification proposed by the standard [9] is based on the comparison of the maximum temperature measured in the heat stress test with the limit temperature of 85 °C, in Figures 20 and 21 only the maximum temperature measured on the roof and on the walls are reported. In these graphs, the more the points are close to the straight line, the more the measured values approach the simulated ones. Since the majority of the temperatures are close to the straight line, it can be stated that measured and estimated temperatures match except for the cases with very thick roofs and filled clearance ($R2_{fi}$ and $R3_{fi}$). For these two tests, the great thickness of the roofs did not allow to establish whether the filling was performed homogeneously: a possible discontinuity of the insulating material

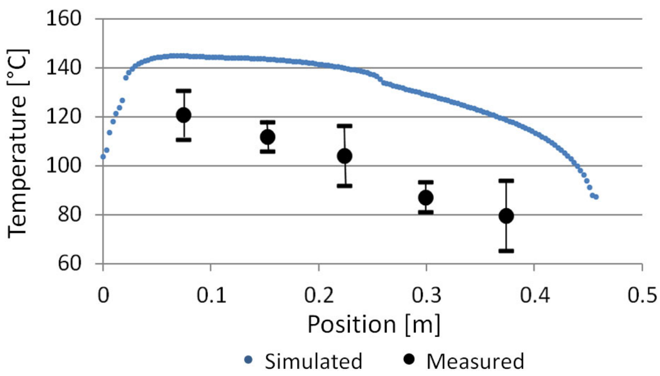

Figure 14. Comparison between simulated and measured temperatures on the walls for R2$_{ad}$.

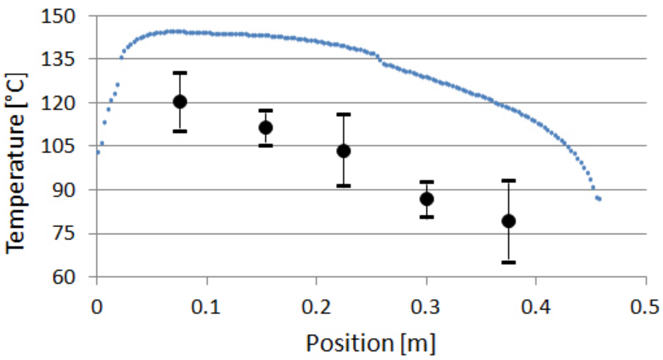

Figure 15. Comparison between simulated and measured temperatures on the roof for R2$_{ad}$.

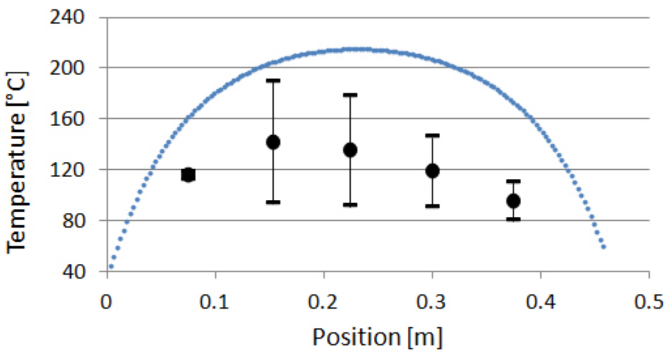

Figure 16. Comparison between simulated and measured temperatures on the walls for R2$_{fi}$.

may had allowed the passage of air and a consequent cooling of the flammable material. Indeed, for the case R1$_{fi}$ in which the thickness of the roof was limited and the filling was probably performed in a better way, the difference in temperature is lower. In real installations it is not possible to establish the quality of a sealing and consequently the quantity of air that flows in the clearance, then simulations can be considered a limit case that would occur if the sealing is done well enough to exclude any air infiltration. For a given installation, the temperature reached by flammable materials in real installations will certainly be lower than that estimated by the model.

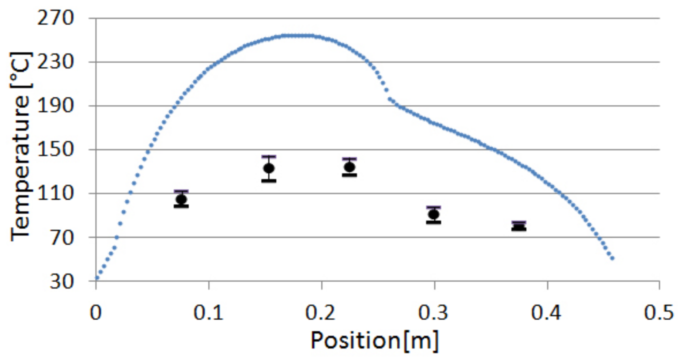

Figure 17. Comparison between simulated and measured temperatures on the roof for R2$_{fi}$.

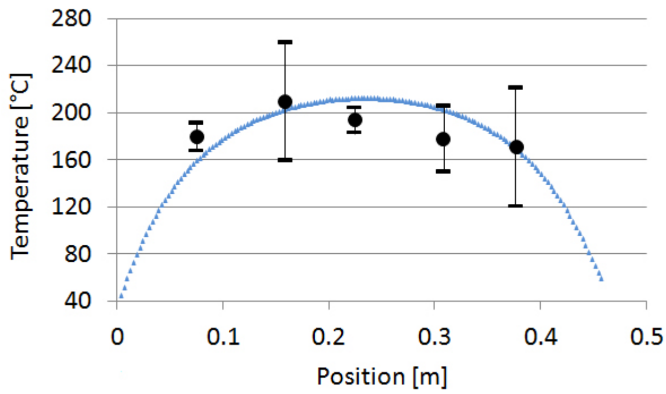

Figure 18. Comparison between simulated and measured temperatures on the walls for R3$_{fi}$.

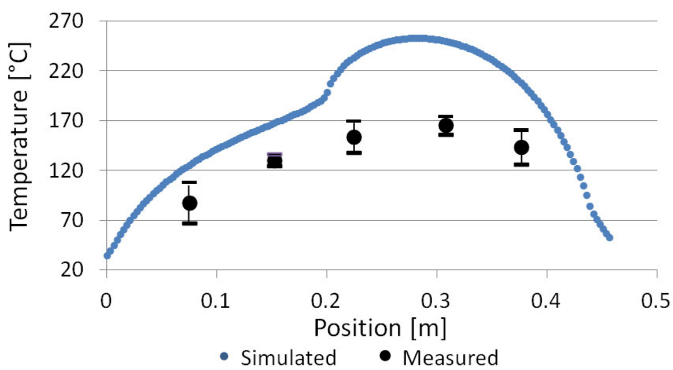

Figure 19. Comparison between simulated and measured temperatures on the roof for R3$_{fi}$.

4 CONCLUSIONS

Since the final test condition defined by the standard [9] does not allow to approach the stationary temperature on flammable materials in the vicinity of a chimney, a lumped element model for determining it from measured data has been set and it has been shown that it allows to determine the stationary temperature reached by flammable materials performing tests shorter than those prescribed by the standard [9]. Moreover, a 3D numerical model for estimating the stationary temperature on

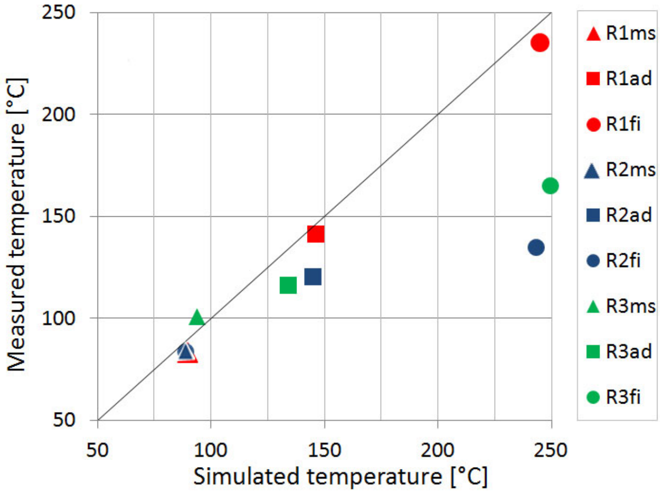

Figure 20. Comparison between measured and simulated maximum temperature related to the roofs.

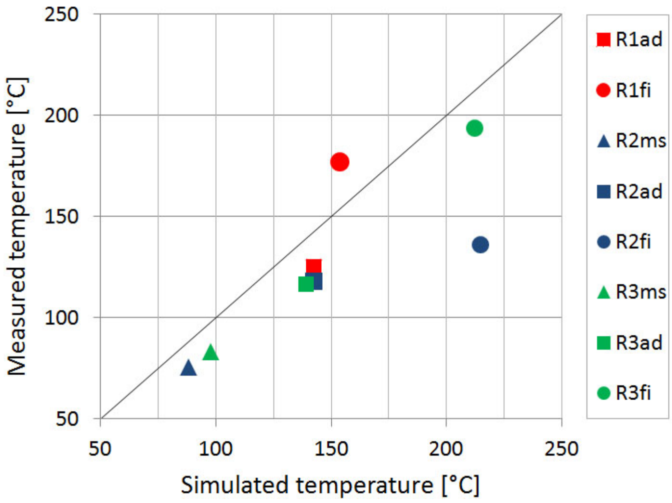

Figure 21. Comparison between measured and simulated maximum temperature related to the walls.

flammable materials in the vicinity of a chimney has been designed and verified. Comparing temperatures estimated by means of the numerical model with those measured in tests and then elaborated by means of the lumped element model, it has been shown that simulations performed with the numerical model could complement the certification procedure and support installers in choosing chimneys to be installed in roofs different from those prescribed by the standard [9]. The numerical model estimates the temperature on flammable material and in favor of security.

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NOMENCLATURE

Symbol	Quantity	SI Unit
A	Surface	m^2
Bi	Biot Number	-
c_p	Specific heat	J/kgK
h	Convective heat transfer coefficient	W/m^2K
m	Slope	-
n	Y-axis intercept	-
R^2	Determination coefficient	-
T	Temperature	
t	Time	hour
V	Volume	m^3
λ	Thermal conductivity	W/mK
ρ	Density	-

Subscript

a	dimensionless
c	calculated
ch	chimney
env	environment
f	final
gas	exhaust gas
i	i-th
m	measured
s	start

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