Parametric CFD analysis of the setting data on evaluation of the Safe Egress conditions in case of fire using FDS

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Abstract. The CFD simulation allows to simulate fire scenario to evaluate parameters influencing Safe Egress. The essential prerequisites to CFD simulations to assure realistic fire conditions of high quality and reliability are the knowledge of fire parameters, such as ignition time and Heat Release Rate of the items involved in the combustion process. Sometimes, the thermo dynamical parameters such as density, thermal conductivity, thermal capacity are not well known or although experimentally measured they are affected by an uncertainty interval; this means that there is a range of values which can influence, significantly, the ignition time and HRR of the combustible materials. The main aim of the present work is to evaluate, by means CFD case study, the influence of uncertainties of input data on the evaluation of environmental conditions for the public building Safe Egress.

1 Introduction

In the last decade, the ‘prescriptive-based’ fire protection design was been gradually substituted by a ‘performance-based’ design, allowing more flexibility to satisfy the fire protection needs of buildings. There are essential prerequisites to computer simulations to achieve representative realistic fire conditions of high quality and reliability i.e. that to evaluate the dominating physical processes and to distinguish empirical parameters that have an essential influence on the specific fire scenario, moreover the correctness of combustion parameters data to set the CFD simulation is very crucial. Sometimes the thermo dynamical parameters such as, density, thermal conductivity, the thermal capacity are not well known or although experimentally measured they are affected by an uncertainty interval, this means that there is a range of values which can influence significantly the ignition time and HRR of the combustible materials.

Typically, results from large or medium scale fire are used to assess the behaviour of products and materials in building fire scenario [1,2], but unfortunately they are limited to prediction of properties connected to heat release, disregarding the smoke production that is one of the important aspect in the safe egress fire scenario. The CFD simulation allows well predict environmental conditions during evacuation, but unfortunately, requires huge computer resources in case of fire scenario in buildings. Some authors in the past have developed screening model to reduce time consuming and expensive operation [3–5]. To perform accurately CFD simulation of fire scenario and evaluate the safe evacuation conditions, the production of smoke and gases have to know accurately. The cone calorimeter test with Thermo Gravimetric Analysis (TGA) allow to measure the heat release rate (HRR) and the smoke.
production rate (SPR) \[6,7\]. A. Steen-Hansen and B. Kristoffersen \[8\] have shown that it is possible to use cone calorimeter test results to predict both Euroclass and smoke classification of wood products based on test results from the SBI test. Moreover, they stated the cone calorimetric results can be used to predict larger scale fire behaviour of wood products, from small scale test results with a high degree of predictability. To analyse the influence of different input data on the CFD results, many authors have used the fire dynamic simulator (FDS) to obtain general indications to mark the influence of the CFD models and settings on the ability of FDS to correctly simulate the real processes \[9,15\]. The aim of the present work is to evaluate, by means CFD case study, the influence of uncertainties of input data on the evaluation of environmental conditions the Safe Egress in public buildings.

2 Methodology

The essential prerequisites to assure realistic fire CFD simulations are the accurate knowledge of fire parameters, which influence the ignition time, Heat Release Rate and soot rate of the involved materials, which themselves are necessary to evaluate the times of achievement of the survival critical values, i.e. concentration of harmful gases, gas temperature and visibility. The time required to achieve survival critical values will allow to evaluate the available time for safe evacuation. Often, the values of physical parameters of the materials involved in the fire scenario, available in literature, not correspond exactly to the materials used for, or even if experimentally measured they are affected by uncertainty. Therefore, the influence of the indeterminateness of these values on CFD simulations has been analyzed. In this paper, the influence of setting fire parameters of the two most common materials in the public offices, wood and cellulosic paper, has been investigated. In particular, the main combustion parameters of FDS has investigated: the Arrhenius constants or, in alternative, the pyrolysis range and the reference temperature. Preliminarily, the fire behaviour of the chipboard has been experimentally evaluated by means cone calorimetric and thermo-gravimetric analysis, to assess the values of pyrolysis range and reference temperature. Successively, a CFD simulation has been carried out to tuning the values of the thermophysical parameters i.e. thermal conductivity, specific heat capacity, comparing HRR curves provided by cone calorimetric analysis and CFD simulation. Instead, to tune the thermophysical parameters for the cellulosic sheet, experimental Arrhenius constant provided in literature \[16\] has been used. Details of the tests and CDF simulations are reported in a previous paper \[17\].

2.1 Tests for chipboard

The preliminary experimental tests performed on chipboard specimen of 720 kg/m\(^3\) of density, have allowed to determine some of setting parameters for FDS fire simulator, as shown in Tab.1. The other physical parameters, chosen from literature and tuned by CFD analysis, are reported in table 2. The figure 1 shows the validation of CFD results with respect to the experimental ones. The authors have set a simulation reproducing cone-calorimetric test, details have discussed in previous paper \[17\]. It can be seen a satisfying agreement of HRR curves up to 1300 s.

| Table 1. Thermo-kinetics proprieties of chipboard. |
|---------------------------------------------------|
| **Value**  | **Unit**  |
| Temperature of maximum heat release rate | 430 \(^\circ\text{C}\) |
| Heating rate | 5 K/min |
| Reference temperature | 320-380 \(^\circ\text{C}\) |
| Pyrolysis range | 80-120 \(^\circ\text{C}\) |
| Heat of reaction | 800 kJ/kg |
| Heat of combustion | 13000 kJ/kg |
| Fuel vapour | 0.7 % |
| Residual | 0.3 % |
Table 2. Thermo-physical properties of chipboard.

| Property              | Value  | Unit  |
|-----------------------|--------|-------|
| Specific heat         | 2÷4    | kJ/kgK |
| Thermal conductivity  | 0.1÷0.2| W/mK  |
| Emissivity            | 0.9    | -     |
| Absorption thickness  | 50000  | 1/m   |

Figure 1. Comparison between HRR curves provided by laboratory test and CFD simulation.

The HRR curve obtained from CFD analysis has used as reference curve to compare with those obtained from parametric analyses. The following figures show the results of the parametric analysis, for different reference temperature (T_{ref}) and pyrolysis range values (parameters linked to peak of combustion). The figures 2a and 2b show the influence of error setting of the reference temperature and the pyrolysis range values on HRR-time curve. For both has been simulated an error ranged in ±20% step 5% respect value used as reference (see tables 1 and 2). In figure 2a, it is possible to note that, for fixed T_{ref}=380 °C, for error equal to -20% (T_{ref}=304 °C), the pick time decreases about of 35 s and the peak of combustion reaches a value about 420 kW/m², instead for an error equal to +20% (T_{ref}=465 °C) the pick of HRR decreases to 180 kW/m² and it delays of about 70 s.

Figure 2. the left side- Particular of influence of reference temperature on the first peak of HRR-time curve; on the right- Particular of the influence of pyrolysis range on the first peak of HRR-time curve, fixed pyrolysis range equal to 120 °C.

Moreover, with regards to the influence of pyrolysis range on HRR-time curve, as shown in the figure 2b, considering the same errors, it is possible to note that, for fixed pyrolysis range =120 °C, an error
equal to -20% (pyrolysis range =96 °C) on the correct value of the reference temperature, involves a
decrease in the time (10 s) at which the first peak of combustion is obtained with a value about 407
kW/m² and an error equal to +20% (pyrolysis range =144 °C) involves a delay of about 60 s of the first
heat release rate peak with a value about 123 kW/m².

2.2 Tests for cellulose

For the cellulosic sheet experimental data from literature has been used [17]. The authors provided
both HRR-time curve and the activation constant \( A = 2.5 \times 10^9 \) 1/s and the pre-exponential factor \( E = 
1.2 \cdot 10^5 \) kJ/kmol involved in the Arrhenius combustion model. The others physical parameters were
chosen from literature and tuned by CFD simulation, as shown in the Tab.3.

| Proprieties of cellulose | Unit     | Value      |
|-------------------------|----------|------------|
| Density                 | kg/m³    | 800        |
| Specific heat           | kJ/kgK   | 1.82       |
| Thermal conductivity    | W/mK     | 0.55       |
| Emissivity              |          | 0.9        |
| Absorption thickness    | l/m      | 50000      |
| Heat of reaction        | kJ/kg    | 500        |
| Heat of combustion      | kJ/kg    | 17000      |
| Fuel vapor yield        |          | 1          |
| Activation Energy       | kJ/kmol  | 0.96-1.44 E+05 |
| Pre-exponential factor  | 1/s      | 2.0-3.0 E+9 |

The figure 3a shows the validation of CFD results with respect to the experimental test provided by
William D. Walton [15]. The figure assesses the goodness of setting parameters and also of the reference
curve. The figures 3b and 3c report the influence of the Arrhenius constant on the HRR picks. The results
show that the exponential factor \( E \) influences the HRR pick greater than the pre-exponential factor \( A \).
The authors have set a simulation reproducing experimental test; in particular the figure 3.c shows that,
for an error equal to -20% (\( E=0.96 \cdot 10^5 \) kJ/kmol) the pick time decreases about of 300 s and the peak of combustion reach a value about 2400 kW/m², instead for an error equal to +20% (\( E=1.44 \cdot 10^5 \) kJ/kmol)
the pick time increases about of 800 s and the peak of combustion reach a value about 1600 kW/m².

![Figure 3](image_url)

**Figure 3.** (a) Validation of CFD simulation- (b) Influence of Pre-exponential factor \( A \) on HRR-
time curve, (c) influence exponential factor \( E \) on the first peak of HRR-time curve.

3 Case study

The investigated case study is a floor of a public building office, in which the ignition of the fire is
caused by the short circuit in workstation which involves the ignition of cellulose material, located in a
waste bin. The floor consists of 4 four offices and a common area. The total area is approximately 224
m² for a height of 2.70 m, except for the common area (2.40 m). It also has two doors of fire resistance class REI 120 communicating with escape routes. Each room features windows with manually opening elements. There are in total 2 smoke detectors, 27 sprinklers and 2 fire extinguishers, as summarized in the table 4. The partitions are composed of laminated chipboard. In figure 4 it is possible to observe the image of the analyzed floor with furnishings and sensors position.

The ignition occurs in room N5 (see figure 4), whose dimensions are of (40 x 40 x 50) cm³. The burner (waste bin) has been modelled by means the assignment of HRRUA of 500 kW/m² and a Rump-up time of 300 s as required by the ISO 13387 standard for medium-growth fires in offices. For all five simulations was required that: 1) all the doors of the individual rooms be closed, 2) the sprinkler system deactivated, 3) opened window configuration.

![Figure 4. layout of domain investigated.](image)

**Tab. 4 devices present in the simulated floor.**

| Plant surface | Height | Typology | #sprinkler | #smoke detector |
|---------------|--------|----------|------------|-----------------|
| N1            | 50.15  | 2.7      | Office     | 6               | 1               |
| N2            | 36.21  | 2.7      | Office     | 4               | 1               |
| N4            | 37.03  | 2.7      | Office     | 4               | 1               |
| N5            | 68.16  | 2.7      | Office     | 9               | 1               |

### 3.1 Methodology

A parametric analysis is carried out by assessing the influence of error the setting of characteristics parameter of the laminated chipboard and cellulose sheets in folders, on the results of the FDS simulations, in the event of a real fire. The parametric analysis results have been used to set the simulations of the case study in order to evaluate the time to reach the activation temperature of the sprinklers, the influence of the variations of these parameters on the time profiles of the CO concentration, the radiative heat flux, the O₂ concentration, the FED, with the aim of obtaining the variation in the times of achievement of the limit values for the safe egress.

The CFD model simulates a fire scenario, in which the values of the thermo physical parameters characterizing the laminated chipboard and cellulose are set. The results of the parametric analysis will be provided for different values of thermal conductivity (k), specific heat at constant pressure (c_p) (thermal parameters), different reference temperature (T_{ref}) and pyrolysis range values (parameters linked mainly to combustion) for the laminated chipboard material and the Arrhenius parameters, activation energy and pre-exponential factor values (E and A) for the cellulose material. In the first simulation, the values of the parameters that characterize the reference cases have been set. In the second and third simulation, the values of the characteristic parameters of the laminated chipboard have been set with an error equal to -20% and + 20% with respect to the values of the reference case, setting the values of the quantities for the reference case for the cellulose. Finally, in the last two simulations, percentage errors of -20% and then + 20% of both the activation energy and the pre-exponential factor have been first imposed, while the characteristic parameters of the laminated chipboard equal to those
have been set of the reference case. The values of the parameters characterizing the case study configurations are summarized in the tables. 5.a and 5.b for both laminated chipboard and cellulose, respectively.

| CFD configuration | k/(W/m) | c_p/(kJ/kgK) | T_ref/°C | Pyrolysis range/°C |
|-------------------|---------|--------------|----------|-------------------|
| First: Base case  | 0.140   | 2.30         | 350      | 100               |
| Second: -20% (chipboard) | 0.112   | 1.84         | 280      | 80                |
| Third: +20% (chipboard) | 0.168   | 2.76         | 420      | 120               |
| Fourth: -20% (paper) | 0.140   | 2.30         | 350      | 100               |
| Fifth: +20% (paper) | 0.140   | 2.30         | 350      | 100               |

| CFD configuration | E (kJ/kmol) | A (1/s) |
|-------------------|-------------|---------|
| First: Base case  | 1.20 E+05   | 2.5 E+09|
| Second: -20% (chipboard) | 1.20 E+05 | 2.5 E+09 |
| Third: +20% (chipboard) | 1.20 E+05 | 2.5 E+09 |
| Fourth: -20% (paper) | 0.96 E+05  | 2.0 E+09 |
| Fifth: +20% (paper) | 1.44 E+05  | 3.0 E+09 |

4 Results
The simulation results concern some heat detectors, positioned in the various points of the simulation domain. In particular, the trends of the t-T curves of the heat detectors which first reach the activation temperature of the sprinklers are analyzed. They are located in room N5 and are named N501 and N502 (see figure 5). The table 6 and figure 6 report the activation time of the sprinklers for all configurations analyzed; in particular, for the base case, the N501 heat detector reaches an activation sprinkler temperature at 379 s, while for the N502 heat detector the activation temperature is 382 s. For the N501 heat detector, for the second configuration (-20% chipboard), the time to reach 74 °C is reduced by about 40 s compared to the base case, while for the fourth configuration (-20% cellulose) a sprinkler activation time is obtained which is reduced by about 25 s.

The table 7 reports the threshold values for the survival of people in according to ISO / TR 16738, ISO / TR 13387, ISO / TS 13571, NFPA 101.

Figure 5. position of heat detectors N501, 502.

The table 8 summarizes the reaching time threshold values for all CFD configurations examined for room N5 because represents the first area of the entire floor where the limit values have been achieved. In particular, one note that Fractional Effective Dose (FED), namely the combination of all harmful effect, can vary from 38% to 34% respect to the values of reference case, instead the radiative threshold values vary from -40% to 40%.
Table 6. CFD results in terms of time needed to reach the sprinkler activation temperature.

| CFD Configuration | Heat detector N501, sprinkler | Heat detector N502, sprinkler |
|-------------------|-------------------------------|-------------------------------|
| Base case         | 379 s                         | 382 s                         |
| -20% chipboard    | 339 s                         | 340 s                         |
| +20% chipboard    | 415 s                         | 421 s                         |
| -20% cellulose    | 354 s                         | 358 s                         |
| +20% cellulose    | 403 s                         | 410 s                         |

Figure 6. Trend of the activation times of the sprinklers for the N501 and N502 heat detectors when the error% of the properties of the laminated chipboard and the cellulose changes.

Table 7. threshold values.

|                      |                  |
|----------------------|------------------|
| Radiative heat flux  | 2 kW/m²          |
| Carbon monoxide concentration (CO) | 5.7E-04          |
| Fractional Effective Dose (FED)    | 0.3              |
| Oxygen concentration (O₂)          | 0.20 kg/m³       |

Table 8. Times required for reaching of the threshold values.

| Configuration | Radiative heat flux | CO  | FED  | O₂  |
|---------------|---------------------|-----|------|-----|
| reference case| 74                  | 91  | 109  | 24  |
| -20% chipboard| 44                  | 52  | 67   | 27  |
| +20% chipboard| 104                 | 126 | 146  | 33  |
| -20% cellulose| 51                  | 62  | 76   | 40  |
| +20% cellulose| 96                  | 114 | 135  | 24  |

5 Conclusions

In this paper, a parametric analysis has performed in order to evaluate the combustion parameters indeterminateness on safe egress time in case of fire. The analysis has performed by FDS. On experimental fire tests, reference parameters have been calculated and reference fire curves have been determinate for two different combustible materials present in the public offices, wood and cellulosic sheets in folders. The parametric analysis has been carried out varying combustion parameters in the range of -20% to 20% respect to those determined from experimental tests. The results show that, in the case of laminated chipboard, the reference temperature represents the more critical parameter on the sprinkler activation time: an error of + 20% of the this parameter causes a reduction in activation time of about 21 s (if compared to the nominal value) while, for an error of -20%, the activation time increases of 34 s. For the cellulose materials, the combustion parameter that most influences the safe egress time evaluation is the activation energy: an error of + 20% of this parameter causes an increase of almost 32 s of sprinkler activation time. In conclusion, the results provide indications to the fire designers about the order of approximation, when the setting parameter are not well known.
References

[1] EN 13501-1 E. Fire Classification of Construction Products and Building Elements Part 1: Classification Using Data from Reaction to Fire Tests. European Committee for Standardization (CEN), Brussels, Belgium, 2002.

[2] EN 13823 E. Reaction to Fire Tests for Building Products Excluding Floorings Exposed to the Thermal Attack by a Single Burning Item. CEN, European Committee for Standardization (CEN), Brussels, Belgium, 2002.

[3] Hakkarainen T, Kokkala MA. Application of a one-dimensional thermal flame spread model on predicting the rate of heat release in the SBI test. Fire and Materials 2001; 25:61–70.

[4] Van Hees P, Hertzberg T, Hansen AS. Development of a screening method for the SBI and room corner using the cone calorimeter. Nordtest Project 1479-00. SP Report 2002:11. SP Swedish National Testing and Research Institute, Sweden 2002.

[5] Hansen AS. Prediction of heat release in the single burning item test. Fire and Materials 2002; 26(2):87–97.

[6] ISO 5660-1:2002. Reaction-to-Fire Tests Heat Release, Smoke Production and Mass Loss Rate Part 1: Heat Release Rate (Cone Calorimeter Method). International Organization for Standardization, Geneva, Switzerland, 2002.

[7] ISO 5660-2:2002. Reaction-to-Fire Tests Heat Release, Smoke production and Mass Loss Rate Part 2: Smoke Production Rate (Dynamic Measurement). International Organization for Standardization, Geneva, Switzerland, 2002.

[8] Kristoffersen, B. Steen-Hansen, A. Using the Cone Calorimeter for Screening and Control Testing of Fire Retarded Treated Wood Products. International Interflam Conference, 10th Proceedings. Volume 2. July 5-7, 2004.

[9] Ayala P., Cantizano A., Gutierrez-Montes C., Rein G., Influence of atrium roof geometries on the numerical predictions of fire tests under natural ventilation conditions, Energy and Buildings, 65, pp. 382-390, 2013.

[10] Zhang P., Fu J., Wu T., Numerical simulation of the Co-operation effect of high-pressure water mist fire protection and mechanical ventilation, Shenyang Jianzhu Daxue Xuebao, Journal of Shenyang Jianzhu University (Natural Science), pp. 854-858, 2008.

[11] Huang S.-S, Lu S.-X, Li C.-H, He Q.-Z., Numerical investigation of fire safety of an indoor pedestrian street, Proceedings – 7th International Conference on Intelligent Computation Technology and Automation, ICICTA 2014,pp. 383-387, 2015.

[12] Wang M.-Y., Lin C. P., Li Y.-T., Ma H.-K, Utilization of fire dynamics simulator model to study rice husk gasification in fixed-bed gasifier, Bioresources, 9(3), pp.3792-3804, 2014.

[13] Nasif, M.S., Al Waked R., Using computational fluid dynamics simulation to perform investigation, Applied Mechanics and Materials, 393, pp. 845-850, 2013.

[14] Hu L.H., Fong N.K., Yang L.Z., Chow W.K., Li Y.Z., Huo R., Modeling fire-induced smoke spread and carbon monoxide transportation in a long channel: Fire Dynamics Simulator comparison with measures data, Journal of Harzardous Materials, 140(1-2), pp. 293-298, 2007.

[15] Mijorski S., Stankov P., CFD modelling of Dalmarnock uncontrolled fire test, Central European Journal of Engineering, 2(2), pp. 279-288, 2012.

[16] William D. Walton, Edward K. Budnick. Quick response sprinklers in office configurations: fire test results. Research Information Center National Bureau of Standards Gaithersburg, Maryland 20899, January 1988

[17] Andreozzi, A., Bianco, N., Musto, M., Rotondo, G., Parametric analysis of input data on the CFD fire simulation. Journal of Physics: Conference Series, 2019.