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Survey on the use of tenability criteria in CFD analyses for Performance-Based Fire Safety Engineering

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Abstract. An online survey on the use of tenability criteria in CFD analyses for PBFSE was conducted, to better understand the current industry practices in fire modelling. 254 participants responded, representing wide range of roles in professional practice. Visibility in smoke is the most used (90.2%) and most influential (91.4%) tenability criterion, while smoke temperatures are being commonly evaluated (76.5%) but more rarely impact the design (45.8%). Criteria related to smoke toxicity were used only by 10.4% - 19.9% of participants, indicating potential gaps in life safety assessments. The paper presents more detailed results, as well as future research directions informed by the outcomes.

1. Introduction

The use of Computational Fluid Dynamics (CFD) as a tool in Performance Based Fire Safety Engineering (PBFSE) design of life safety systems, such as smoke control, has become the preferred approach in many legislations. The output of the analyses is mainly driven by the input and assumptions, as well as by the rules, models and threshold values used to evaluate the analysis results. In this paper we focus on determining the industry approach to the latter, i.e. the result analysis process and the definition of so called tenability criteria [1]. We recognize that multiple tenability criteria exists, which can be generalized as either (1) quantitative and direct measures of physical properties of the fire environment, e.g. temperature or species concentrations; (2) models such as visibility in smoke or Fractional Effective Dose (FED)/ Fractional Effective Concentration (FEC) for toxicity; or (3) threshold values related to the safety system performance, e.g. hot smoke layer height and temperature. Choosing which tenability criteria to use and where to measure them is often ambiguous. Multiple variables can be traced concurrently, but the time at which one of the variables reaches its tenability criterion value is considered as the end of the Available Safe Evacuation Time (ASET[2]), which usually is treated as a final outcome in PBFSE life safety assessment without further qualitative investigation [3]. Therefore, the first variable to reach their tenability criterion is effectively determining the level of safety within the building.

All of the tenability criteria are only proxies of life safety, often not very direct, and the calculations of the associated indicators feature large uncertainties. These uncertainties result from the modelling itself, from operational problems (the intended use is often different from the real use), and not least from physiological reasons (not everybody responds in the same way). It is thus not generally clear which criterion is a better indicator of life safety in case of a fire, nor a single criterion can be declared as an ultimate one. Ultimately, the goal of the fire safety engineer is to convince stakeholders that the building is safe, and their confidence in the criterion used is therefore crucial. To gain insight into the practice in PBFSE in relation to the use of advanced models, and interpretation of their results, an online survey was developed and conducted. The target responders for the survey included fire safety engineers, developers, architects, fire services and researchers. Understanding the role of tenability criteria by the practitioners may help the scientific community steer its efforts in future development of tools and models.

A working hypothesis applied to this research, based on a common perception and previous studies conducted on a smaller sample [4], was that the 'visibility in smoke' is the most influential and most widely used tenability criterion. Verification of this hypothesis, as well as the survey of main factors influencing the choice of tenability criteria was the primary goal of this research. Other detailed goals of the study included the assessment of (1) the professional education level of the respondents and their experience in the field of fire and smoke modelling; (2) the number of projects completed by respondents, the use of CFD-modelling indicating the scale of use of tenability criteria in fire engineering; (3) familiarity of the participants with the ASET/RSET concept; (4) respondents' choice of those reliability criteria that are measured most often, as well as those that most influence the final decision; (5) methods and geometric features of reliability criteria measurement; (6) which of the tenability criteria are the most often currently used as the final criterion when evaluating the results of a CFD analysis.

2. Tenability criteria

Prior to building the survey, tenability criteria used in PBFSE were studied and identified. First, we have identified criteria that are directly tracked in the CFD simulation and for which a threshold value may be defined. Secondly, we have listed tenability criteria that use derived quantities based on models – such as visibility in smoke or FED/FEC. Finally, we identified parameters related to smoke control system, such as smoke temperature, smoke layer height and gas velocities. Below we briefly discuss the commonly used tenability criteria, the way they are evaluated (modelled) and the reason for which they are included in engineering calculations.

Smoke temperature may be considered as the simplest criterion to be defined, and different threshold values may be introduced for the life safety assessment, property damage or for fire spread considerations. In many cases smoke with temperature exceeding threshold as low as 45 °C may be considered as untenable for general building occupants [1], while this tolerance may be exceeded for firefighters or for specific (e.g. dry) conditions. In case of systems in buildings, high temperatures may damage plastic casings and cables, or goods stored in the building. Some fire safety solutions, such as high temperature extraction fans [5] are designed with the expected maximum smoke temperature in mind. Directly related to smoke temperature is the radiant heat flux emitted from the smoke layer. If the smoke is stratified in an upper layer sufficiently high above the evacuation pathways, the occupants are not directly exposed to smoke. However, they may be exposed to the thermal radiation from the smoke layer, with commonly used threshold values related to skin burn thresholds of 2.5 kW/m^2 for short (30 s) exposure, corresponding to smoke layer temperature of approx. 200 °C (for an optically thick layer).

The visibility through smoke is commonly defined as the distance, at which a certain object (an evacuation sign, obstacle, person) can be observed through a smoke layer. While based on the theory of radiation in participating media (light absorption and scattering through smoke), the modelling of visibility depends on the nature of the object seen through the smoke (e.g. light emitted by the object), and is thus intrinsically empirical [6]. In the practice of PBFSE, the visibility in smoke value is not a measure of the distance at which object can be seen, but rather is the outcome of an empirical model, correlated with the local mass density of smoke through the Jin's approximation [7,8], with multiple assumptions influencing the outcome [9]. Other measures related to smoke refer to the toxicity, i.e. toxic gas products concentrations (mainly CO and HCN) and oxygen concentration. The values are either compared to a known threshold concentration value, or analysed as a dose through FED. Impact of multiple gasses can be traced together in the FEC model.

Finally, parameters such as smoke layer height [3,10] or airflow velocities (e.g. critical velocity in tunnels [11]) may be introduced as proxies of the life safety system performance.

3. Survey, demographics and experience

3.1. Design of the survey

An online survey was developed with use of Google Survey form, and was made available to the international audience through personal communication and public posts on the authors' private and institutional social media channels, primarily on LinkedIn and Twitter platforms. The survey was open for participation from 2021-03-23 to 2021-05-05. The survey included a set of closed-ended and open-ended questions, which allowed to conduct a qualitative assessment of the results. The survey was disseminated in English language, therefore restricting the group of respondents to English-speaking participants. The survey was limited to the selection of proposed questions and did not always include additional discussions and clarifications. Respondents were allowed to choose individual answers in the tab 'other' and were allowed to write an open comment at the end of the survey. This technical simplification of the questionnaire made it possible to easily process the results of the survey, relying mainly on the responses of the majority of participants.

The questions were presented to the respondent such that first the information about education and work experience were gathered, and gradually moved on to professional questions regarding the application of CFD modelling and tenability criteria. The complete list of questions in the survey and detailed summary of responses is available at request.

3.2 Participant demographics

In total 254 participants from all over the world either fully or partially completed the survey. Participants came from 43 different countries. The most of them were from United Kingdom (12%), Poland (9%), Germany (9%), Australia (7%), and the USA (6%), which indicates potential overrepresentation of the engineers coming from Europe in the survey, and underrepresentation of Middle East, Latin America, Africa and Asia. The majority of respondents indicated that they currently work in engineering, analytics, architecture (82%), and that their work includes performing fire modelling. 7% of the respondents were researchers and lecturers, and 6% were representing fire services or Authorities Having Jurisdiction (AHJ). 58% of participants have professional education in the field of Fire Safety/Protection Engineering, 29% in Mechanical Engineering, 9% and less – in the field of Civil or Structural Engineering and others.

3.3 Participant experience with CFD tools

44% of the participants have more than 10 years' experience and 13.8% were people who have recently entered the profession. Over a third of respondents (36%) are involved in 4 - 10 projects every year. Almost three quarters of respondents (70.5%) perform CFD simulation by themselves, and 17.7% have a supervisory role on CFD analyses. These demographics illustrate that the study participants have sufficient practical experience in performing PBFSE analyses with use of CFD tools, thus fulfilling the intend of the survey to study the experiences of active fire engineering professionals. Asked for the CFD tool of use (multiple choice), 95.9% of users declared use of Fire Dynamics Simulator (FDS), followed by ANSYS Fluent/CFX by 12.5%, OpenFoam/FireFoam by 6.7% and Smartfire by 3.1%. Among 224 responses to this question, 2.1% indicated use of non-CFD tools, such as various zone models. Four participants have mentioned a popular FDS pre-processor "PyroSim" as their CFD model.

Participants were asked about to the decision factors related to the choice of particular software package. Again, multiple answers could have been chosen. The respondents' choice of software is most influenced by '*validation & verification*' (81.7%), and that a software it is '*approved by Fire Authorities*' (53.1%). The practical aspects were also important, as a large part of the choice falls on: robustness (46.0%), cost (38.8%), ease of use (36.6%). Interestingly, the processing time was the least impactful with only 23.7% responses.

4. Survey results

Before proceeding to the tenability criteria, the respondents were asked whether they were familiar with the ASET/RSET concept, which influenced what further question will be presented to them. 87% of respondents confirmed, and were allowed to participate in the rest of the survey.

The CFD users are tracking and using multiple criteria concurrently, but may base their engineering decisions on just a few of most impactful ones (or often, on the first that exceeds the set threshold). For this reason, the participants were separately asked to rate on a scale from 1 to 5 which tenability criteria they measure the most, and which criteria influence the final decision-making. In here 5 would mean a criterion is always measured/used in analysis, 3 would mean that a criterion is sometimes used, and 1 would mean that a criterion is never used. The detailed results are shown in table 1 and 2.

Table 1. Distribution of responses to the question "how often the tenability criteria are used"

	1 (almost never)	2	3 (sometimes)	4	5 (always)
Temperature	4.5%	11.3%	7.7%	13.6%	62.90%
Visibility	2%	4%	5%	6%	84.20%
Smoke concentration	19.0%	23.5%	12.7%	12.7%	32.10%
Radiant heat flux	10.40%	21.30%	24.40%	18.10%	25.80%
Toxic gases concentrations	20.40%	24.40%	25.30%	10%	19.90%
Oxygen concentration	47.10%	19.90%	13.60%	7.70%	11.70%
Smoke layer height	8.10%	8.60%	6.80%	19.50%	57%
FED	36.70%	25.30%	15.80%	7.70%	14.50%
FEC	57.50%	23.10%	9.50%	4.50%	5.40%
Gas velocity	35.70%	19%	19%	13.60%	12.70%

Table 2. Distribution of responses to the question "how often the tenability criteria influence the design choices of the participant"

	1 (almost never)	2	3 (sometimes)	4	5 (always)
Temperature	20.8%	26.2%	7.2%	14.9%	30.90%
Visibility	3.2%	1.8%	3.6%	10.4%	81.0%
Smoke concentration	30.8%	18.6%	13.5%	13.1%	24.00%
Radiant heat flux	29.9%	25.3%	15.4%	13.6%	15.8%
Toxic gases concentrations	40.3%	24.4%	15.4%	8.1%	11.8%
Oxygen concentration	59.7%	16.7%	10.9%	6.8%	5.9%
Smoke layer height	15.4%	9.5%	15.8%	17.6%	41.7%
FED	42.5%	24.9%	14.9%	8.6%	9.1%
FEC	61.5%	19.5%	8.6%	5.4%	5.0%
Gas velocity	60.2%	15.4%	15.4%	3.6%	5.4%

Among all tenability criteria, the following tenability criteria are measured the most often (sum of responses 4 and 5): visibility (90.1 %); temperature (76.5 %); smoke layer height (76.5 %). Less than 1/4th of responders is commonly measuring the oxygen concentration (19.4 %), FED (22.2 %) and FEC (9.9 %). In contrary to the dose measurements (FED, FEC), 29.9 % of responders indicated they measure toxic gas concentrations.

Following tenability criteria were indicated as almost never used (sum of responses 1 and 2) FEC (80.6 %); O_2 concentration (67 %); FED (62 %) and gas velocity (54.7 %). 15.8 % of responders rarely measures temperature and 6 % of responders rarely measures visibility. Overall 12 % of the respondents chose to add their own tenability criteria, and among them the most common were: the pressure differential, net heat flux, extinction coefficient, CO concentration, optical density, convective heat flux and fire area.

According to the respondents, visibility (91.4 % of answers 4 - 5) has the greatest influence on their design process, followed by the smoke layer height (59.3 %). The least influential tenability criteria were the gas velocities (9 %), FEC (10.4 %), O_2 concentration (12.7 %) and FED (17.7 %). The biggest observed difference between use and impact was for, where 76.5 % do use it often, but only 45.8 % (30.7 pp. difference) considers that it often influences their design choices. For smoke layer height this difference was 17.2 pp. and for radiant heat fluxes 14.5 pp.

The participants were also asked on how exactly do they measure the tenability criteria. Among the 221 surveyed respondents, 71 % answered that in their research they use point measurements, 89.7 % use slice plots, 44.8 % use iso-surfaces and 22.6 % use the volume statistics.

Participants were also asked about the height at which this measurement takes place (a list of options between 1.5 m to 2.5 m, multiple choice). More than half of the respondents (55 %) measure the tenability criteria at a height of 2.0 m, and almost a third (30.2 %) at a height of 1.8 m). Another question was asked about the choice of the threshold value of visibility in smoke used in the analysis. 76 % of respondents answered that they use a threshold value in visibility at a distance of 10 m. The value of 10 m is present in some legal systems and its origins may be traced to 1960's and some surveys done among Fire Chiefs in US [12]. For other threshold values of the visibility in smoke 1.7 % of respondents choose 15 m as the criterion; 5 % choose 20 m and 30 m of visibility. 3.9 % of respondents choose 8 m, 7.3 % choose 5 m, 1.1 % choose 3 m. The survey also included questions related to the constants in visibility in smoke model (so called C-factor). Most of the responders use a set value of this parameter (3 for light reflecting – 34.4 %

and 8 for light emitting – 10.4 %). 31.2 % of the respondents choose the value of C dependant on the project. Less than 10 % of respondents refers to ranges of values instead of constants, as in source material presented in the SFPE Handbook [12] and [13].

5. Conclusions

The aim of the survey was to understand the current practice of use of tenability criteria in CFD analyses used for PBFSE. As indicated by the scatter in responses, the choice of the tenability criteria can be considered ambiguous. While many variables are traced, the most influential one was visibility in smoke, as indicated by 91.4 % of the participants. On contrary, temperature was commonly measured in the analyses, but rarely impacted the engineering decisions. The study has also demonstrated limited use of toxicity-related criteria, which indicates a potential gap in fire safety assessments. Furthermore, ambiguity in the choice of measurement heights for evaluating tenability criteria highlighted the need for standardization, as different heights can lead to significant differences in engineering analyses.

Future research should focus on investigating the most effective measurement heights for tenability criteria, re-evaluating visibility threshold values, and exploring the potential benefits of incorporating advanced toxicity-related criteria and smoke representation methods into fire safety engineering practices. Additionally, further examination of the C factor in Jin's model will be critical for the development of standardized guidelines and more accurate evaluations of building safety.

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