FIRE SAFETY ENGINEERING: A NEW SUBJECT AREA

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ABSTRACT

With the rapid development of construction projects with new architectural design, 'engineering performance-based fire codes' are widely used in many countries overseas. This leads to the new subject discipline 'Fire Safety Engineering (FSE)', in contrast to the traditional fire engineering. FSE is a high-level subject about transferring knowledge of fire science to practical use to provide safety, and will be briefly introduced. In addition, the heat release rate of burning combustibles; and mathematic fire modelling, including zone and field or Computational Fluid Dynamics models, are briefly described. Further, education and training opportunities are pointed out.

1. INTRODUCTION

New architectural features such as atrium buildings are found in large-scale development projects including shopping centres. The occupancy level and usage of the buildings may be changed. Converting the open space in a shopping mall into a food court is a typical example. New design concept on green or sustainable buildings gives even more new architectural features. Fire safety provisions are difficult to be designed through prescriptive fire codes. On the other hand, the topic on fire safety has drawn public attention as a consequence of several serious accidental fires. People have started to be aware of the hidden problem on fire safety and queried whether they are sufficiently protected while staying inside a building.

Obviously, fire codes, even those by NFPA [e.g. 1], cannot be updated so rapidly to cope with the changes. This is particularly obvious for buildings of special hazards requiring individual design considerations, leading to Engineering Performance-Based Fire Codes (EPBFC) [1,2]. Therefore, scientific research for fire safety provision must be enhanced, leading to the new subject discipline of Fire Safety Engineering (FSE). This is different from the traditional fire engineering where only routine 'cut and paste' designs on fires service installations are carried out. FSE is briefly introduced in this talk. The following two topics are highlighted:

- Heat release rate of burning combustibles [e.g. 3].
- Fire modeling [4,5], including zone [6] and field [7] or Computational Fluid Dynamics (CFD) models.

Finally, education and training opportunities expected [8] are outlined.

2. FIRE SAFETY ENGINEERING

There are many definitions of Fire Safety Engineering (FSE). For example, in technical report BS ISO/TR 13387-1 (1999) [9] in UK:

- FSE can mean many things to many people. At one level, it can mean the calculation of pipe sizes for sprinkler systems or the calculation of the structural response of a building element, such as a beam or a column, from a knowledge of the material properties at elevated temperatures, the temperatures they achieve, the loads acting, and so on.

- At another level, requiring the use of integrated computer programmes, it can mean evaluating the life safety consequences of a specified fire, which involves defining the context, defining the scenario and calculating the hazard.

- At a more strategic level, FSE can mean a package of measures (methodology, calculation tools and data) which has the objective of reducing the potential for injury, single deaths and multiple deaths in and nearby the building to an acceptable level.

FSE is commonly applied for those buildings where prescriptive fire codes cannot be followed. An obvious example is to provide sprinkler at a high headroom atrium in Hong Kong. This might give adverse effects such as steam production and smoke logging. Different standard methods are specified in assessing those designs. Examples are BS ISO/TR 13387-1:1999 in UK [9], American approaches such as SFPE guide [e.g. 10] and Japanese approaches, say on assessing a building type [e.g. 11]. As drafted by the International Code Council (ICC), there are three parts [12]:

- Documentation.
- Design levels.
- Topic specific intent.

The following items should be judged, if necessary:

- Fire safety objectives and acceptance criteria.
- Design parameters.
- Characterization of buildings and its occupants.
- Identification of potential fire hazard scenarios and their possible consequences.
- Assessment against the safety criteria.

Hong Kong is now working on EPBFC. But basically, only those deviated from the existing prescriptive codes would be assessed. Therefore, the objective of the FSE approach is quite clear, i.e. based on existing prescriptive codes.

Similar to what have been summarized by Lillicrap [13], the following questions are usually raised:

- What level of fire safety is acceptable?
- What are the precise features and dimensions of the building?
- What factors limit possible solutions?
- What are the main hazards and consequences?
- What fire safety measures are going to be in place?
- What scenarios are going to be studied?
- What method of analysis is going to be used?

Knowledge of fire science and engineering was applied together with practical experience under local conditions. Mathematical fire models [e.g. 4-7], either zone models or field models, were used to analyze potential fire scenarios. Full-scale burning tests [14], scale models studies and site measurements on evacuation pattern [15] are required when necessary.

3. IMPORTANCE OF HEAT RELEASE RATE

A common question always asked is:

How big is a fire?

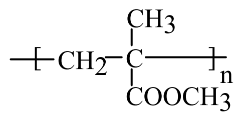
To answer that, the heat release rate has to be assessed. A database on heat release rate [3] should be developed for determining a design fire. This is one of the most important parameters that can be used to characterize an unwanted fire by providing:

- An indication of the size of the fire.
- The rate of fire growth, and consequently the release of smoke and toxic gases.
- The time available for escape or suppression.
- The types of suppressive action that are likely to be effective.
- Other attributes that define the fire hazard.
- Whether flashover would occur.

Different values were used by the designers in the past:

- Terminal hall: up to 7 MW
- Shopping mall: 5 MW
- Atrium: up to 7 MW
- Train compartment: 1 MW

Some values were accepted by the Government, but some were rejected. This is due to the lack of a database for local products. But most important, heat release rate is taken as the input parameter for fire model. As in a liquid pool fire, it is obvious that turbulence, intermediate combustion chemistry and thermal radiation have to be included instantaneously. Taking poly(methyl methacrylate) PMMA as an example [16], the chemical structure is:



The chemical reactions of combustion of PMMA are very complex with intermediate reactions classified under the following seven groups [17]:

- Thermal decomposition
- Thermal oxidative decomposition
- Decomposition of monomer MMA
- Methane combustion
- Methanol combustion
- Formaldehyde oxidation
- Acetylene combustion

Taking only the group on methane combustion [18], there are 77 intermediate reactions as shown in Table 1!

These phenomena cannot be modeled accurately in the coming ten years. Therefore, heat release rate of burning objects must be measured and taken as the parameter in fire hazard assessment. Previously, that was measured by the mass-loss-rate method. Now, the oxygen consumption method based on the assumption that burning 1 kg of oxygen would give 13.1 MJ of heat is used. An exhaust hood with a fan-duct system is required to collect flue gas, with an accurate oxygen analyzer for measuring the amount of oxygen consumed.

Table 1: Methane oxidation due to Glarborg et al. (1992)

$H+O_2 = O + OH$ (1)	$CH_2(S) + O_2 \rightarrow CO + OH + H$ (40)
$O + H_2 = H + OH$ (2)	$CH_2(S) + CO_2 \rightarrow CH_2O + CO$ (41)
$OH + H_2 = H_2O + H$ (3)	$CH + H = C + H_2$ (42)
$OH + OH = H_2O + O$ (4)	$CH + O \rightarrow CO + H$ (43)
$H + OH + M \rightarrow H_2O + M$ (5)	$CH + OH \rightarrow HCO + H$ (44)
$H + O_2 + M \rightarrow HO_2 + M$ (6)	$CH + OH = C + H_2O$ (45)
$HO_2 + H \rightarrow OH + OH$ (7)	$CH + O_2 \rightarrow HCO + O$ (46)
$HO_2 + OH \rightarrow H_2O + O_2$ (8)	$CH + H_2O \rightarrow CH_2O + H$ (47)
$CO + OH = CO_2 + H$ (9)	$CH + CO_2 \rightarrow HCO + CO$ (48)
$CH_4 + H = CH_3 + H_2$ (10)	$C + OH \rightarrow CO + H$ (49)
$CH_4 + O \rightarrow CH_3 + OH$ (11)	$C + O_2 \rightarrow CO + O$ (50)
$CH_4 + OH = CH_3 + H_2O$ (12)	$NH + H \rightarrow N + H_2$ (51)
$CH_3 + H \rightarrow CH_4$ (13)	$NH + O \rightarrow NO + H$ (52)
$CH_3 + H = CH_2 + H_2$ (14)	$NH + O \rightarrow N + OH$ (53)
$CH_3 + H = CH_2(S) + H_2$ (15)	$NH + NO = N_2O + H$ (54)
$CH_3 + O \rightarrow CH_2O + H$ (16)	$N + OH \rightarrow NO + H$ (55)
$CH_3 + OH = CH_2 + H_2O$ (17)	$N + O_2 \rightarrow NO + O$ (56)
$CH_3 + OH = CH_2(S) + H_2O$ (18)	$N + NO = N_2 + O$ (57)
$CH_3 + OH = CH_2OH + H$ (19)	$O + N_2 + M \rightarrow N_2O + M$ (58)
$CH_3 + O_2 \rightarrow CH_2OH + O$ (20)	$N_2O + H \rightarrow N_2 + OH$ (59)
$CH_3 + HO_2 \rightarrow CH_2OH + OH$ (21)	$HCN + O \rightarrow NCO + H$ (60)
$CH_3 + HCO \rightarrow CH_4 + CO$ (22)	$HCN + O \rightarrow NH + CO$ (61)
$CH_2OH + M \rightarrow CH_2O + H + M$ (23)	$HCN + OH \rightarrow CN + H_2O$ (62)
$CH_2OH + O_2 \rightarrow CH_2O + HO_2$ (24)	$HCN + OH \rightarrow NCO + H_2$ (63)
$CH_2O + H \rightarrow HCO + H_2$ (25)	$CN + OH \rightarrow NCO + H$ (64)
$CH_2O + OH \rightarrow HCO + H_2O$ (26)	$CN + O2 \rightarrow NCO + O$ (65)
$HCO + M \rightarrow CO + H + M$ (27)	$NCO + H \rightarrow NH + CO$ (66)
$HCO + H \rightarrow CO + H_2$ (28)	$NCO + OH \rightarrow NO + CO + H$ (67)
$HCO + OH \rightarrow CO + H_2O$ (29)	$NCO + NO \rightarrow N_2O + CO$ (68)
$HCO + O_2 \rightarrow CO + HO_2$ (30)	$CH + N_2 \rightarrow HCN + N$ (69)
$CH_2 + H + M \rightarrow CH_3 + M$ (31)	$C + N_2 \rightarrow CN + N$ (70)
$CH_2 + H = CH + H_2$ (32)	$CH_2 + NO \rightarrow NCO + H_2$ (71)
$CH_2 + O \rightarrow CO + H + H$ (33)	$CH_2(S) + NO \rightarrow OH + HCN$ (72)
$CH_2 + O \rightarrow CO + H_2$ (34)	$CH + NO \rightarrow HCN + O$ (73)
$CH_2 + OH \rightarrow CH_2O + H$ (35)	$C + NO \rightarrow CN + O$ (74)
$CH_2 + OH = CH + H_2O$ (36)	$C + NO \rightarrow N + CO$ (75)
$CH_2 + O_2 \rightarrow CH_2O + O$ (37)	$N + CO_2 = NO + CO$ (76)
$CH_2 + O_2 \rightarrow CO_2 + H_2$ (38)	$N + CH_2 \rightarrow HCN + 2H$ (77)
$CH_2(S) + M = CH_2 + M$ (39)	

4. MATHEMATICAL FIRE MODELS

Knowledge of fire science and engineering has to be applied in assessing the fire safety designs. Mathematical fire models [4-7] are useful in the analysis of consequences of fire hazard scenarios. Instead of carrying out physical tests, they have to be used in implementing EPBFC. There are arguments and debates on using fire models. If the predicted results are not verified scientifically, say by full-scale burning test [14], the process would appear as a 'curve-fitting exercise'. Since the intermediate chemistry in burning materials, mixing of air and fuel due to turbulence and thermal radiation are difficult to model in a fire, the heat release rate is taken as the input parameter in most mathematical fire models. Full-scale burning tests should be carried out to establish a heat release rate database on local materials and consumable products.

Zone models [6] can be applied to understand the fire environment with a certain design fire. This is based on a two-layer picture with heat and mass transferred through the fire-induced plume. There are eleven key equations derived from physical laws and seven constraints, giving four ordinary differential equations to solve. However, care should be taken for tall buildings and buildings with large floor areas. Concerns that can be jotted down immediately are:

- Time taken for a smoke layer to develop in large buildings.
- Traveling time of smoke front up a tall building.
- Assessment of the ventilation opening conditions.

Fire field models or application of CFD [e.g. 7] in fact is a natural convective problem. Air flow will be induced by the fire, taken as a thermal object. Conservation equations and flow variables are solved. Basically, there are three key elements:

- Turbulence modeling.
- Algorithms for solving the velocity-pressure linked equations as there is no explicit equation on pressure.
- Discretization scheme on the convective term appeared in the conservation equations.

Since combustion chemistry, thermal radiation and turbulence have to be simulated together, heat release rate should be put in the CFD package. Therefore, this approach is good only for studying smoke movement at the moment. Problems encountered in addition to the hardware constraints are:

- Assignment of free boundaries by extending the computing domains to outside the building.

- Although commercial CFD packages are user-friendly, theories behind CPD should be well understood. Experts are required to carry out CFD simulations for studying fire-induced air flow, not just relying on an engineer without good training in CFD.

Note that CFD itself is a rapidly developing subject. Even in describing the turbulent effects, there had been lots of arguments on using different approaches such as the Reynolds Averaging Navier-Stokes equation or Large-eddy simulations [21]!

Fire models, both zone and field, were applied where necessary. There had been arguments on different issues while applying fire models in Hong Kong:

- Design fire

  As described above, this is the input parameter for almost all fire models. There had been lots of arguments on taking the heat release rate of a design fire as, say 1 MW in an atrium!

- Use of zone model

  There was another project on simulating smoke movement in a long and narrow corridor. The two-layer zone model CFAST [19] was used without dividing the compartment into multi-zones. Again, that was picked out with the design to be revised.

- Turbulence model

  CFD had been used once for studying the fire induced flow without a turbulence model! That was considered not acceptable without physical justification. Therefore, the project was not approved and the design had to be revised by following the codes.

From the past experience on FSE, the following are recommended:

- Zone model

  This is recommended to understand the fire environment with a certain design fire. However, care should be taken on the geometry of the building. Height and floor area should be watched. The time taken for a smoke layer to develop is to be included in a building with a large height to cross-sectional area aspect ratio. Ventilation opening arrangement should be assessed as airflow though horizontal ceiling vent is difficult to estimate. Whether hot smoke can move out or cool air will be pushed in depends on buoyancy.

- Fire field/CFD model

  This is good only for studying smoke movement at the moment. Care should be taken while specifying the boundary conditions. Free boundaries should be assigned where appropriate by extending the computing domains to outside the building. In this way, the neutral plane height can be predicted.

- New generation of fire model

  New version of the commercial CFD packages might be capable of generating the mesh system and linking to the CFD engine automatically. This is much more user-friendly.

5. IMPACTS OF FIRE SAFETY ENGINEERING : HONG KONG AS AN EXAMPLE

Prescriptive fire codes have been developed for many years. Both building designers and officers who have responsibilities to enforce the codes are very experienced in applying them. The codes are generally clearly presented, though there might be difficulties to follow for buildings with unusual geometrical design or in developing new building designs, new building types, and changes in style of living. Following prescriptive-based fire codes may end up either killing innovative building design or failing to maintain a suitable degree of fire safety in a building of unusual type.

With the worldwide movement from prescriptive codes to engineering performance-based fire codes, advanced countries should follow the route on providing fire safety design to give a better and safer indoor environment. However, there are some difficulties in implementing EPBFC. The most essential one is how performance requirements should be specified. Those requirements include human safety, prevention of spread hazards, assurance of fire-fighters access, and many others. Furthermore, there is still room for improving the accuracy of those field models, especially, validation of the models. Besides, it is a pre-requisite that both building designers and relevant government officials shall be properly trained in using fire models before they can handle the EPBFC. As a result, non-prescriptive-based approach was only applied for building designs with new architectural features in Hong Kong.

The consultancy fee varies from project to project in Hong Kong. It is difficult to judge as personal relation is a key factor. There was a ‘one-dollar’ consultancy job on carrying out an urban development project of US$100,000. But there are two key factors in Hong Kong:

- Land price
- Human resources

The minimum cost for running a consultancy firm can be worked out by updated figures on the above. If a professional engineer is able to handle one project per month, the project sum cannot be less than HK$100,000!

Since July 1998, numerous projects based on FSE were submitted for approval. Fire safety designs for new projects considered by a full panel are:

- Evacuation pattern of a 4-storey single family house failed to satisfy the local codes in a residential estate.
- Provision of open strip ceiling in lieu of smoke barrier around escalator voids of a shopping mall.
- Atrium exceeding the maximum compartment space volume of 28,000 m^3.
- Fire resistance requirement for structural steel work in a temporary golf building.
- Travel distance in a carpark not complied with local code on evacuation.
- Combustibility of cladding of an industrial building.
- Internal polypropylene drainage pipes in a laboratory.
- CFD analysis on smoke movement in a balcony.
- Fire safety design of a shopping mall.
- Fire protection on structural framework for a new building complex.
- Smoke extraction system in a protected lobby.
- Fire safety in a television broadcasting and production centre.
- Fire safety for a senior citizen hostel.
- Evacuation of an auditorium.
- Smoke management in a large atrium.

6. EDUCATION AND TRAINING

Continued professional development on advanced topics is necessary [9]. The Hong Kong Polytechnic University, with the objective to provide ‘Quality Teaching’, is proud to announce that three levels of education on FSE are offered for providing adequate education in this field:

- BEng (Hons) in Building Services Engineering with specialism in Fire Engineering [48]: 25 students already graduated in June 2001.
- MSc in Fire and Safety Engineering: started in September 2000 admitting 25 students every year.
- MPhil/PhD research project: about 20 postgraduate students are carrying out research projects on fire engineering.

There are collaborations with universities in China for promoting the education and training on FSE.

Concerning research and development, there are some research activities carrying out at local higher education institutions. Examples are:

- Fire field modeling.
- Water systems.
- Atrium engineering.
- Engineering performance-based fire codes.
- Fire hazard assessment for special types of buildings such as airport terminals, industrial buildings, restaurants, hotels and universities.
- Heat release rate studies.
- Evacuation modeling.
- Risk analysis.

Academic staff and research students concerned were sent to attend overseas conferences, and industrial attachment of periods up to one year. An International Journal on Engineering Performance-Based Fire Codes was established with support from the PolyU. Experiences of implementing EPBFC in other countries can be shared.

7. CONCLUSION

With the rapid development of new materials, new building products, and new architectural features, EPBFC should be implemented. This leads to a new subject area: FSE. There are education and training opportunities for the new professionals. Offering degree programmes up to MSc level is a good starting point to help upgrading the quality of fire engineering personnel.

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Q & A

Q1: How can we estimate the fire size such as heat release rate?

Prof. Chow: We can measure the heat release rate of different materials to set up a database. A clear concept of fire size is then achieved. If the response of the oxygen analyzer is not fast enough, we might need to carry out some calibrations. Besides, micro electrical and mechanical systems (MEMS) can be used. If fibrication technology is good, we can measure the heat release rate and CO concentration, etc. However, it might take at least five years to develop.