International Journal on Engineering Performance-Based Fire Codes, Volume 1, Number 1, p.1-10, 1999

A PRELIMINARY DISCUSSION ON ENGINEERING PERFORMANCE-BASED FIRE CODES IN THE HONG KONG SPECIAL ADMINISTRATIVE REGION

W.K. Chow
Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

ABSTRACT

The possibility of implementing Engineering Performance-Based Fire Codes (EPBFC) in the HKSAR is briefly discussed. Topics in the existing codes where EPBFC can be applied are outlined, following a brief review. Fire models are useful while implementing EPBFC as they are good in hazard assessment. Both 'zone' and 'field' models are discussed with the ones most suitable for local use recommended. Application of the zone model CFAST to study the downstands of an escalator shaft located in a shopping mall is demonstrated. Training and education for fire engineers to implement EPBFC are discussed.

1. INTRODUCTION

Although there are many new architectural design features such as atria, curtain-walled buildings and multi-purpose complexes in the Hong Kong Special Administrative Region (HKSAR, formerly Hong Kong), there is still plenty of room for improvement on fire safety [1,2]. It can be seen that big fires happened not only in old highrise buildings [3] where most fire protection systems such as sprinkler were not yet installed, but the new airport terminal also experienced a 3-hour fire [4] before its opening, with smoke filling up the entire hall.

What will happen when there is a fire in the atrium of a big multi-level shopping mall on a Sunday? It would just be another Lan Kwai Fong tragedy [5], and perhaps, claiming more lives. Can installed fire services systems in a new building control a fire effectively? Is there any good fire safety management? It seems that even the escape routes are not clearly indicated in some buildings. Also, it is common to have large litter bins placed at the back staircases of each floor of many residential buildings.

Therefore, the fire codes [6-9] should be updated regularly to keep pace with the development of new building designs and changes in style of living. Perhaps, the old codes have to be reviewed as they are good only for buildings of older generations. An obvious example is the use of space volume to determine whether smoke extraction systems have to be installed in a big hall. This concept is certainly inadequate [10] if the geometry is not included. Others such as sprinkler heads placed in a high headroom atrium are difficult to actuate. Even if water is discharged, steam produced would bring adverse effects to the trapped occupants. Specifying what should be the best fire safety design for different types of buildings is very difficult. It depends on many factors such as the geometry and use of the buildings, occupancy levels, traffic loading, fire load density, nature of the combustible contents and style of the building users. Further, fire safety management should also be included.

It is obvious that simple sets of fire codes are insufficient for dense urban areas like the HKSAR with so many new architectural features and modern living styles. Fire safety must be designed carefully with respect to passive structures, active systems and fire safety management [11]. Engineering performance-based fire codes (EPBFC) [12-14], developed based on research results from fire science and engineering, statistical fire record, fire-fighting experiences and fire investigations, are proposed. New Zealand [15-17] is one of the countries promoting this actively. Review of the EPBFC works in different countries were clearly presented in various symposiums [16,18,19] and journal papers [20].

Mathematical fire modelling technique [21] supported by full-scale burning tests is very useful for assessing the fire hazard scenarios of buildings and their consequences. From the results, the performance of fire services systems can be evaluated. Fire risk analysis based on probability theory and statistical fire record can be carried out in order to obtain a safety ranking level. Fire safety design can then be made based on those high-level studies [22].

Approval of fire safety design and inspection of the works are held responsible by different government departments. Basically, almost all building fire safety aspects [6-8] are taken care of by the Buildings Department (BD). Whereas, the requirement and installation of fire protection systems [9] are determined by the Fire Services Department (FSD).

Government departments in the SAR are very open in accepting ideas from the industry and academics. Consultation papers [23,24] are commonly distributed for comments. A Fire Safety Committee of the BD has been established in early 1998 to oversee the building fire safety design with an “Engineering Approach”, and in fact, implement some kind of EPBFC. This is definitely a great leap forward while approaching the new century in demonstrating how ‘open’ the SAR government is when making decisions to provide good fire safety to its citizens.

2. ASD IN CONSTRUCTION : PROJECT ON ENGINEERING PERFORMANCE-BASED FIRE CODES

Research on fire science and engineering are carrying out actively at the Department of Building Services Engineering (BSE), The Hong Kong Polytechnic University (PolyU). Studies of this new area are seriously considered by BSE as the results achieved in those fire research projects can be applied directly to develop EPBFC. Support to carry out this study is gained from the project on EPBFC, Construction Industry Development Studies and Research Centre (CIDARC), Area of Strategy Development (ASD) in Construction. The project has the following objectives :

- To identify the areas where EPBFC can be applied and carry out feasibility studies.
- To study the preliminary parameters for fire risk analysis, including the fire load density and occupancy levels in different buildings.
- To apply mathematical fire models in fire hazard assessments.
- To evaluate the performance of fire protection systems.
- To propose guidelines for developing EPBFC.
- To promote the above by organizing international conferences and short courses for local professionals.
- To publish an International Journal on Engineering Performance-Based Fire Codes (IJEPBFC).

This project on EPBFC was started in June 1996 with initial funding HK$925,000, and top-up funding of HK$580,000 was made in June 1998. It is expected to be completed by December 1999. In order to carry out studies of interest to the HKSAR, full-scale burning facilities are developed. Further support on Fire Safety Engineering came from the PolyU President. Longer-term projects are funded by another ASD in Advanced Buildings Technology in a Dense Urban Environment (ABTDUE) with additional support of HK$3 million. The projects are expected to be completed by December 2001.

The results achieved at the first stage of study had already been put into the teaching programmes for the courses at the PolyU up to MSc degree level. The results will also be recommended to the local authority for implementing EPBFC.

The First International Symposium on Engineering Performance-Based Fire Codes was held on 9 September 1998 [25] for promoting the concept and exchanging results with various parties. Such kind of activity is to be held regularly. Several short courses were offered with fire expertise overseas.

The first issue of the journal (IJEPBFC) will be launched in May 1999. International experts in this subject area were invited to join the Editorial Board. Nominal costs on printing and mailing were charged. The journal will also be distributed free to those research workers who have difficulties in attracting research funding.

3. REVIEW OF FIRE SAFETY CODES

As reviewed earlier [22], key areas of fire safety codes in the HKSAR are the building type, compartmentation, structural protection, escape routes, fire-fighting accessibility and fire engineering systems.

- Building Type

Various fire protection provisions prescribed in the codes are designated for 43 different types of classified buildings [9]. Occupant conditions and activities in the building are considered.

- Compartmentation

Classification is based on the space volume of the compartment [7]. Critical values are 28,000 m^3 for spaces above ground, 7,000 m^3 for underground spaces, and smaller values down to 3,500 m^3 for warehouses higher than 30 m. Larger compartment volume might be allowed if provision of fire protection systems giving equivalent safety are demonstrated.

- Structural Protection

A fire resistance period (FRP) is specified for structural elements [7]. For example, FRP of 1 hour minimum for the elements in residential buildings, hotel bedrooms and offices, and 2 hours for all industrial buildings and warehouses. The FRP of the compartment floor and wall should not be less than 4 hours.

- Escape Route for Building Occupants

'Egress' and 'refuge' strategies are adopted with sufficient provision, design and construction of escape routes recommended. The maximum travel distances of people are specified by the usable floor area per person with values varied from 0.5 for assembly halls to 30 for warehouses. A code of practice emphasizing the provisions of escape route is developed [8]. Refuge floor is recommended for all buildings higher than 25 storeys.

- Fire-Fighting Accessibility to Building's Interior

Requirements of the access to the building's interior are described in the local code of practice [6]. Sufficient number of access staircases, fireman's lifts, fire-fighting and rescue stairways must be provided.

- Fire Engineering Systems

Fire engineering systems include fire detection system, fire alarm system, fire-fighting system and smoke management system. The minimum requirements of fire services installations and equipment are specified in the fire safety codes of practice [9]. The installations and equipment required depend on the classification of the building, its height and floor area.

4. SPECIFIC AREA OF APPLICATION

There are four key references [6-9] that should be followed carefully while designing building fire safety:

- Fire Resistance Construction (FRC) [7]

Buildings have to be protected from fire by inhibiting fire spread and ensuring integration of the structural elements. Key requirements are described in this code. However, there are several areas where the specifications are not too clear. Some of them are not demonstrated to be supported by scientific principles, engineering judgement nor past fire experiences. For example, no physical explanation was reported on the maximum compartment volume. There were some studies carried out before on thermal fire resistance of a compartment using an assumed value of fire load density. However, the thermal responses might not be so important compared with the smoke aspect. To describe smoke movement, geometry of the compartment is more important than the space volume. Moreover, external weather conditions and the presence of mechanical ventilation and air-conditioning (MVAC) systems are significant. These are also mentioned in the sections on protection against spread of fire and smoke where downstands of 450 mm are required to surround the escalators. It is obvious that the fire environment should be clearly understood before making a conclusion.

Further, the FRP of the structural elements can be predicted by studying the heat and moisture transfer through the building materials such as concrete [26]. Transport phenomena and computer models are useful.

- Means of Escape (MoE) [8]/ Means of Assess (MoA) [6]

Two key areas that must be considered carefully are the Means of Escape (MoE) and the Means of Access (MoA) for fire-fighting and rescue. Buildings should be designed in the way that the occupants can escape quickly in case of a fire. The time needed to escape has to be shorter than the time required for the fire to spread. Escape routes should not be too long nor too complex. The types and number of occupants and their patterns of behaviour are important factors to be considered.

Building evacuation models can be applied to understand the optimum evacuation pattern. This should be an important element in designing MoE and MoA.

- Fire Engineering Systems [9]

The fire protection systems required in different types of building uses are specified in this 'red book' [9]. However, detailed designs are not described, though well-known design guides [27] for sprinkler designs are commonly referred to. Again, the fire environment has to be understood. For example, is sprinkler required in a high headroom atrium?

Smoke management system is another key area where there are lots of arguments and debates. Smoke control is important as smoke is one of the major causes of death in a fire. However, detailed designs of smoke management systems [28,29] are difficult to specify and this is another area where EPBFC should be applied. A typical example is whether the requirement of 6 air changes per hour (ACH), 8 ACH, 10 ACH, or even 12 ACH should be applied in atria. Selection of a design fire is important as there are arguments over whether to use 2.5 MW, 5 MW or 7.5 MW. Furthermore, integration and interaction of the smoke control systems with MVAC systems must be considered carefully.

Hot topics to consider in addition to those common practices are:

- Application of fire models to understand the hazard scenarios and their consequences.
- Design fire size.
- Application of building evacuation models [30] to understand the planning of escape routes and actions taken by the building operations in case of a fire, which is an essential part in fire safety management.

5. BUILDING FIRE MODELS

It is important to understand the indoor environment after a fire starts. Conducting full-scale experiments are very expensive and it is difficult to repeat some tests for the same building but with different fires. Those studies are good only for measuring empirical parameters, validating theories and fire investigations. An alternative approach is to apply mathematical fire models which have been developed and reported in literature [21]. Empirical equations based on a fire source are found in the literature. Some of these are compiled in computer programs called as fire engineers' calculator such as FIREFORM/ FPETool [31] and FIRECALC/FIREWIND [32]. More complicated fire models are in general classified as zone models [33], field models (application of Computational Fluid Dynamics CFD) [34] and airflow network models [35]. Simulations have to be carried out in computers, previously with a mainframe, now on a stand-alone work-station or a Pentium personal computer. If used carefully, they are suitable for simulating the fire environment for design purposes.

Most of the zone models available in the literature have been validated [36] and can be accessed readily by the users. In a zone model, the compartment concerned is divided into an upper hot layer and a lower cool layer. A plume is formed above the burning object with heat and mass transferred between the two layers through the plume. Equations describing the conservation of mass, momentum and enthalpy are solved numerically together with plume models, vent flow equations, radiation and combustion models. As reviewed by Forney and Moss [37], there are eleven variables to be solved, namely mass, internal energy, density, temperature and volume for the upper and lower layers (M_U, E_U, ρ_U, T_U, V_U and M_L, E_L, ρ_L, T_L, V_L), and pressure P. Seven constraints can be derived from fire physics and so four of those variables have to be chosen as solution variables. Similar pairs of variables such as m_L and m_U or T_L and T_U are selected so that similar numerical solvers can be employed. Many zone models are available in the literature, for example, ASET [38], BRI2 [39], CFAST/FAST/ FASTLite [36], FIRST [40] and the zone models in FIRECALC/ FIREWIND [32].

In the past decade, the fire field modelling technique [34,41] or application of CFD has been developed and used to some extent for design purposes. This is believed to have great potential to achieve reliable results and is useful for predicting fire environment in big enclosures such as an atrium or a tunnel. Although the computing time required is still quite long, it has been improved with efficient numerical schemes and fast computers. A three-dimensional simulation can be executed successfully even in a Pentium PC. There should be no problem in doing the 'number crunching' exercises if an Unix stand-alone workstation is available.

The field model can be applied to simulate the fire-induced field of flow, temperature and smoke concentrations within an enclosure. Current development [41-44] has reached the stage that the flow and temperature field can be simulated successfully by taking the burning object as a heat source. To the best of knowledge, apart from using the simple chemical reacting system approach, attempts were made in the Sweden/U.K. project [45] in using the flamelet model to develop a chemistry library, although combustion effects of the burning process still have to be simulated with empirical parameters such as using the empirical formula for the burning rate [46]. The flamelet model had not yet been integrated into a field model (PHOENICS/ JASMINE in their case) as reported by Tuovinen [45]. The field model is still a natural convection problem good only for predicting the flow field driven by buoyancy at a distance away from the fire source. Flame spread process cannot be simulated realistically without studying the detailed combustion chemistry, unless using empirical equation. Nevertheless, the predicted results are good enough for building services engineers to assess the performance of fire protection systems.

Engineering consultancy firms might not be able to afford a group of experts for developing field modelling software. Therefore, commercial CFD packages available in the market are very useful to them. Of which, the PHOENICS family (e.g. JASMINE from Fire Research Station [41,45] and other versions from CHAM [47,48]) and CFX have been applied as fire field models most frequently. For PHOENICS released from CHAM, there is a

FLAIR menu serving as a pre-processor so that the geometry and fire of the problem can be input easily. The package can be executed in a Pentium PC. However, it is still difficult for a small consulting firm to keep more than three CFD engineers who can use commercial packages.

6. USE OF ZONE MODELS

Most of the available zone models had been validated by different research groups and are demonstrated to be good for simulating fire in general compartments (of normal dimensions up to 10 m) including multi-room structure. Important physical phenomena such as expressions for the fire plume, ceiling jet, vent flow and door jet had been modelled carefully. Also, the computing time required for simulating compartmental fires is relatively faster than a field (CFD) model and so it is feasible to run a zone model in a personal computer. The models are usually simple to use and with good graphical pre- and post-processors. There is no reason why the models are not recommended for design purposes. If they are used appropriately, the models are very useful for simulating the fire environment for buildings of different uses.

A major problem of using a zone model is whether a clear two-layer structure is formed for fires in special buildings such as atria, long corridors, tunnels or big enclosed spaces. Experimental verification is necessary and should be carried out as soon as possible to understand the smoke spreading mechanisms. There might be problems in using a zone model for simulating fires in a building with a sloped ceiling. For example, entrainment for a ceiling jet could be very different from that for a flat roof.

A tool suitable for local use is the Consolidated Model of Fire Growth and Smoke Transport (CFAST) [36] developed at the Building and Fire Research Laboratory, National Institute of Standards and Testing (NIST), U.S.A. This model is one of the most recent zone models with updated development. It can predict the fire environment in a multi-compartment building. The fire is specified in terms of either the mass loss rate of the fuel or the heat release rate. The transient smoke layer thickness, the associated hot gas temperature, the temperature of the lower cool air zone, the vent flow and the radiative heat acting on an object in each room can be predicted. The four key parameters to be solved are:

- pressure above the reference value
- volume of the upper layer
- temperatures of the upper layer
- temperatures of the lower layer

Versions above 2.0 include simulation of forced ventilation system and horizontal ceiling vents. The program can be run in a personal computer (PC) and is included in HAZARD1 by NFPA [49] for fire hazard assessment. The updated series are renamed as FASTLite, which can be downloaded from the NIST website.

7. USE OF FIELD MODELS

For the case of field models, to the best knowledge of the author, experimental validations have not been studied as for the zone models. In fact, very limited experimental works (apart from the recent data by Ingasson and Olsson [50] on sprinkler fires) were performed for verifying field models. The data reported by Steckler et al. [51] was performed originally for studying the doorway flow but had been used repeatedly by field modellers for verifying their models, e.g. Satoh [42], Chow and Leung [52] and the Greenwich University group on illustrating the use of FLOW3D (now CFX) and PHOENICS/ JASMINE [43,44].

There are many reasons why the field model is so attractive. The predicted ‘microscopic’ picture of the thermal environment described by the velocity vector diagram, temperature, pressure and smoke concentration contours are useful for deriving the relevant macroscopic parameters for engineering purposes. The calculated vertical distribution of the air temperature is useful in studying the thermal sensitivities of sprinkler heads. Also, the air entrainment rates for a fire plume can be calculated from the predicted horizontal velocity components. The time required to get the predicted results has now shortened a lot because of the development of efficient computing schemes and high speed computers. For instance, simulations in previous studies [53] performed in a Pentium PC took up to a day’s CPU time for steady-state simulations. That is a great advancement compared with the past years when even a two-dimensional fire simulation would take days of CPU time in a minicomputer [52]. An attractive point is the beautiful graphical presentation of the geometry, temperature fields and velocity vectors. All these are driving forces to promote the use of CFD technique for fire simulations.

However, there are still lots of developmental works and inappropriate application of the technique would lead to wrong results. It is obvious that there must be problems in simulating a complicated physical system described by a set of partial differential equations using a set of relatively simple linear equations derived from the finite difference methods, or the control volume method for most cases. Care must be taken that most CFD works [54] refer to the simulation of the mean flow variables, and the velocity vectors come from the mean components only. There are at least three parts to consider even for simulating the fire-induced air flow in a simple building of rectangular shape:

- The physical principles behind the turbulence have to be reviewed. Current turbulence closure models [54] might give many parameters for fine-tuning. This becomes even more complicated when combustion of the burning processes of the object or evaporation effects of a sprinkler water spray are studied.

- The schemes for discretizing the set of equations have to be considered carefully if finite difference method is used. The control volume method together with those different schemes might not be the only solution.

- The algorithms in solving the system of pressure-linked equations have to be reviewed.

In addition, treatment of the boundary conditions would be very important. Results have to be compared and be consistent with those derived from simple theory. The orifice coefficient for a vertical vent is an obvious example. More importantly, experimental works designed for studying field models must be performed for verifying the results, tuning the parameters concerned in the physical equations and deriving new solution methods.

The PHOENICS is a suitable commercial CFD package for local use. However, there are several points to note when using it as a fire field model:

- The heat release rate might have to be switched on in steps. Otherwise, very high air temperature would be predicted if a large value (say 600 kW for reported simulations [53]) is used.

- Specifying the fire by either an area heater or a volume heater has to be selected carefully. It is because heat above the fire would be fixed. This point can only be omitted when the combustion chemistry in the burning process is included.

- For relatively simple structures like the NBS fire chamber [51], it is better to extend the computing domains to the outside of the door. Otherwise, the pressure difference across the hot smoke layer and the cool air has to be measured experimentally. Also, the neutral plane height can be derived. This is also pointed out by Mawhinney et al. [44] in their simulations, and explored further by Chow and Yin [55] with a modified version of TEAM [56] and CFX.

- The free boundary opened to the outside air is important and at least one boundary condition of this kind must be specified. It should be noted that too small an opening would also give high indoor air temperature.

8. DESIGN FIRE

It is important to specify a design fire for fire hazard assessment. Putting this into a fire model enables the calculation of the time reaching untenable conditions for occupants. These include smoke layer interface height, smoke temperature, elevated heat flux and toxic gases parameters such as the Fractional Effective Dose (FED) [57]. The escape time required should be shorter than the time required to reach untenable conditions. Further, the time at which flashover would occur can also be determined by inspecting whether the flashover criteria are satisfied.

Many design fires are recommended and used, examples are:

- Constant value or steady burning fire

  A fire of constant heat release rate 5 MW is commonly assumed, but smaller values such as 2.5 MW might be used. Higher values are used for tunnels or atria [58].

- Transient fire

  A t^2-fire with heat release rate Q (kW) given in terms of time t (s) by the following equation is commonly used [29]:

$$Q = Q_0 \left(\frac{t}{t_g} \right)^2 \tag{1}$$

  Q_0 is commonly taken as 1,000 kW, with t_g of values 75 s, 150 s, 300 s and 600 s for ultra-fast, fast, medium and slow t^2-fires respectively.

- Curves determined experimentally

  Heat release rates libraries for common materials are developed in the literature from measurements with the oxygen consumption method such as cone calorimeter and furniture calorimeter, or other empirical methods involving measurement of transient mass loss of fuels.

Thorough reviews such as those by Höglander and Sundström [59] are found in the literature. There are always argument on the fire load density and the heat release rate, say too low or too high [60].

9. A SELECTED EXAMPLE

Downstands up to 450 mm are required in escalator shafts [7]. One of its functions is to prevent smoke spreading to the escalator shaft. This can be demonstrated by zone model simulations with CFAST2.0 [36].

A shopping mall as shown in Fig. 1 is taken as an example. There is a shop linking to a corridor through a door of 3 m wide and 2 m high. The corridor can lead to the escalator shaft connected with an upper space. The doors of other shops are assumed to be closed to give such a simple configuration. A slow NFPA t^2-fire of 1 m^2 was started at the centre of the shop. Effects of the downstands of different lengths of 200 mm, 450 mm and 800 mm on the smoke spreading pattern to the shaft are shown in Fig. 2.

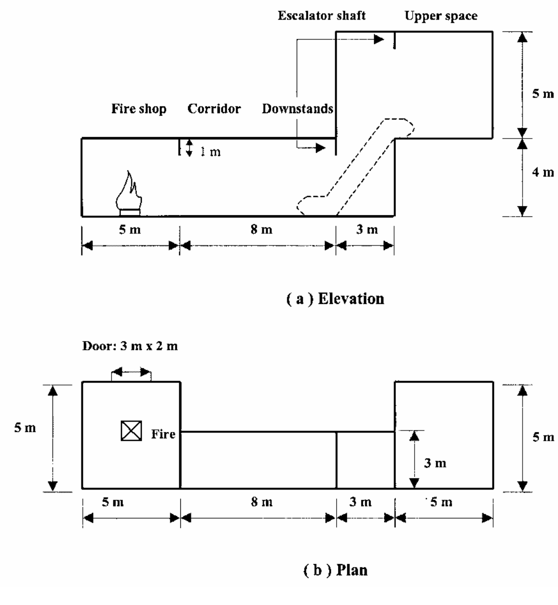

Fig. 1: Part of a shopping mall

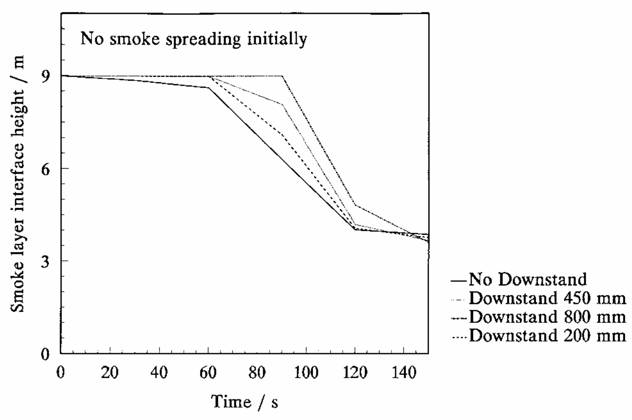

Fig. 2: Smoke filling in the escalator shaft

It is obvious that the escalator shaft can be kept away from smoke at the early stage of a fire if there are downstands. The shaft can be protected from smoke for over 100 s when very long downstands are used. However, constraints on the ceiling height might not allow installing long downstands. Therefore, fire engineers have to demonstrate to the Authority that sufficiently long downstands would give a safe period at the escalator shaft.

10. CONCLUSION

Building fire codes in the HKSAR are briefly reviewed with the specific areas having the possibility of implementing EPBFC outlined. Fire models will be the key tools in this activity and demonstration of the application of zone model to study the effect of the downstands on the smoke spreading to an escalator shaft of a shopping mall is made. It is clear that EPBFC has to be implemented for most of the new buildings. But doing this would require sufficient knowledge. Therefore, training and education of fire engineers are very important.

Training can be short courses, workshops and symposiums offered to the construction industry. This is one of the main objectives of this EPBFC project funded by ASD in Construction through CIDARC. Two short courses on Fire Dynamics and Smoke Control were offered successfully in 1997 and 1998. Areas required immediate actions are:

- Smoke Control System
- Fire Zone Model
- Fire Field Model
- Building Evacuation Model
- Fire Safety Management

Education should be carried out as a long-term development. The PolyU, with the mission to become a ‘preferred university’, is very conscious about that. There are strong elements on fire engineering, might be as much as 30% of the course content, for all the sub-degree, BEng (Hons)/ MEng degree and MSc degree programmes in Building Services Engineering. A BEng (Hons) degree in Building Services Engineering with Specialism in Fire Engineering was started in September 1997 [61]. This is a 4-year part-time programme with the first batch of students to be graduated in June 2001. After that, 25 students will be graduated annually. There is also planning to offer a MSc degree course in Fire Engineering in September 2000 for professional engineers working in this area. Higher degree programmes by research leading to MPhil and PhD have been started at the PolyU since 1988. At the moment, over 20 PhD students have registered at BSE who are working on research projects related to fire.

Lastly, exchanging ideas with experts from different countries is of great importance. The EPBFC project funded by ASD in Construction will definitely serve this purpose well. With the smooth reunification of Hong Kong to China, good collaboration among local and overseas government officers, industrial experts and academics, are key factors leading to the success of EPBFC to give very safe buildings. The journal (IJEPBFC) is a good stepping stone to achieve that. Experts are welcome to submit papers for publication in the journal.

ACKNOWLEDGEMENT

The study is funded by CIDARC, ASD in Construction, through the Engineering Performance-Based Fire Codes project.

REFERENCES

1. W.K. Chow, “Fire aspects for atrium buildings in Hong Kong”, Proceedings of the 7th International Research and Training Seminar on Regional Development Planning for Disaster Prevention: Improved Fire Safety Systems in Development Countries, United Nations Centre for Regional Development, 17 October 1994, Tokyo, Japan, UNCRD Proceedings Series No. 7, pp. 99-109 (1995).
2. S. Rose, “Fire Services Supplement-Fire Legislation in Hong Kong”, Building Journal, Hongkong China, February 1997, pp. 50-51 (1997).
3. “Governor to decide on Garley fire probe”, South China Morning Post, Hong Kong, 13 December (1996).
4. “Chek Lap Kok terminal blaze”, South China Morning Post, 30 April (1998).
5. “Lan Kwai Fong tragedy”, South China Morning Post, 2 January (1993).
6. Code of Practice for the Provision of Means of Access for Firefighting and Rescue, Buildings Department, Hong Kong (1995).
7. Code of Practice for Fire Resisting Construction, Buildings Department, Hong Kong (1996).
8. Code of Practice for the Provision of Means of Escape In Case of Fire, Buildings Department, Hong Kong (1996).
9. Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection and Testing of Installations and Equipment, Fire Services Department, Hong Kong (1998).
10. W.K. Chow, “On the evaluation of a ‘time constant’ for studying the smoke filling process in atrium spaces”, Fire and Materials, Vol. 18, No. 5, pp. 327-331 (1994).
11. R.H. Jensen, “Fire protection and life safety for targeted buildings”, Proceedings of Fire Safety Frontier ’94, Tokyo International Fire Conference, 18-22 October 1994, Tokyo, Japan, pp. 27-32 (1994).
12. “NFPA’s future in performance-based codes and standards”, Report of the NFPA In-House Task Group, National Fire Protection Association, Quincy, Ma, U.S.A. (1995).
13. Fire Engineering Guidelines, 1st Edition, Fire Codes Reform Centre Ltd., Sydney, N.S.W., Australia (1996).
14. CIBSE Guide E, “Fire Engineering”, The Chartered Institution of Building Services Engineers, London, U.K. (1997).
15. C.R. Barnett and M.R. Simpson, “Fire code review - New Zealand’s performance based fire code”, Proceedings of Asiaflam ’95 Conference, pp. 27-44 (1995).
16. A. Buchanan, “Five years of performance-based fire safety in New Zealand”, Proceedings of The First International Symposium on Engineering Performance-Based Fire Codes, 8 September 1998, Hong Kong, pp. 32-46 (1998).
17. A.H. Buchanan, “Implementation of performance-based fire codes”, Fire Safety Journal, Vol. 32, No. 4, pp. 377-383 (1999).
18. H.P. Morgan, “Moves towards performance-based standards in the U.K. and in the European committee for standardization (CEN)”, Proceedings of The First International Symposium on Engineering Performance-Based Fire Codes, 8 September 1998, Hong Kong, pp. 7-14 (1998).
19. T. Tanaka, “Performance based fire safety design standards and FSE tools for compliance verification”, Proceedings of The First International Symposium on Engineering Performance-Based Fire Codes, 8 September 1998, Hong Kong, pp. 47-53 (1998).
20. G.V. Hadjisophocleous, N. Benichou and A.S. Tamim, “Literature review of performance-based

fire codes and design environment", Journal of Fire Protection Engineering, Vol. 9, No. 1, pp. 12-40 (1998).

21. R. Friedman, "Survey of computer models for fire and smoke", Forum for International Cooperation on Fire Research, Factory Mutual Research Corporation, Norwood, Ma 02062, U.S.A. (1991).

22. W.K. Chow & L.T. Wong, "Fire safety codes for Hong Kong: Inadequacy for atrium design", Building Services Engineering Research and Technology, Vol. 19, No. 2, pp. 93-99 (1998).

23. Consultation paper on fire safety improvements to old commercial buildings, Government Secretariat, Security Branch, May 1997, Hong Kong (1997).

24. Consultation Paper on Licensing Control of Karaoke Establishments, Urban Services Department (USD) and Regional Services Department (RSD), February 1998, Hong Kong Special Administrative Region (1998).

25. W.K. Chow (editor), Proceedings of The First International Symposium on Engineering Performance-Based Fire Codes, 8 September 1998, Hong Kong (1998).

26. L.Y. Cooper, R.J. Dexter, K. Glvary and J.M. Franssen, "Fire performance of high-performance construction materials", Proceedings of the Fifth International Symposium on Fire Safety Science, Edited by Y. Hasemi, Tsukuba, Japan, pp. 1347 (1997).

27. NFPA-13, Installation of sprinkler systems, National Fire Protection Association, Quincy, Ma, U.S.A. (1991).

28. J.H. Klote, "Method of predicting smoke movement on atria with application to smoke management", NISTIR 5516, National Institute of Standards and Technology, Gaithersburg, MD, U.S.A. (1994).

29. NFPA 92B, Guide for smoke management systems in malls, atria and large area, National Fire Protection Association, Quincy, Ma, U.S.A. (1991).

30. E.R. Galea, "A general approach to validating evacuation models with an application to EXODUS", Journal of Fire Sciences, Vol. 16, No. 6, pp. 414-436 (1998).

31. H.E. Nelson, "FPETOOL: Fire Protection Engineering Tools for Hazard Estimation", NISTIR 4380, National Institute of Standards and Technology, Gaithersburg, Maryland, U.S.A. (1990).

32. FIRECALC, Fire Engineering Computer Software, Division of Building, Construction and Engineering, CSIRO, North Ryde, Australia (1990/92).

33. J.G. Quintiere, "Fundamentals of enclosure fire 'zone' models", Natural Fire Protection Association, Annual Meeting for Society of Fire Protection Engineer, 18 May 1987, Cincinnati, Ohio (1987).

34. K.T. Yang, "Recent development in field modelling of compartment fires", JSME International Journal, Vol. 37, No. 4, pp. 702-717 (1994).

35. J.H. Klote and J. Milke, "Design of smoke management systems", ASHRAE Publications 90022 (1992).

36. R.D. Peacock, G.P. Forney, P. Reneke, R. Portier and W.W. Jones, "CFAST, the consolidated model of fire growth and smoke transport", NIST Technical Note 1299, NIST, U.S. Dept. of Commerce, Gaithersburg, Maryland, U.S.A. (1993).

37. G.P. Forney and W.F. Moss, "Analyzing and exploiting numerical characteristics of zone fire models", Fire Science & Technology, Vol. 14, No. 1, pp. 49-60 (1994).

38. L.Y. Cooper, "A mathematical model for estimating available save egress time in fires", Fire and Materials, Vol. 6, pp. 135 (1982).

39. T. Tanaka and K. Nakamura, "A model for predicting smoke transport in buildings", Report of the Building Research Institute No. 123, Building Research Institute, Ministry of Construction, Tsukuba, Japan (1989).

40. H.E. Mitler and J.A. Rockett, "User's guide to FIRST: A comprehensive single-room fire model", NBSIR 87-3595, September, Center for Fire Research, National Bureau of Standards, Gaithersburg, MD, U.S.A. (1987).

41. G. Cox, "Some recent progress in the field modelling of fire", Fire Science and Technology, Proceedings of the First Asian Conference, Edited by W. Fan and Z. Fu, International Academic Publisher, Beijing, China, pp. 50-59 (1992).

42. K. Satoh, "Three-dimensional field model analysis of fire-induced flow in an enclosure", Report of Fire Research Institute of Japan, No. 60, pp. 53 (1985).

43. L. Kerrison, E.R. Galea, N. Hoffmann and M.K. Patel, "A comparison of a FLOW3D based fire field model with experimental room fire data", Fire Safety Journal, Vol. 23, pp. 387-411 (1994).

44. R.N. Mawhinney, E.R. Galea, N. Hoffmann and M.K. Patel, "A critical comparison of a PHOENICS based fire field model with experimental compartment fire data", Journal of Fire Protection Engineering, Vol. 6, No. 4, pp. 137-152 (1994).

45. H. Tuovinen, "Modelling of laminar diffusion flames in vitiated environment", Paper presented at the 4th International Symposium of Fire Safety Science, Ottawa, Canada (1994).

46. M. Luo and V. Beck, "Modelling fire behaviour in a full-scale building", Paper presented at the 8th International Symposium on Transport Phenomena in Combustion (1995).

47. "The PHOENICS - 2.0 Companion", CHAM Report/TR 313 - CHAM, London, U.K. (1993).

48. "FLAIR User Guide", CHAM Report/TR 312 - CHAM, London, U.K. (1993).

49. R.D. Peacock, W.W. Jones, G.P. Forney, R.W. Portier, P.A. Reneke, R.W. Bukowski and J.H. Klote, “An updated guide for HAZARD1 version 1.2”, NISTIR 5410, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland, U.S.A. (1994).

50. H. Ingason and S. Olsson, “Interaction between sprinklers and fire vents (full scale experiments RANDFORSK project 406-902)”, Fire Technology SP Report 1992: 11, Swedish National Testing and Research Institute, Sweden (1992).

51. K.D. Steckler, J.G. Quintiere and W.J. Rinkinen, “Flow induced by fire in a compartment”, NBSIR 82-2520, National Bureau of Standards, U.S.A. (1982).

52. W.K. Chow and W.M. Leung, “Solid-wall boundary effect on a building fire field model”, Combustion Science and Technology, Vol. 71, No. 1-3, pp. 77-93 (1990).

53. W.K. Chow, “Use of Computational Fluid Dynamics for simulating enclosure fires”, Journal of Fire Sciences, Vol. 13, No. 4, pp. 300-334 (1995).

54. D.B. Spalding, “Mathematical modelling of fluid mechanics, heat transfer and chemical reaction processes”, Computational Fluid Dynamics Unit Report No. HTS/80/1, Imperial College of Science & Technology (1980).

55. W.K. Chow & R. Yin, “CFD simulations of air movement in a big hall induced by a ‘bare cabin’ fire and studies on free boundary conditions”, Journal of Fire Sciences – Accepted to publish (1998).

56. P.G. Huang and M.A. Leschziner, “An introduction and guide to the computer code TEAM”, Research Report, UMIST, Manchester, U.K. (1984).

57. D.A. Purser, “Toxicity assessment of combustion products”, in SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, Ma, U.S.A. (1995).

58. M.E. Dillon, “Case study of smoke control system testing for a large enclosed stadium”, ASHRAE Transactions: Symposia, Vol. 100, Part 2, pp. 878-892 (1994).

59. Höglander and B. Sundström, “Design fires for preflashover fires: Characteristic heat release rate of building contents”, Fire Technology, SP Report 1997:36, SP Swedish National Testing and Research Institutes, Boräs, Sweden (1997).

60. J.C. Jones, “A contribution to the discussion of the cabins fire safety design concept”, Journal of Fire Sciences, Vol. 16, No. 6, pp. 410-413 (1998).

61. W.K. Chow, L.T. Wong, K.T. Chan, N.K. Fong & P.L. Ho, “Fire safety engineering: comparison of a new degree programme with the model curriculum”, Fire Safety Journal, Vol. 32, No. 1, pp. 1-15 (1999).