Review on Modelling of Fire Physics and Risk Assessment

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ABSTRACT Fire brings civilizations to human, at the same time it brings risk to human. To prevent and control fire is one of the important fields of fire researches, and fire risk analysis and fire modelling are premises to study fire prevention and fire control. This paper reviews on modelling of fire physics and fire risk assessment.

The conformation of this paper is introduced in section 1, developments of fire risk assessment are reviewed in section 2; fire growth models (including field model, zone model, network model) are reviewed in section 3); some practical software package of fire risk assessment are introduced in section 4. Finally, the future development of fire risk analysis is prospected.

KEYWORDS: Fire Model, Risk Analysis, Review.

1 INTRODUCTION

Much research and many publications address fire risk assessment. There is evidence that fire is one of the critical disasters all over the world. With rapid development of economy, science and technology, major fire accidents, which caused great loss of human lives and economy and polluted environment, happened frequently. So the public and governments pay close attention to fire and its related disasters. To reduce fire damage to human lives and resources is one of the major and instant problems that must be resolved.

Using experiments and computer simulations, researchers studied fire process and analyzed its risk. This paper reviews much of the modeling of fire physics and risk assessment. The literature is collected mainly from major journals and conference proceedings. The author has tried to be reasonably complete, but those papers which are not included were either inadvertently over looked or considered peripheral to this survey. The writers apologize to the readers as well as to the researchers if we have omitted any relevant papers.

There are rules for fire occurring, growing and fire protecting. These rules, however, are neither totally deterministic nor totally probabilistic. They have both deterministic and probabilistic characters. Only when we study not only its determinability but also its probability and furthermore study their combination, can we understand the rules of fire as a whole [1].

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The duality of fire rules can be understood by taking the fire occurrence as an example. If fuel and environment conditions are fixed, it can be determined whether a specified fire source can cause a fire with experiment and computer modeling presently available. However, as a hazard, fire always covers a wide range. The variety of human behavior, fuel, environment condition and fire source inevitable gives fire to the uncertainties of fire occurrence. It means impossible to predict definitely whether or when or where a fire will occur. A reasonable goal of study is to provide a probability of fire occurrence and its connections with various factors.

A prime method to study the determinability of fire is modeling including experiment and computer modeling, while statistics analysis is the main method to investigate the probability or risk. The framework of fire risk assessment is shown in figure 1.

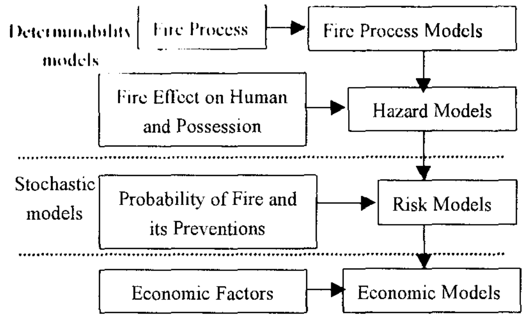

FIGURE 1. The framework of fire risk assessment

2 FIRE RISK ASSESSMENT

The goal of building fire risk assessment is to determine the consequences of a specific set of conditions called scenario. The scenario includes details of the room dimensions, contents, and materials of construction, arrangement of rooms in the building, sources of combustion air, position of doors, numbers, locations and characteristics of occupants, and any other details which will have an effect on the outcome.

Reference [2] introduces two quantitative risk analysis (QRA) methods: standard QRA and extended QRA, which may be used to evaluate the risk which the occupants of a building may be subject if a fire breaks out. They differ in terms of how uncertainties in the variables are considered. The extended QRA explicitly considers uncertainty as it is a part of the methodology. The standard QRA has to be complemented with a sensitivity analysis to fully provide insight into the uncertainty inherent in the scenario.

Reference [3] developed a quantitative method for predicting the expected life safety loss (or risk) of the building fire. Fire incidents and fire deaths can be classified by scenario. The number of fire deaths or risk associated with each fire scenario is :

D_i (Number of deaths from scenario i) = n_i (number of fire of scenario type i) × d_i (average number of deaths per fire in scenario i)

The total number of deaths is then the sum over all scenarios involving the product. The approach for the method involves eight steps: (1)choosing product and occupancy, (2)fixing the occupancy characteristics, (3)the scenario generator- relating fire severity to fire frequency, (4)designing the fire model, (5)describing and predicting escape of occupants, (6)calibrating the model, (7)predicting the fire risk for a new product, and (8)sensitivity analysis and test of assumptions.

Swade, C. and Whiting P. proposed a method of fire risk assessment known as the Building Fire Safety Engineering Method (BFSEM)[4]. The method has mainly been developed at Worcester Polytechnic Institute in the USA and is designed for use by persons with knowledge and experience of fire behavior and building construction. The main components of the method include evaluation of the probability of the fire self-terminating, probability of automatic suppression, and probability of manual suppression by a fire service. The probabilities are combined to form an L-Curve describing the probability of limiting the fire to defined areas of the building. Comparison of L-Curves for different fire protection options forms the basis of the risk assessment.

Zako M. and Kurashiki T. Studied a probabilistic estimation approach of the risk based on the developed simulation in order to estimate the spread of damages by fire and explosion in chemical plant with many tanks [5]. The risk can be determined with two factors, which are the relative values for equipment in plant and, the occurrence of probability of fire. The probability of fire is calculated with the developed simulation and Monte Carlo method considering variance of heat radiation from fire to tanks due to the inclination of the shape of tank fire by the effect of various velocity and direction of wind.

JCIA (Japan Chemical Industry Association) developed a system named chemPHESA21 for quantifying physical, human health, and environmental risks. For the assessment of human health risk, especially for direct exposure at workplace or consumer usage, a concept of "Unit Scenario" was proposed. The specific conditions of scenario were divided to the finest level, and the two step description of the process defines a Unit Scenario [6].

In 1994, the Fire Risk Unit of Fire Research Station developed a fire risk assessment methodology (CRISP) based on simulation models and Monte Carlo methods [7]. The model includes mechanisms that represent the physical and chemical processes of fire development as well as the behavior of the people trying to escape from the fire.

References [8] proposed a methodology for assessing the frequency of exposure of a consumer product in a building to an ignition source and presents a heat transfer model for use in a scenario where upholstered furniture is the target product and an auxiliary heating device is the ignition source. A probability of the frequency of exposure of consumer products to some auxiliary heating devices is given. Reference [9] presented an approach for assessing the frequency of ignition of a consumer product in a building. Deterministic thermal models of the heat transfer processes are coupled with parameter uncertainty analysis of the models and with a probabilistic analysis of the events involved in a typical scenario.

The Fire & Explosion Index (F&EI) has been used widely in the world [10]. It is the leading hazard index recognized by the chemical industry. The present F&EI provides key information to help evaluate the overall risk from fire and explosion. The purpose of the F&EI is to: (1) quantify the expected damage of potential fire, explosion and reactivity incidents in realistic terms; (2) identify equipment that would be likely to contribute to the creation or escalation of an incident; (3) communicate the F&EI risk potential to management.

3 MODELS FOR FIRE GROWTH

In order to investigate the law of fire risk, researchers do many fire experiments such as building fire and compartment fire [11,12]. Reference [13] reported an extensive series of over 140 natural gas fires in a 2/5ths-scale model of a standard room. BFRL of NIST extends the reduced-scale enclosure study to a full-scale enclosure and focuses on comparing the gas concentrations and temperatures of the upper layers and the ventilation behaviors of the two compartments. The findings are useful to realistic fire models and can be used in the development of strategies for reducing the number of details attributed to carbon monoxide [14].

In a recent international survey, many models for predicting fire behavior have been identified [15]. These models that start with the principle of conservation of mass, momentum and energy can be used to predict the environment generated by fire at a given time in a specified volume by assuming the physical parameters to be uniform within the volume which is referred to as a control volume. Different models divided the studied domain into different number of control volumes depending on the desired level of detail. In summary, there are four kinds of fire models. They are zone models, field models, network models and combined field-zone-network (FZN) models.

Zone Model

In zone models the basic element is divided into several areas or zones over which conditions are uniform. In particular two main zones are assumed; a hot upper smoke layer and a lower cooler layer. Within each of the two layers, the temperature, smoke and gas concentrations are assumed to be exactly the same. This two-layer approach has evolved from real-scale experimental observations. While these experiments show some variation within the same layer, they are small compared to the difference between the layers.

The governing equations for zone models can be derived from the conservation of mass, energy and species. For each zone- modeling room, the total volume does not change during the fire process.

The main advantage of this approach is the simplification to a relatively small number of ordinary differential equations which can be handled more comfortably. The disadvantage is that such a model can give only a general overall picture with no fine detail and make large errors in some cases such as in a domain with complicated geometry, a strong fire source or strong ventilation.

Field model

In the case of a field model which are based on computational fluid dynamics technology, the compartment is divided into a (relatively) large grid or mesh and field variables such as temperature and gas concentration are defined at each grid point. In order to model the fire and trace the development of the field variables the solution to a very large number of partial differential equations must be found numerically. The set of partial differential equations can be written in the general form as follows:

$$\partial(\rho\Phi)/\partial t + div(\rho V\Phi - \Gamma_\Phi grad\Phi) = S_\Phi \tag{1}$$

where Φ is the dependent variable, Γ_Φ is the diffusion coefficient of Φ, S_Φ if the source term which represents the production and consumption of Φ.

This method yields a much more detailed picture of the fire but requires more intensive computation. Typically, field models require long CPU time and large computer storage. They are usually used when detailed calculation is necessary, such as in the fire-origin room of strongly ventilated spaces. Due to the limit of computer capacity, it will not be practicable to predict a whole high-rise building fire with field models in the foreseeable future [16,17].

Network model

The network model is based on the assumption that mixing is complete and the properties of the gas are uniform throughout the room [18,19]. It uses only one element to describe each room. Due to the assumption, it is valid only for the spaces remote from the fire- origin room where mixing is relatively complete. It is much simpler than both field and zone models. This simplicity makes it useful for the prediction of smoke spreading in high-rise building. It is practical and economical to implement the network model for remote rooms in a complex high- rise building fire [20]. Network model includes three basic principles as follows:

Mass Conservation Law

$$\sum_{i=1}^{N} a_{ij} Q_i = 0 \tag{2}$$

Where Q_i is the air flow of the branch i, m^3/s;
N is the total number of branches;
a_{ij} is the relating matrix.

Resistance Law

$$h_i = R_i Q_i^2 \tag{3}$$

Where R_i is the resistance of branch i,
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$$\sum_{i=1}^{N} C_{Ki} R_i \left(\sum_{k=1}^{M} C_{Ki} Q_K \right)^2 - F_K(Q_K) - h_{nK} = 0 \tag{4}$$

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$F_K(Q_K)$, h_{nK}, h_K are fan pressure, natural flow pressure and total pressure in branch K respectively, N/m^2.
m is the number of the independent cycle paths.

Junction temperature computation

In network model, air was mixed in the junction connecting with airways, and the air temperature in junctions can be determined by

$$C_p T \sum m_i = C_p \sum (m_i T_i) \tag{5}$$

where C_p is heat capacity of air,
m_i is the mass in airway i before mixing,
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Other Models

A combined field-zone-network model which is based on the coupling of field, zone and network models and proposed by the State Key Lab of Fire Science of China is modified with a volume-conservation method and is used to simulate two building fire cases. The simulation results of the FZN model are generally in agreement with some experimental results. Though temperature rise in the zone-modeling rooms is usually higher than measurement, the FZN model can give a detailed map of the temperature rise and the isotherm shape [21].

As part of the NIST program to study the burning properties of large pool fires, the Large Eddy Simulation (LES) model of smoke transport was developed to predict the concentration of combustion products downwind of a large fire. The model consists of the

volume by assuming the physical parameters to be uniform within the volume which is referred to as a control volume. Different models divided the studied domain into different number of control volumes depending on the desired level of detail In summary, there are four kinds of fire models. They are zone models, field models, network models and combined field-zone-network (FZN) models.

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conservation equations of mass, momentum and energy which describe the steady- state and convective transport of heated gases introduced into the atmosphere by a steadily burning fire and blown by a uniform ambient wind. Baum, H. R. et al studied the velocity and temperature fields of fire plumes theoretically and computationally using the authors' large eddy simulation techniques [22]. Gravity Currents (GC) are important physical phenomena which transport smoke and hot gases in corridors of buildings. they are studied using large eddy simulations (LES). The LES computations require no adjustable parameters, and are found to agree well with available experimental results in the absence of heat transfer [23].

Wade, C. and Barnett, J. developed a computer fire model BRANZFIRE intended for evaluating the performance and hazards associated with combustible room lining materials [24]. It comprises a single-room zone model fully integrated or coupled with a concurrent flow flame spread and fire growth model applicable to a room-corner fire scenario. The fire growth model uses fire property data obtained from a cone calorimeter as input. The computer model is compared with some available experimental data, with reasonable agreement. It is shown that the model has the potential to differentiate the fire hazards associated with different combustible walls and ceilings in enclosures using a sound scientific approach.

In the light of duality rules of fire (determinability and probability) proposed by Fan *et al* [25], models described above are determinability models. Some stochastic models of building fire growth are reviewed in the following.

3.1 Stochastic Models for Fire Growth

The development of stochastic models for compartment fires is particularly important for performance-based codes and standards. There are a number of 'real' problems in the stochastic analysis of building fires. Answering questions such as those given below is important to analyzing a fire risk in a building:

(1) Will the compartment flash over? If it will, then given a variety of ignition sources, how fast will this occur?
(2) What are the potential room-to-room fire spread mechanisms which can occur?
(3) What is the range of post-flashover time vs temperature expected for the compartment?

Various attempts have been made to introduce statistical variability in fire growth models. Ramachandran G. has done many early researches. However, the approaches presented to date do not explicitly consider the underlying physical process. On the other hand, various models of greater or lesser complexity which appeal to fluid mechanics and thermal physics as well as experimental measurements have been developed [26, 27]; but they are still completely deterministic.

The fire growth model developed by the National Research Council of Canada (NRCC) only takes account of uncertainties governing certain parameters, considered as random, in a deterministic model of fire spread relating to a single material or object. The model does consider uncertainties governing the spread of fire from object to object.

Platt et al outlined the principal elements of a probabilistic model that analyzed the spread of fire in multi-compartment buildings with respect to time. Their analysis used a graph theoretic network and an event hierarchy to determine the probability of fire spreading to different locations. The probability of fire spreading between compartments was based on a comparison of the probability density functions of the expected fire resistance and the fire severity: failure being the condition that severity exceeded resistance [28].

Using NRCC model, a stochastic model for compartment fires in building is derived from basic physical laws [29]. It consists of just three variables: the gas temperature T (degrees Celsius), the rate of fuel burning R (g/min) and the oxygen mass fraction in the compartment

v These variables form a Markov vector satisfying a stochastic differential equation. The deterministic version of the model can be calibrated to closely mimic more elaborate models. The main advantage of the stochastic model over the present complex models based on fluid mechanics is that it is extremely easy to simulate and its output realistically models the observed behavior of fires. With the addition of reasonable assumptions regarding the variability of the phenomenon, the probability of extreme values of the fire load can be estimated by a Monte-Carlo simulation and can be used as an input to the probabilistic fire risk analysis of the building under consideration. On the other hand, in deriving the model the effect of certain variables on some other parameters were ignored.

3.2 Nonlinear Model for Fire Growth

Over the last two decades there has been a great increase in research associated with nonlinear systems and there is now a growing activity aimed at applying such ideas to practical systems [30,31]. In the field of fire modeling, stability and bifurcation analyses have been applied in an attempt to understand better the conditions which give rise to flashover in a compartment fire and that work has lead to the models of Bishop *et al* [32]. Fractal theory provides a method of characterizing geometry that cannot be described by conventional methods of Euclidean geometry. The dimension of a set is roughly the amount of information needed to specify points on it accurately. Recently, in fire science many developments have been achieved by the method of fractal especially in determining the premixed flame speed [33,34,35].

Flashover is an important phenomenon in building fires whereby a relatively small, localized fire can suddenly undergo a rapid increase in its rate of growth and intensity. Such an effect may have played a key role in both the Bradford City football stadium fire in 1985 and the King's Cross underground fire in 1987 [36], with violent and tragic consequences. In a compartment flashover is characterized by a sharp increase in both the burning rate of the fire itself and the temperature of the hot gas layer which forms above [37]. Chow, W.K investigated the possibility of flashover in compartment fires using two criteria established earlier [38]. SKLFS also did many flashover experiments in full- scale compartments.

The nature of the flashover jump (sharp increase or drop) suggests that a nonlinear dynamical process is at work, so many researchers investigate flashover and other instabilities which may occur by applying modern geometrical methods and computational techniques of nonlinear dynamics to a mathematical model of compartment fire [39,40]. Initial attempts to understand this phenomenon have already made by Thomas *et al* to model flashover as a jump phenomenon [41]. In the work by Thomas *et al.* a zone model was constructed which assumes that the compartment is divided into two homogeneous regions: a hot/smoke zone and a cool/lower zone. A quasi-steady state assumption was made. Thermal radiative feedback is seen as the significant factor in this model. In general the existence of radiative heat transfer ensures that the equations governing the behavior are highly nonlinear and likely to present a rich field of study for nonlinear instabilities. Bishop *et al.* [42] used the approach of Thomas *et al.* And conducted a qualitative analysis of the occurrence of flashover. They considered an idealized energy balance of the hot layer in a compartment fire which has the following form

$$\frac{dE}{dt} = G(T, t) - L(T, t) \tag{6}$$

where $G(T, t)$ and $L(T, t)$ are, respectively, the rate of gain and loss of energy, E, of the layer. T and t are gas layer temperature and time respectively. Using mathematics transferring, the eigenvalue λ is get. The eigenvalue may then be used to determine the stability or otherwise of the state:

$\lambda > 0$ Unstable (7)

$\lambda < 0$ Stable (8)

Flashover is a typically nonlinear phenomenon that has yet been far from being resolved. However, as suggested by previous work, nonlinear methods can effectively help construct models of flashover that relate fire behavior to the physical characteristics of the system. This improved understanding should also facilitate the formulation of effective regulations to govern fire safety.

Table 1 classifies the literature according to fire growth models.

TABLE 1. Classifies the literature according to fire growth models

Zone Model	[1],[43],[44],[45],[46],[47]
Field model	[16],[17],[45]
Network model	[18],[19],[20],[31]
FZN model	[21],[25],[48]
LES model	[22],[23],[49]
Stochastic model	[26],[27],[28],[29]
Nonlinear model	[30],[31],[32],[33],[34],[35],[38],[50]

4 SOFTWARE PACKAGES OF FIRE RISK ASSESSMENT

With the development of experiment and theoretical researches [51], many software packages for fire risk analysis were published continuously. They use those fire growth models and fire risk analysis models reviewed above, and their interfaces are friendly, so people can use these software packages conveniently.

Over the past decade the fire program of the BFRL has developed computer program based models as a predictive tool for estimating the environment which results in a building when a fire is present. In the beginning, there were three models: FAST, FIRST and ASET. In 1985, development of the CCFM (Consolidated Computer Fire Model) was begun. It was originally intended to be a benchmark fire code, with all algorithm of fire phenomena available fore experimentation. In 1989, a decision was made that development of many computer programs was not the best possible course. Two programs resulted from that, The two were CFAST and FPETool [52].

The model First Simulation Technique FIRST comes from HAVARD IV and is probably one of the first generations of fire zone models. This is a fire zone model written in FORTRAN which can be executed in a personal computer, work-station or mainframe. There is no graphical pre- processing nor post-processing programs for running the model. There are choices on the plume models. In preparing a new input file, questions would be asked on the geometry of the room, fire sizes, vent sizes etc. An output data will be generated and the necessary information can be read by printing or editing the output file. Some sort of preliminary graphics would be obtained by printing the results in text mode.

The model CFAST is one of the most recent zone mode available in literature. This model 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 at an object etc. in each room can be predicted.

HAZARD I is a famous software for building risk analysis. Its first release of version 1.0 was in the summer of 1989. HAZARD I version 1.1 was released in the spring of 1992. Version 1.2 was published in the spring of 1994. Many improvements have been made in the documentation which accompanies the software. These improvements are a result of the experiences fire protection engineers and others have had in using the methodology. HAZARD version 2.0 has implemented a ceiling jet algorithm which takes into account heat loss from a fire placed in an arbitrary position within a compartment [53].

Exit 89 was designed to model the evacuation of a large building with the capability of tracking each occupant individually. The output of this model, in combination with a fire and smoke movement model using the same building layout, can be used to predict the effects of cumulative exposure to the toxic environment present in a structure fire. The model has recently been modified to simulate the evacuation of disabled occupants by reducing the walking speeds of selected occupants [54].

FASTLite was published by NIST. FASTLite retains the set of simple algebraic equations of FIREFORM, but replaces the single room fire model FIRE SIMULATOR with a (maximum) three room version of CFAST modified to provide the operational features of FIRE SIMULATOR which users have come to depend on.

In reference [55], the evacuation route was divided into three types: ideal evacuation route, feasible evacuation route and fleeing evacuation route. The writers consider that the shortest evacuation route doesn't imply the shortest evacuation duration. The NEFECT can help users confirm the optimum evacuation route. The regularities of human and evacuation behavior were studied in [56], and the simulation system, RHBXF, of human escaping behavior in building fire was developed. The computer model 'SIMULEX' was designed to simulate the escape movement of thousands of individual people through large, geometrically complex building spaces. The model was intended for use both as a research and design tool to analyze the evacuation of large populations through a wide range of building environments [57, 58]. The version 2.0 of the SIMULEX package only modeled the movement of people on a single, level surface using the relationship between walking velocity and inter- person distance. SIMULEX does not model more complex psychological aspects of escape movement such as the time taken for a person to react to an alarm; the spoken communication amongst the members of an escaping group of people; the familiarity of escape routes; and the effects of 'anxiety' and 'stress' on the occupants.

FIRECALC from Australia, or ARGOS from Denmark are the most frequently cited. The Japanese prefer BRI2 and the French use MAGIC as these are locally produced and the local language for the software and manuals. Several nations have or are developing engineering Codes of Practice, e.g., China, Japan, UK, Australia, and New Zealand; and the SFPE Handbook of Fire Protection Engineering is a universal reference work for underlying science, although Japan has its own version of a comprehensive engineering handbook. Since all fire hazard assessments involve a small number of scenarios or design fires, no special software arrangements are needed. This is not true for risk assessments which typically involve hundreds to thousands of scenarios. Special software packages which run the cases and summarize the results have been developed. These include FRAMEworks[59], ALOFT-FTTM (A Large Outdoor Fire plume Trajectory model -Flat Terrain), ASCOS (Analysis of Smoke Control Systems), ASET-B (Available Safe Egress Time - BASIC), ASMET (Atria Smoke Management Engineering Tools), BREAK1 (Berkeley Algorithm for Breaking Window Glass in a Compartment Fire), CCFM (Consolidated Compartment Fire Model version VENTS), DETACT-QS (DETector ACTuation -Quasi Steady) [60], ELVAC (Elevator Evacuation) , FiRECAM , and CRISP II [61].

Recent advances in the techniques for generating 'Virtual Reality' by computer methods suggest a way for building fire risk assessment. These allow the user to experience various fire scenarios with great realism. It may also be feasible to translate architectural drawings generated by standard CAD packages into a format that the virtual reality software will recognize as objects with definite physical properties. Using these methods, users hope that fire safety professionals will be able to create their own risk assessment models. Then they will be able to work out for themselves the safety implications of design modifications and different fire protection strategies.

5 CONCLUSIONS

With the developments of modern science and technology, fire risk analysis is an important part of design such as construction performance design, and many approaches of fire risk assessment were developed. Meanwhile, in the light of the results of fire risk analysis many measures and technologies are adopted to reduce or eliminate fire risk of buildings and plants. So, fire risk assessment is significant to insure life safe. In the future, the main tasks of those who study in fire risk analysis are to develop reliable and useable methods and softwares.

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