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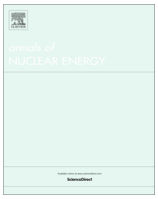

Fire risk analysis based on one-dimensional model in nuclear power plant

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ABSTRACT

Fire probabilistic safety assessment (fire PSA) is developed to give the insight of nuclear power plant risk induced by fire accident and the main contributors, and fire accident scenario analysis is one of the important parts in the work to get the key factors such as time to target damage and time to detection. The thermal–hydraulic model simulating fire accident should have enough accuracy and high speed to satisfy the request of fire PSA. Many researches indicate that in a large volume the hot fluid will concentrate in the upper part while the cold fluid will be in the lower part because of density difference under fire condition, that is, the gradients of temperature and of some other parameters in vertical direction are much greater than in horizontal direction. Based on such thermal stratification theory a one-dimensional model is developed, and the buoyant jet is used to simulate the process of heated air flowing up. In this paper a fire in a compartment is analyzed based on one-dimensional model and the temperature distribution is obtained, the results are compared with those of commercial software such as FDT, CFAST and FDS, then the time to target damage is evaluated based on results of different models and the fire non-suppression probabilities are evaluated. The results illustrate that one-dimensional model has better accuracy than FDT and CFAST since such a model can simulate the thermal stratification and natural circulation which exist in the volume simultaneously. Moreover when the fire power is low, the thermal stratification is apparent and air temperature in the hot upper layer is much lower than the critical value of target damage, the one-dimensional model has enough accuracy to be used directly in fire PSA. While the thermal stratification will be weakened when the fire power increases because of the effects of radiation heat transfer and the entrainment by the jet, so more detailed model such as FDS is needed for such situations, however the results of one-dimensional model can give the advice for the proper simulation time of FDS to improve the calculation efficiency when the upper part temperature is close to or higher than the critical value.

1. Introduction

More and more attentions are paid to improve the nuclear power plant (NPP) safety under outside disasters (Born and Lambright, 1990; Chen et al., 1991; Peterson et al., 2004) in recent years especially after Fukushima accident (International Atomic Energy Agency, 2011), and fire accident is one of the most important outside events which should be analyzed. Fire probabilistic safety assessment (fire PSA) Kassawara and Hyslop, 2005; Nicoleau et al., 2014; Foret, 2003 is developed to give the insight of nuclear power plant risk induced by fire accident and the main contributors. How to simulate the fire accident development is one of the most important parts in fire PSA (Poghosyan et al., 2014; Lin et al., 2014), since the time to target damage and the time to detection (Kassawara and Hyslop, 2005) usually should be gotten by accident scenario analysis (Kassawara and Hyslop, 2005; Salley and Kassawara, 2009), which are crucial factors effecting the probability of fire non-suppression. Popular software developed for fire accident analysis can be classified as three classes (Salley and Kassawara, 2009; Hees, 2013): Empirical models including FDT (Salley and Kassawara, 2007a) and FIVE (Salley and Kassawara, 2007b) tools, Zone models including CFAST (Salley and Kassawara, 2007c) and MAGIC (Salley and Kassawara, 2007d) tools, and CFD models such as FDS tool (Salley and Kassawara, 2007e). The former two kinds of models have high operating speed, however the results are usually too conservative to satisfy the request of fire PSA, while the FDS model can provide the results with high accuracy, but this method always needs very long time to accomplish one round of simulation, unfortunately in fire PSA several hundreds of scenarios are always needed, so it is

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necessary to develop a new method with enough accuracy and high calculation efficiency. Stratification is identified as an important phenomena occurring in a large volume induced by temperature or concentration gradient in the vertical direction (Peterson, 1994; Peterson et al., 1998; Zhao, 2003), that is, the differences of temperature and of some other parameters are mainly in the vertical direction and the differences in the horizontal direction can be ignored. Based on the thermal stratification theory a one-dimensional model (Peterson, 1994; Peterson et al., 1998) is developed and the fire source can be seen as source of thermojet. In this paper we analyze the fire accident in a compartment and evaluate the time to target damage with FDT, CFAST, FDS and one-dimensional model, then calculate the fire non-suppression probabilities based on the results of commercial software and our model. Finally we analyze the applicability of the one-dimensional model in NPP fire PSA.

2. One-dimensional model

Based on the thermal stratification theory one dimensional model is put forward, in which the air heated flowing up to the top of the volume can be seen as a plume and only the longitudinal grid is needed for fluid in the volume.

2.1. Buoyant plume model

Under fire accident the air near the ignition source will be heated and flow up, which can be described by plume model. Since the mass and energy transfer between the plume and the ambient fluid is influenced by the entrainment process importantly, that is, ambient air in the volume will be entrained into the plume and the air in the top will flow down, so the characteristic local volumetric entrainment and characteristic plume entrainment velocity are important parameters to describe the plume as well as the plume dimension (Peterson, 1994; Peterson et al., 1998), here Q_{bj} and M are volume flux and local momentum flux which can be calculated as

$$Q_{bj} = k_{\mu} B^{1/3} z^{5/3} \tag{1}$$

$$M = k_m B^{2/3} z^{4/3} \tag{2}$$

where z is the local height, k_u and k_m are coefficients which are approximately 0.35 and 0.15 respectively, and B is the specific buoyancy flux,

$$B = g \frac{(\rho_a - \rho_0)}{\rho_a} Q_0 \tag{3}$$

Q_0 is the volume flow rate of the source, ρ_0 and ρ_a are densities of the fluid in plume and of the ambient fluid respectively, g is the acceleration of gravity. Then the characteristic local volumetric entrainment $Q_{bj}{}'$ and entrainment velocity u_e can be calculated as

$$Q'_{bj} = \frac{5k_{\mu}}{3} B^{1/3} z^{2/3} \tag{4}$$

$$u_e = \frac{Q_{bj}{}'}{\pi d_{bj}} \tag{5}$$

The characteristic plume dimension is

$$d_{bj} = \frac{Q_{bj}}{M^{1/2}} = \frac{k_{\mu}}{k_m^{1/2}} z \tag{6}$$

Here the buoyant flume (Peterson, 1994; Peterson et al., 1998) is induced by the density difference between injected fluid and ambient fluid, so the specific buoyancy flux B is related to the density difference and the source Q_0, while the fluid properties have little influence on the result.

2.2. Ambient air model

Based on the experiments the thermal stratification will be easy to form under plume in the large volume, and one-dimensional model (Peterson, 1994; Peterson et al., 1998) can be used to describe the fluid performance in the volume,

$$A(z)\frac{\partial G}{\partial t} + \frac{\partial F}{\partial z} \tag{7}$$

here $A(z)$ is the cross section area at the height z, and

$$G = \begin{bmatrix} \rho \\ 0 \\ \rho i \end{bmatrix} \quad F = \begin{bmatrix} \rho Q_{sf} \\ P \\ \rho i Q_{sf} - A(z) k \frac{\partial T_{sf}}{\partial z} \end{bmatrix} \quad s = \begin{bmatrix} \rho Q' \\ -\rho g \\ \rho i Q' \end{bmatrix} \tag{8}$$

Here, ρ is density, P is pressure, i is enthalpy, k is thermal conductivity, which are attributes of the ambient fluid, T is temperature, Q_{sf} is volumetric flow rate of ambient fluid and subscript sf represents ambient fluid.

When the plume arrives at the top of the volume, it will spread and mix with the ambient fluid thoroughly, then the hot air in the top volume will flow down because of thermal expansion, thus the natural circulation can be described by the buoyant plume and ambient fluid models, and convection heat transfer model is used between the ambient fluid and the wall.

3. Probability model

In fire PSA the fire non-suppression probability (Kassawara and Hyslop, 2005) can be calculated by

$$P = e^{-\lambda t_{ms}} \tag{9}$$

Here P is the fire non-suppression probability, λ is the rate of fire suppressed and t_{ms} is the time available for manual suppression,

$$t_{ms} = t_{dam} - t_{fb} - t_{det} \tag{10}$$

where t_{dam} is the time to target damage, t_{fb} is the response time of the fire brigade, and t_{det} is the time to detection (e.g. the time for fire detecting by detector response or by operator). t_{dam} and t_{det} can be calculated by thermal–hydraulic model and t_{fb} depends on the given plant. We can see that time to target damage is an important parameter influencing the result, since P is exponential function of t_{ms}, so the shorter of t_{dam}, the more important of it.

4. Results

4.1. Accident analysis

In this paper a single compartment fire shown in Fig. 1 (Steckler et al., 1982) is analyzed as an example, the walls and ceiling are covered with ceramic fiber insulation board, and a porous plate diffusion burner with 30 cm diameter is placed in the center of the floor. The height of the compartment is 2.18 m and the wide and depth are both 2.8 m. The door in the wall is open between the compartment and the outside, whose wide is 1.83 m and height is 0.74 m respectively. In order to analyze the time to target damage and its effect on the fire non-suppression probability, two values of fire power are used as 62.9 kW and 158 kW. The air temperature is 20 °C and atmospheric pressure is 0.1 MPa. In order to verify the results of the model, experimental results (Steckler et al., 1982) for temperature distribution in the room when fire power is 62.9 kW are shown in Fig. 2, which illustrates the thermal stratification existing apparently.