論 文 の 内 容 の 要 旨

論文題目 Application of Computational Fluid Dynamic (CFD) in the modelling of internal and external building fire

(建築火災(内装と外装)のモデリングにおける CFD の応用)

氏 名 周　彪

With rapid development of super-computer and fruitful theoretical modelling, the fire research performed with tests and theoretical have been widely used. Some of results have made contributions to the current fire protection of building fire. However, as the new building materials and complex structures emerge nowadays, the fire protection of buildings performed with above new materials show a big challenge for the current research. At the same time, some serve fire accidents happened in the world which resulted in serious results. Therefore, research over building fire is necessary and urgent.

Regarding the internal building materials fire, the knowledge summarized from bench-scale fire test and intermediate scale could be useful for fire protection. However, the new fire features including high Heat Release Rate (HRR) and combustion gas toxicity have attracted more and more attentions. The knowledge between building materials parameters and reaction-to-fire performance is still unclear. Regarding the external building materials fire, the preliminary empirical equations are available and have been used for fire protection. However, it seems hard to be used when the new heavy melt-flow materials are performed in the external part. Furthermore, the effects of opening edge, core materials thickness and combustion heat intensity on the fire performance is unclear. The influence of external building materials parameters on the fire performance is unavailable. In addition, the real external fire is reported to be hard evaluated by the results of small-scale and intermediate-scale fire tests.

Under this condition, the attempts to use the Computational Dynamic Simulation (CFD) in the application of building fire are conducted in this work. It is aimed at solving several problems which is difficult to be solved in building fire experimental tests, reporting the advantages and disadvantages of

CFD in fire simulation, providing an insight in the further study for CFD fire research and hoping to make a little contribution for fire researcher who has no CFD background to well understand CFD.

A series of experimental tests and simulation are carried out. The specimens are divided into two types, external building material and internal building materials. The tested internal building materials are composed of some polymers used widely and external building materials are consisted of ETICS fire and cedar façade. The tests for internal fire includes TG-DTA, Cone according to ISO 5660 standard method, and model-box test according to ISO TS 17431 standard method. The tests for external fire includes Intermediate Scale Calorimeter (ICAL) test according to ISO 14696 standard method, External Thermal Insulation Composite System (ETICS) façade fire, cedar timber façade fire according to JIS A 1310 standard method and Fire Propagation Apparatus (FPA) test according to ISO 12136 standard method. The numerical models were modeled by using popular fire CFD tools, such as FDS (version of 6.5), FireFOAM (version of 2.2.x) and ThermoKin (version of 2D).

Regarding the application of CFD in internal building materials fire, the pyrolysis model of polymer extruded polystyrene (XPS), polyurethane (Urethane), poly-isocyanurate (Nurate) and poly-isocyanurate containing fire-retardant (None-Nurate) were modeled using FDS and validated by Cone. Furthermore, the phenomena how coating layer influences Cone test was discussed by using FDS and verification tests. In addition, the capability of FDS to simulate model-box fire was evaluated using specimens Urethane and None-Nurate and validated by corresponding tests. It was found that the FDS could perform well for pyrolysis model. However, some limitation was also clear that lacking of flame heat flux model reduce about 15% heat flux in Cone. The simulation results are grid-dependent and the parameters-dependent. The heat of combustion and heat capacity imposes heavy effect on mass loss rate. When the simulation with strong pyrolysis products and heavy smoke, the literation are unstable. During the simulation, the mixing-control model seems insufficient for fire which is characterized by complex flame spread and combustible gas diffusion. The discrepancy found at the beginning of test is interred to be attributed to the mixing-control model, which makes the predicted time to generate flashover much shorter than experimental time.

In addition to the application of CFD in external building materials fire, the fire features of EPS ETICS was discussed by testing a series of EPS ETICS specimen varying heating intensity from 100 kW to 1100 kW, EPS thickness from 50 mm to 300 mm, polymer mortar type including SBR polymer mortar and acrylic resin mortar, reinforcement including one layer and two layer's glass fiber mesh, and opening edge treatment method differs from back-wrapping method to fire barrier method. When the EPS ETICS specimen is treated by back-wrapping opening edge treatment method, the peak temperature, EPS burn area, time (20 min) averaged temperature and heat flux density become low. The time (20 min) averaged temperature of each position from T1 to T5 versus EPS thickness is linear at heating intensity 300 kW or 600 kW. A comprehensive fire risk evaluation method of EPS ETICS based on EPS burn area and façade surface temperature profiles of JIS A 1310 tests is proposed. This method could easily classify the effect of mortar, reinforcement, EPS thickness and opening edge treatment method on EPS ETICS fire performance and also provide a method to predict the fire risk of EPS ETICS. It is concluded that in JIS A 1310 method, the fire risk of EPS ETICS could be classified by fire propagation index (FPI) and index method. The fire characteristics of window ejected fire were discussed by investigating the correlation between dimensionless temperature and vertical position z in an over-ventilated condition using a series of intermediate-scale tests with a 1.35 m (L) ×1.35 m (H) × 1.35 m (W) fire compartment (chamber 1) with window opening varied from 0.91 m (H) × 0.41 m (W) to 0.91 m (H) × 0.91 m (W) and HRR differed from 200 kW to 1000 kW. The Yokoi's correlation was modified on basis of the test results by considering the influence of fire plume re-attaching-to-wall behaviors, varied neutral plane positions and window opening aspect n. The heat characteristics of cedar façade exposed to controlled heat was discussed by using k-type thermocouples to record the temperature distribution over façade surface, calcium silicate board, and support frame. The HRR and THR were also recorded.

Error of the simulated MLR and HRR curves is approximately 13%-19 % compared with Cone Calorimeter test results. The discrepancies between the calculated and measured MLR and HRR curves can be explained by it that the flame heat flux is not accounted for in the FDS model. As discussed above, error of the calculated MLR and HRR curves could be well explained that the flame flux accounts for 15 % of external heat flux in FDS 6.5 and 18.0 % of external heat flux in ThermaKin2D. Therefore, a well modelling work of flame heat flux is needed in the next step research. The vertical direction flame spread is hard to be simulated by FDS. The large eddy simulation (LES) of buoyant window ejected fire plume which comes from the intermediate-scale compartment was modeled using FireFOAM. It was found that with optimal configuration the simulation results shows a agreement compared with tested data on the basis of discussion on flames shapes, temperature vertical distribution inside the chamber, temperature distribution versus vertical distance over external facade surface, heat flux density and temperature over non-combustible walls. The discrepancies are found in the bottom temperature of fire compartment. Temperature profiles vs. vertical distance inside chamber of simulation was believed to be lower than experimental values in the region which is near the bottom of the chamber. FDS is more sensitive to grid mesh size change. The FireFOAM simulation takes high computer cost. After the modelling the cedar pyrolysis model and validation by FPA test, the cedar façade fire was modeled by optimal gird size and input parameters. The good agreements indicates with the optimal input, an intermediate-scale cedar façade fire could be well reproduced using FireFOAM model. The importance of parameters over time-to-pHRR, pHRR and THR of cedar façade fire are compared.

Regarding the fire stop configuration in a three layer's cedar façade of building, it is found that both the position and width of fire stop would show heavily effects on the cedar façade fire spread. It is found that the distance should be designed to avoid the 0.8 m and 1.2 m because when the fire stop performed with these two distance, the fast spread flame and highest THR are found. It is hard to make a conclusion which is good without the analysis of balance between fire prevention and architectural aesthetics, which is believed to be necessary to be taken into account. The discussion is compared with difference of fire prevention capacity. Before the determination of optimal fire stop configuration, it is better to conduct the numerical prediction firstly.