12.1 Improvement of a Combustion Model in MELCOR Code

Masao Ogino and Takashi Hashimoto
Systems Safety Department, NUPEC
Phone: 03-5470-5461, Facsimile: 03-5470-5466
e-mail: ogino@nupec.or.jp, @n T-HASHIMOTO@nupec.or.jp

ABSTRACT

NUPEC has been improving a hydrogen combustion model in MELCOR code for severe accident analysis. In the proposed combustion model, the flame velocity in a node was predicted using five different flame front shapes of fireball, prism, bubble, spherical jet, and plane jet. For validation of the proposed model, the results of the Battelle multi-compartment hydrogen combustion test were used. The selected test cases for the study were Hx-6, 13, 14, 20 and Ix-2 which had two, three or four compartments under homogeneous hydrogen concentration of 5 to 10 vol %. The proposed model could predict well the combustion behavior in multi-compartment containment geometry on the whole.

MELCOR code, incorporating the present combustion model, can simulate combustion behavior during severe accident with acceptable computing time and some degree of accuracy. The applicability study of the improved MELCOR code to the actual reactor plants will be further continued.

Keywords: lumped-parameter code, hydrogen, combustion model, containment vessel

1. INTRODUCTION

There are two approaches for simulating the hydrogen mixing and combustion behavior in a containment vessel. One is the multi-dimensional (or field) approach, applied in GASFLOW[1] and CFX-F3D[2] for example, which allows simulating the local hydrogen behavior mechanistically. But it requires considerable CPU resources, as well as memory resources, making the multi-dimensional simulation of the complete containment geometry impractical. The other is the lumped-parameter approach, applied in MELCOR[3] and RALOC[4] for example, which has an advantage that a complete geometry can be represented by a series of nodes and junctions, and that the simulation can cover the whole physical time of a severe accident in a limited CPU time. However, due to the limitations of the approach, it can not simulate the local hydrogen behavior, such as the flame propagation, in a node.

NUPEC has been using MELCOR code for the severe accident analysis. To simulate the combustion behavior in a multi-compartment vessel of actual reactor plants with an acceptable accuracy, NUPEC proposed a combustion model, which modified a model in MELCOR code to simulate the combustion behavior in a multi-compartment containment vessel with an acceptable accuracy and computing time. To verify the proposed model, the GRS/Battelle combustion test data were used.

2. COMBUSTION MODEL

In the original MELCOR code, one dimensional propagation combustion model is used. That is, the burning rate is defined as the flame velocity multiplied by the constant cross sectional area and the time lag for flame propagation between adjacent nodes, specified as user input.

The proposed model calculates the laminar and turbulent burning velocity. The burning rate is defined as the flame velocity multiplied by the front surface of the glowing fire shape, considering the three dimensional geometry of the nodes and the connection junctions.

(1) Node geometry

Figure 1 shows the node geometry of the combustion model. The node geometry is rectangular, in which flame is generated and propagates. The node dimensions are characterized by length (L), height (H), and width (W) and the node is interconnected by several junctions to other nodes. The location of an igniter and the flame front are specified by Cartesian coordinate of X, Y and Z.

(2) Flame propagation model

The flame velocity in each node is predicted using five different flame front shapes of fireball, prism, bubble, spherical jet, and plane jet, as shown in Fig.2. The fireball changes into a prism or a bubble shape depending on the compartment geometry. When a fireball arrives at the ceiling of a node, it changes into a prism. When it expands enough in a horizontally narrow node before arriving at the ceiling, it changes into a bubble. When these flames propagate to an adjacent node, they can change into a spherical jet and then grow into a plane jet, depending on the geometry and the mixture composition in the adjacent node. The plane jet can change into other fire shapes in propagating to an adjacent compartment, which depends on the geometry and the mixture condition in the adjacent nodes.

Figure 3 summarizes schematically the flame propagation in five different shapes described above. The upward flame front velocity S_r of the fireball is the sum of the propagation velocity, the upward velocity U_{bl} and the expansion velocity exerted by combustion. The upward velocity U_{bl} is determined by a force balance as follows:

$$\frac{dU_b}{dt} = g\left(\frac{\rho_u}{\rho_b} - 1\right) - \frac{3}{8}C_D\frac{\rho_u}{\rho_b}\frac{U_b^{\ 2}}{r_b}$$

where, ρ_b: burned gas density　　C_D: drag coefficient

ρ_u: unburned gas density　　r_b: radius of the fireball

The prism, contacted with a ceiling, has two flame propagation velocities S_h and S_d in horizontal and vertical directions. The horizontal velocity S_h includes the expansion velocity and the spreading velocity exerted by the buoyancy force. The vertical velocity S_d includes the expansion velocity and the upward velocity exerted by buoyancy force. In the bubble flame, the upward and downward velocities S_u and S_d are determined by the expansion velocity and the upward velocity U_h defined as follows:

$$U_b = 0.48\left(gR\frac{(\rho_u - \rho_b)}{\rho_u}\right)$$　　R: hydraulic radius

The shape of spherical jet and plane jet was determined by the upper stream gas conditions mainly dependent on junction velocity U_J.

(3) Burning velocity

In the combustion model, a laminar burning velocity derived from experiments[5] and the turbulent burning velocity reported by AECL[6] are adopted. This turbulent burning velocity consists of the laminar burning velocity S_u and multiplier of the turbulence intensity factor ϕ, as follows:

$$\phi = \sqrt{1 + B\left(\frac{u'}{S_u}\right)^2} + \frac{u''}{S_u}$$

where,

ϕ : turbulence intensity factor

S_u: laminar burning velocity

B: constant value of 16

u': turbulence velocity of the flame front

u": turbulence velocity generated by the flame

$$u'' = \frac{S_u}{\sqrt{3}}\left(1 - e^{-\frac{u'}{S_u}}\right)\left(\frac{\rho_u}{\rho_b} - 1\right) \quad [m/s]$$

3. GRS/BATTELLE COMBUSTION TEST

For the validation of the proposed model, the results of the GRS/Battelle multi-compartment hydrogen combustion test[7] were used. Figures 4 and 5 show the GRS/Battelle model compartment and the compartment configuration of the Hx-14 test case, respectively. The initial gas composition was homogeneous hydrogen-air mixture, and the initial temperature and pressure were room temperature and atmospheric pressure, respectively. The configurations of the compartments used for the present analysis were two-, three- and four-compartment cases, in which the number of compartments and the way of connection of the compartments differed.

4. ANALYTICAL RESULTS

The calculated results by the proposed model were compared with the GRS/Battelle test results focussed on the pressure behavior in the compartments. Figure 6 shows the calculation results of Hx-14 in comparison with the test results.

In Hx-14, the ignition started at time zero in R7. When the flame propagated into R5, a jet ignition occurred in R5. This resulted in an instantaneous pressure rise to a peak value of about 1.69 kPa at 2.4 s. This pressure rise in R5 caused a reverse flow from R5 to R7, which caused a jet ignition in R7. This resulted in a pressure rise to a peak value of about 1.74 kPa in R7 at 2.5 s, 0.1 s later from the first pressure peak. Then the pressure decreased rapidly in both R5 and R7 due to venting to R9 which had a large free volume.

The calculated peak pressures of R5 and R7 and that propagation timings were well agreed with the measured results, as shown in Fig 6. The analytical results of five test cases are summarized in Table 1. A partial discrepancy between the measured and calculated values was found in some cases. That is, the pressure peak in the case of Hx-13 and the burning behavior in the case of Hx-20 were not well predicted. This discrepancy was supposed to be caused mainly by the prediction of inadequate fire shapes. But, on the whole, the proposed model could predict well the combustion behavior in multi-compartment containment geometry with acceptable time and degree of accuracy.

5. CONCLUSIONS

From the above analytical results, following conclusions were obtained:

- NUPEC proposed a lumped parameter combustion model, considering local hydrogen behavior, to simulate combustion behavior in a multi-compartment containment vessel. This model was incorporated into MELCOR.
- On the whole, the proposed model could predict well the combustion behavior in the GRS/Battelle test.
- Therefore, the improved MELCOR code with the proposed combustion model can simulate combustion behavior in a multi-compartment vessel.
- In the future, the verification study of the improved MELCOR using NUPEC's large-scale combustion test will be carried out.

ACKNOWLEDGMENT

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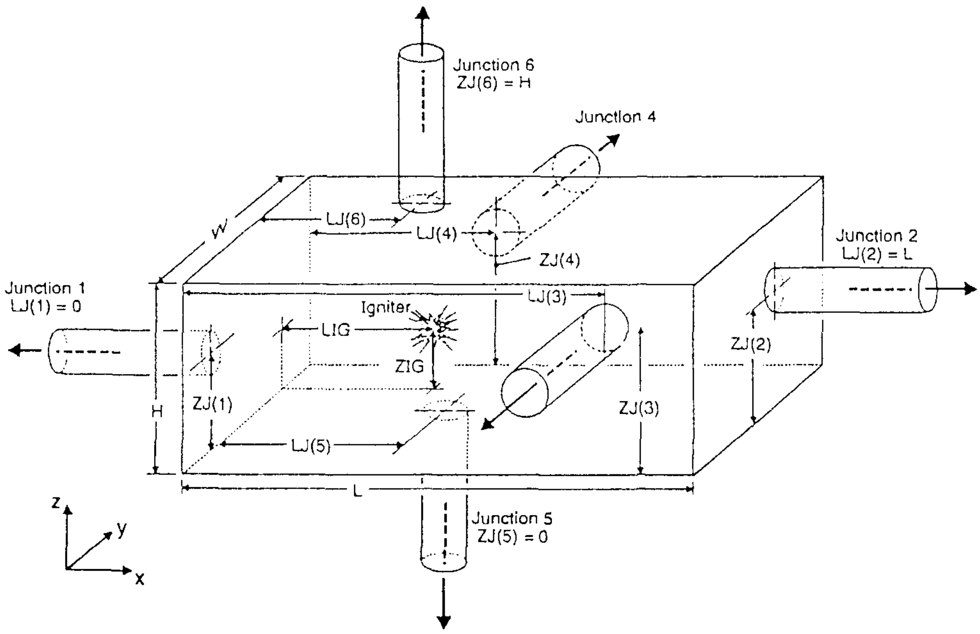


Fig. 1 Node model of the proposed combustion model

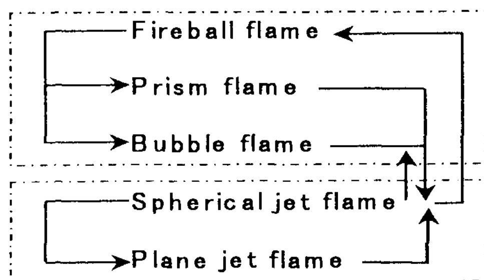


Fig. 2 Variation of five different flame shapes

Table 1 Summary of analytical results of GRS/Battelle combustion test

Cases	Peak pressure	Propagation time (*)
Hx-14	○	○
Ix-2	○	○
Hx-6	○	○
Hx-13	×	△
Hx-20	×	△

(*) Flame propagation time to adjacent compartment
(**) ○ : Good agreement
△ : Small discrepancy
× : Large discrepancy

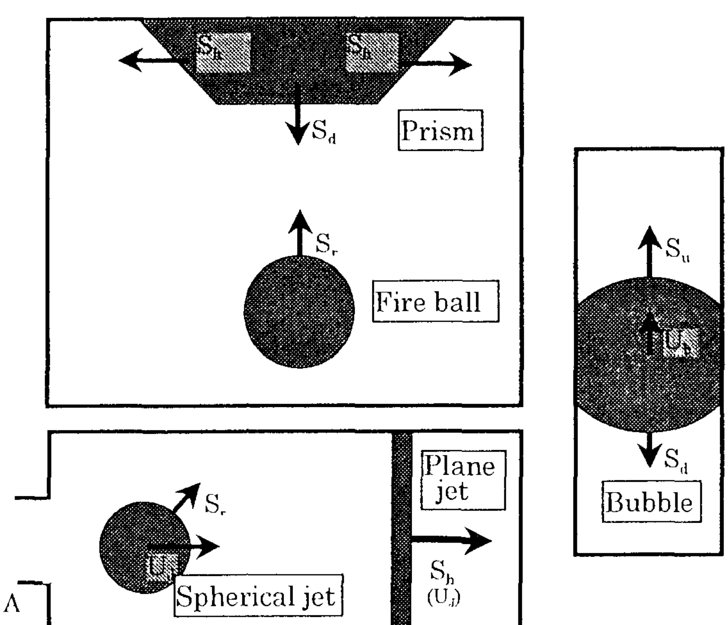


Fig. 3 Schematic of five different flame shapes model

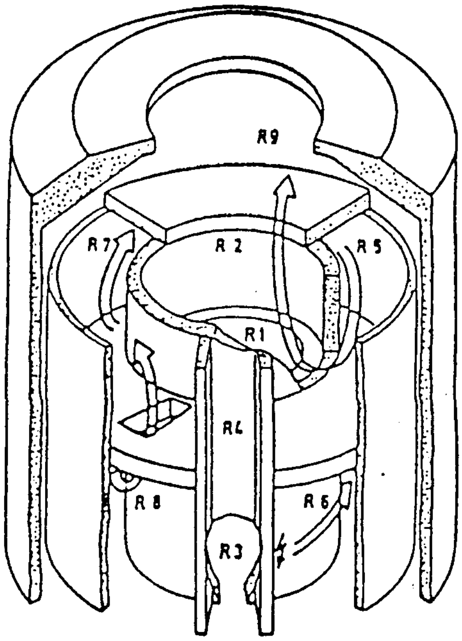
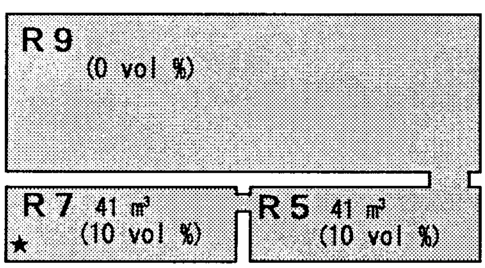


Fig. 4 GRS/Battelle model containment vessel



Note :
★ : Ignition source
( ) : H_2 concentration

Fig. 5 Compartment configuration for the analysis (Hx-14)

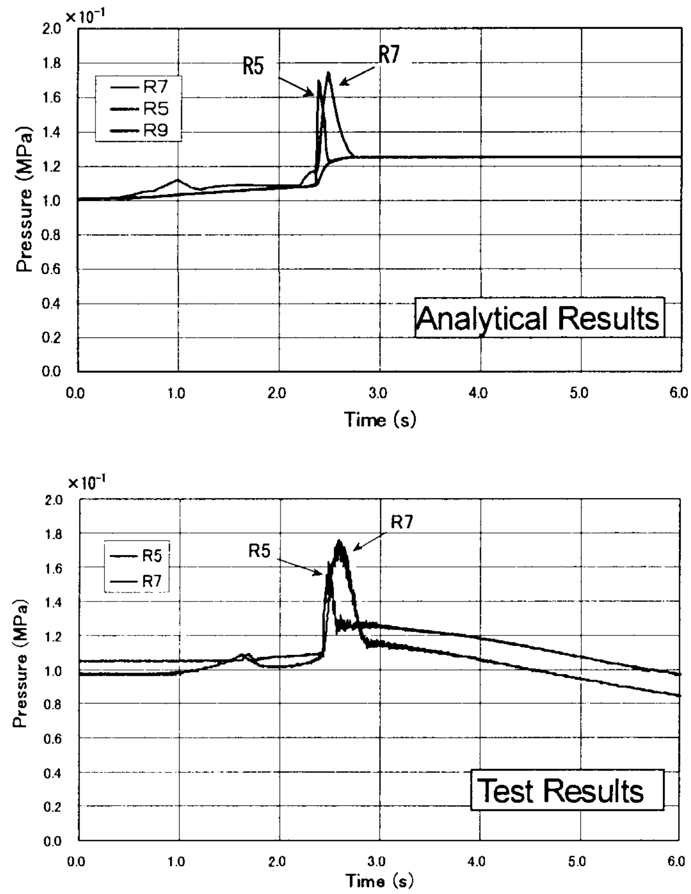


Fig. 6 Analytical results comparing with test results (Hx-14)