Sensitivity Calculations on Spark Ignition Model for a CFD Analysis of the JAEA Explosion Test in the Open Space

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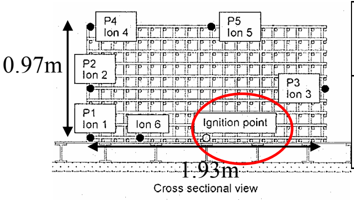
1. Introduction

A preliminary spark ignition model for a high ignition energy (40J) based on an energy conservation law was developed to be used in the CFD (Computational Fluid Dynamics) analysis for the JAEA explosion test [1,2]. However, accurate values of a pressure and a volume of the spark ignition model should be determined through the sensitivity CFD calculations against the test data. Therefore, five conditions by varying the values of the pressure and the volume were proposed. The selected values of the pressure and the volume with the spark ignition model may be used to determine a safety distance between a Very High Temperature Gas-Cooled Reactor (VHTGR) and a hydrogen production facility.

2. JAEA Explosion Test

JAEA performed a gas explosion test in an open space by varying the gas concentration, the ignition method and the existence of an obstacle, and measured the overpressure and the flame front TOA (Time Of Arrival) inside the tent where the flammable gas was located and around the tent (Fig. 1). The selected test case for the CFD analysis is a mixture of methane (9.5 vol. %) and air with an obstacle under a spark ignition.



Tent Volume : 5.6 m^3 Obstacle Volume : 0.4 m^3	
Obstacle ; - Steel Tube - I.D/O.D [mm]: 15.9/ 21.3	

Fig. 1. JAEA gas explosion test facility

3. CFD Analysis

3.1 Spark Ignition Model

In the JAEA explosion test, the electric spark device was used to ignite a mixture of methane and air, and the equivalent energy for the spark operation is reported as 40 J. This value is very large when compared to the spark ignition energy of about 10 mJ in an ordinary combustion test [1]. Thus, an effective spark ignition model representing the pressure, the temperature and the volume of an activated region due to a spark is necessary. Therefore, a spherical activated region model based on an energy conservation under the assumption of an adiabatically confined condition was introduced as Eq. (1).

$$\begin{aligned} E_{spark} &= m_{act}\overline{C_p}(T_h - T_c) = V_{act}\rho_m\overline{C_p}(T_h - T_c) \\ &= V_{act}(\rho_{m,h}C_{p,h}T_h - \rho_{m,c}C_{p,c}T_c) \quad (1) \\ &= V_{act}(\frac{P_h}{R_g}C_{p,h} - \frac{P_c}{R_g}C_{p,c}) \\ &= \frac{V_{act}}{R_g}(P_h C_{p,h} - P_c C_{p,c}). \end{aligned}$$

For available data the specific heat capacity data of the mixture of methane and air is from 2,000K to 3,000K. However, the calculated radius at the temperature of 3,000K is about 7~10cm at the pressure of about 1.75bar. It is a reasonable volume when considering the nominal spark operation. Thus, five cases of Fig. 2 at 2,000K were carefully selected (Table 1) to find the optimized pressure and radius values of the spark ignition model.

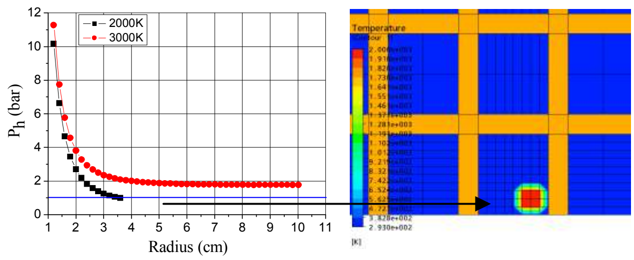


Fig. 2. Range of pressure and radius of the spark ignition model

Table 1 Sensitivity calculation conditions

Case	Pressure (P_h, bar)	Radius (R, cm) ($V_{act} = 4\pi R^3/3$)	Temp. (T_h, K)
1	1.38	2.80	2,000
2	1.40	2.77	2,000
3	1.42	2.75	2,000
4	1.47	2.60	2,000
5	1.57	2.50	2,000

3.2 Grid Model and Boundary Condition

A 3-dimensional grid model (20m x 20m x 10m) simulating the tent and its environment was developed based on JAEA's CFD work [1]. A total of 1,058,400 hexahedral meshs cells were produced, and a dense mesh cell distribution was located around the tent to resolve a rapid propagation of a flame. The obstacle inside the tent was directly modeled by a rectangular closed tube instead of a circular tube. An opening condition was applied to all the surrounding surfaces except for the bottom surface [3]. The stoichiometric distribution of methane (9.5 vol. %), oxygen and nitrogen was given to the tent volume for an initial condition.

3.3 Flow Field Models and Combustion Model

The governing equations used in this study are the Navier-Stokes, the energy and the species transport equations with a coupled solver algorithm implemented in the CFX-10 [3]. Turbulent flow was modeled by the standard k-ε turbulent model, and the buoyancy was modeled by the Boussinesq approximation. And also, a discrete transfer model was used for the radiation heat transfer. The Eddy Dissipation Model was used for the one step combustion reaction of methane and air. A transient calculation was performed with a time step of 0.001 sec.

3.4 CFD Analysis Results

The peak overpressure results of the CFD calculations (Fig. 3) show that the overpressure variation from 0.003 seconds to 0.008 seconds at the same pressure measurement location (Fig. 1) is linearly proportional to the initial pressure value given by the spark ignition model.

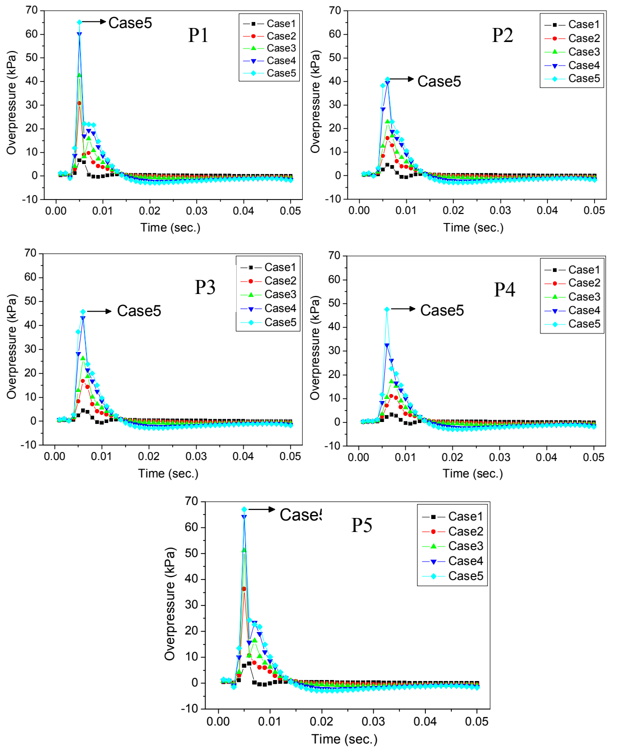


Figure 3. Peak overpressure prediction results (P1~P5)

However, the peak overpressure at the locations of P1 and P5 is about 50% larger than those of P2, P3 and P4. This means that the pressure wave inside the tent does not propagate as a symmetric form. This is because the obstacle in the tent turns the direction of the propagation of the pressure wave into a space between the obstacles. As a result of the comparison of the CFD results and the test data, we can find that the results of Case 2 are almost agreed with the test data even though the difference between the average peak pressure and the maximum peak pressure is about seven times larger than those of the test. And also, the location of maximum peak pressure is not predicted accurately. The results of Case 3 are also close to the test data. However, the maximum peak overpressure is about two times larger than that of the test.

Table 2. Max. peak overpressure and flame front TOA results at measurement locations (P1~P5)

Case	P1 (kPa)	P2 (kPa)	P3 (kPa)	P4 (kPa)	P5 (kPa)	Avg. (kPa)	Max. (Loc.) (kPa)	Flame Front TOA (m/s)
1	6.59	4.58	4.46	3.20	7.57	5.28	7.57 (P5)	~97
2	30.74	15.88	16.78	11.06	36.26	22.14	36.26 (P5)	~160
3	42.54	22.85	26.19	17.10	51.12	31.96	51.12 (P5)	~163
4	60.16	39.60	43.15	32.56	64.20	47.93	64.20 (P5)	~165
5	65.01	40.97	45.71	47.53	67.00	53.24	67.00 (P5)	~170
JAEA Test Results ; (1) Avg. peak pressure : 25.4 kPa, (2) Max. peak pressure/Location: 27.5 kPa / P4, (3) Flame Front TOA : 163 m/s								

4. Conclusion

According to the CFD analysis results for the JAEA explosion test, we can see that the CFD analysis can predict the peak overpressure and the flame front TOA accurately when the pressure of 1.44bar and the radius of 2.77cm for the spark ignition model were chosen. Therefore, the CFD analysis can be used for the prediction of the peak overpressure for a gas explosion under a complicated geometry configuration.

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