Proceedings of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, 2004

A Structured Evaluation of the Steam Explosion Model

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Abstract

A coherent methodology for the evaluation of the steam explosion load at reactor scale is proposed by a structured evaluation of the steam explosion model against the experimental data. Being part of the OECD/SERENA program, appropriate data were selected by the world-class experts and the analytical model of TEXAS-V was selected. The procedure consisted of two steps. The pre-mixing model was verified against the FARO L-14 and FARO L-28 data. The explosion model was verified against the experimental data of KROTS-44, FARO L-33, TROI-13, and TROI-34 data. The capabilities and deficiencies of the fundamental models of the TEXAS-V are reviewed in the aspect of adequacy in the simulation of the steam explosion in the reactor scale.

1. Introduction

The computational model for the steam explosion phenomena [1] should be able to describe the multi-phase, multi-dimensional, and multi-component phenomena at different length scale. The fundamental phenomena involved is melt jet break up and interfacial heat transfer between the melt and two-phase mixture during mixing phase which occurs is in a order of seconds, and the thermal-hydrodynamic fragmentation and the heat transfer during explosion phase, which occurs in a order of ms. The length scale involved in those processes is widely spread from the scale of the jet diameter to the fine particles. So, constructing even a simplified model is a formidable task.

Here, a rather simplified computational model to simulate various phases of steam explosion phenomena is used to simulate the carefully selected international experimental data. The name of the computational model is TEXAS-V and is widely used for the analysis of the steam explosion load during a hypothetical severe accident in the nuclear power plant, where a molten core material at very high temperature is in contact with water. The exercise of the computational model against the selected experimental data is a part of internationally collaborated research called the OECD/SERENA project. The objective of the research is to pursue a converged understanding of the fundamental physics of the steam explosion phenomena, which are necessary for the prediction of the steam explosion load in reactor scale and identify the shortcomings of the existing models and experimental data [2].

Two sets of experimental data are carefully selected for the validation of the major physical models of the computational model in the OECD/SERENA program. The experimental data of FARO L-14, L-28 were selected for the validation of the hydrodynamic jet break up model and related heat transfer models. KROTOS-44, FARO L-33, and TROI-13 are selected for the simulation of the explosion fragmentation model and relevant heat transfer models. The results of the simulation will form the basis of the reactor calculation.

2. The Evaluation of Pre-mixing Model

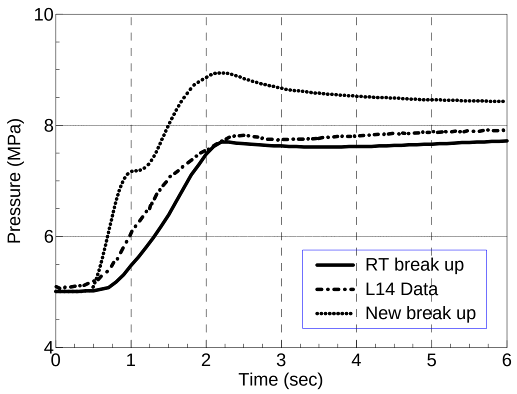
The analytical models, which has major role are the heat transfer correlations and the jet break up model. A comprehensive discussion on the results of TEXAS-V simulation for the jet break up models and relevant thermal-hydraulic model against the experimental data of FARO L-14 and L-28 is provided in reference 3. Table 1 below compares the major parameters of two experiments. In case of L-28, the duration of pour is much longer is at low pressure.

Table 1 Major parameters of FARO L-14 and L-28 experiments

	L-14	L-28
Corium Mass (kg)	125	175
Release diameter (m)	0.1	0.05
Pressure (MPa)	5.0	0.51
Sub-cooling (K)	0	0
Water Depth (m)	2.05	1.44
Gas volume (m^3)	1.26	3.528
Water volume (m^3)	0.798	0.564
Melt delivery (s)	1.0	5.21

The two break up models implemented in TEXAS-V are used in the analysis. It was shown that while the old break up model based on Rayleigh Taylor instability and the new break up model, which has more mechanistic break up mechanism including the Rayleigh Taylor, boundary layer striping, and Kelvin Helmholtz instability, do not show much difference for the simulation of FARO L-14 as shown in Fig.1, two break up models show quite different behavior in case of FARO L-28 as shown in Fig.2.

It was shown that the computational model was adequate enough to predict the jet break up model and thermal hydraulic response during the premixing phase for a transient with rather short pour and at a high pressure. However, it was necessary to increase the effectiveness of Kelvin Helmholtz instability substantially to match the L-28 pressure. It is suggested that the break up model be improved further to adequately model the thermal-hydraulic response of the system and jet break up model during a rather long pour. Also, another fundamental difference is the system pressure. It is quite probable that the heat transfer correlations used in the computational model is rather tuned for the high-pressure experiments.



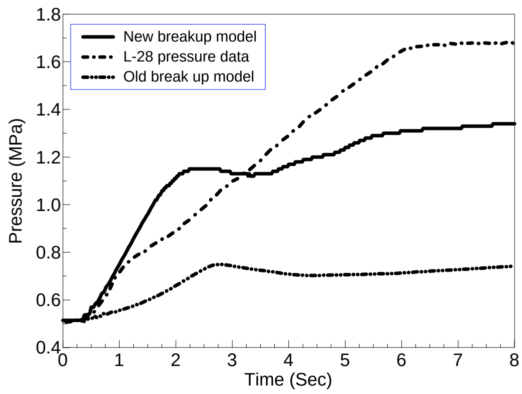


Fig.1 Comparison of pressure for L-14

Fig.2 Comparison of pressure for L-28

3. The Evaluation of Explosion model

KROTOS-44, FARO L-33, TROI-13, and TROI-34 were selected in the OECD/SERENA program for the simulation of the explosion fragmentation model and relevant heat transfer models. Initial and boundary conditions for each experiment is provided in Table 2, a brief summary of the results of analysis for the explosion phase only is provided in Table 3, and a brief summary of the results of analysis for the integral calculation is provided in Table 4.

Table 2 Initial and boundary conditions

	FARO L-33	KROTS-44	TROI-13	TROI-34
Melt Composition	UO_2/ZrO_2, 80:20	AL_2O_3	UO_2/ZrO_2, 70:30	UO_2/ZrO_2, 70:30
Released Mass (kg)	100/25	1.45	7.7	10.5
Release Diameter (m)	0.05	0.03	0.02	0.02
Pressure (MPa)	0.41	0.1	0.1	0.1
Sub-cooling (K)	124	10	81	32
Melt Velocity (m/s)	1.3 – 3.0 m/s	~ 1m/s	~ 7 m/s	~ 7 m/s
Free Fall (m)	0.77	0.43	3.8	3.35
Water depth (m)	1.62	1.115	0.67	0.67
Gas volume (m^3)	3.5	0.23	8.03	8.03
Pool Diameter (m)	0.71	0.2	0.6	0.6
External Trigger	Yes	Yes	No	Yes

Table 3 A Summary of Analysis Results for the explosion phase only

	FARO L-33	KROTS-44	TROI-13	TROI-34
Explosion only	Yes	Yes	Yes	Yes
Melt fraction /Total mass (kg)	0.026/25	0.026/1.5	0.000636/1.14	0.000636/1.14
Explosion Model Constants	R_f=20 μm, C_{fr}=0.002 T_{fr}= 1 ms	R_f=20 μm, C_{fr}=0.002 T_{fr}= 1 ms	R_f=100 μm, C_{fr}=0.002 T_{fr}= 1 ms	R_f=100 μm, C_{fr}=0.002 T_{fr}= 1 ms
Calculated Pressure (MPa)	100	75	3	25
Fuel Diameter (mm)	3.6	15	3	3
Pre-mixture Height (m)/Width(m)	1.7/0.3	0.75/0.2	0.7/0.2	0.7/0.2
Void fraction	0.05, uniform	0.09	0.04,uniform	0.04,uniform
Trigger	14MPa/14 μs	14 MPa/ 1ms	Spontaneous	10 MPa/0.2 ms
Explosion Model Constants	R_f=20 μm, C_{fr}=0.002 T_{fr}= 1 ms	R_f=20 μm, C_{fr}=0.002 T_{fr}= 1 ms	R_f=100 μm, C_{fr}=0.002 T_{fr}= 1 ms	R_f=100 μm, C_{fr}=0.002 T_{fr}= 1 ms

3.1 Analytical Models

TEXAS-V computer code has a fragmentation model by Tang [5] during the explosion presented as

$$M_f = C_{fr}\, m_p(P - P_{th})^{0.5}/(\rho_c R_p^2)^{0.5} g(\tau)F(\alpha)$$

C is a parameter to match experimental data. P_{th} is the threshold pressure necessary to cause film collapse. Nelson [6] and Kim's [7] study indicate that the threshold pressure is between 0.2 – 0.4 Mpa for the tests at atmospheric pressure. Each master fuel particle group has a corresponding group for its fragmented particles. We assume all fragmented fuel quenches to coolant and gives its energy at once to coolant in evaporating liquid to vapor.

R_p is an estimated size of fragmented particles and τ is the fuel fragmentation time interval. There was sensitivity study for the effect of these parameters on the dynamic pressure. Tang [5] did parametric used C_{fr} between 0.001 and 0.002 and τ between 0.2 to 4 ms for KROTOS 21 and KROTOS 26. It indicated that the pressure peaks increases and the explosion wave propagates faster as the proportional constant C_{fr} increases. Tang [5] chose 0.001 and 0.002 for KROTOS 21 and 26 respectively. Nelson's experiment [8] indicated that as the ambient pressure increases the characteristic time for fragmentation decreases. However, as there is no data, the parameter is adjusted to match the KROTOS 21 (2 ms) and 26 (0.5 ms) data. Tang [3] did parametric study on characteristic time (0.0012 and 0.012) and void fraction (0.27 – 0.35) for KROTOS 44 while keeping CFR as 0.002. Based on these observations, standard values of C_{fr}=0.002 anτ = 1 ms were chosen for the simulation of KROTOS-44.

The compensating factor for the coolant void fraction $F(\alpha)$ is introduced because the film collapse and coolant jet impingement gradually become less likely to occur as the void fraction increases. The factor decreases from 1 to 0 when the void fraction is above 0.3.

3.2. Analysis of KROTOS-44 test

KROTOS-44 test belong to a series of tests dedicated for the identification of explosion behavior using Alumina melt. It is one of the best experiments for the validation of explosion model, as it is a kind of analytical experiment where the test section has one-dimensional geometry and it has strong constraint for the explosion to maximize the energy of explosion. The configuration of the experiment is shown in Fig.3.

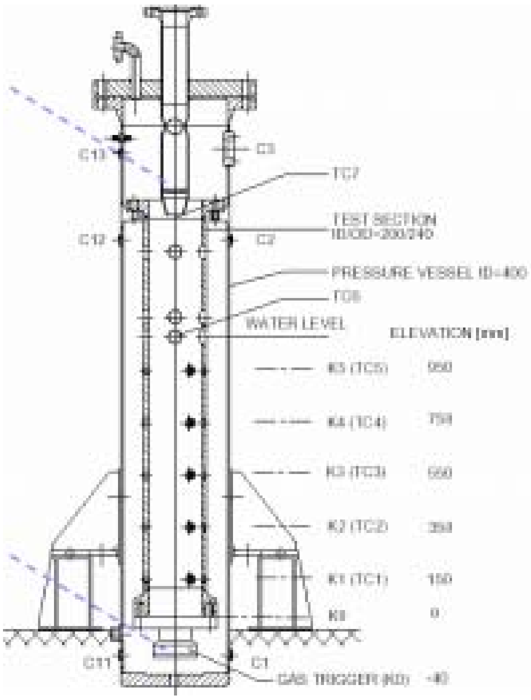


Fig. 3 The geometry of KROTOS experiment

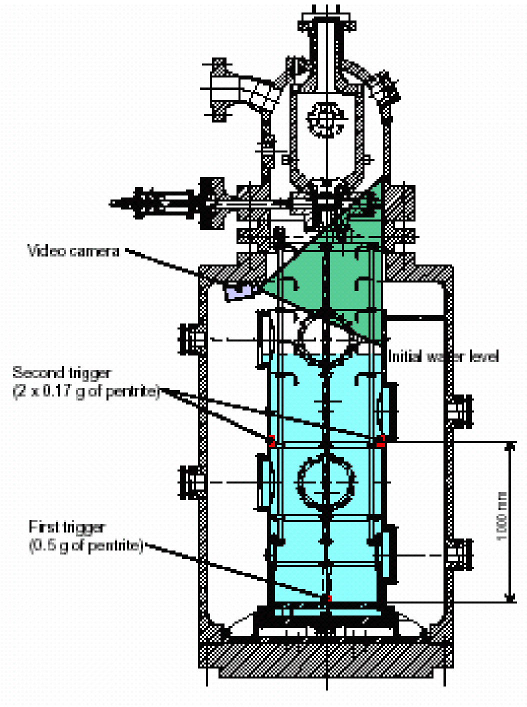


Fig. 4 Configuration of FARO L-33 test

The initial condition for the pre-mixture was determined from the experimental data and prescribed from the OECD/SERENA project. A pre-mixture just before the explosion is determined from the experimental data and prescribed as initial condition for the explosion calculation. It consists of volume fractions for each phase and component, mean particle diameter, liquid temperature, gas temperature, and melt temperature. Below the pre-mixture there is a waster slug region. Above the pre-mixture there is a region of two-phase plug and cover gas. The explosion is triggered by a injection of the high-pressure gas at the bottom. As the pre-mixture just before the explosion is well defined, it is a good analytical experiment to exercise the explosion model in the computational model.

3.2.1 The input model for TEXAS-V

Though the TEXSA-V allows only one-dimensional nodes, it is suitable for the simulation of KROTS-44 as the geometry and associated phenomena is nearly one-dimensional. The input model for KROTS-44 has 30 nodes for the simulation of the facility. It has 24 nodes for the test vessel and 6 nodes on the top to simulate the cover gas region. The initial void fraction and melt fraction in each region are initialized to match the prescribed conditions. To have a uniform melt fraction of 0.026 in the pre-mixture, particles are distributed in 10 cell with 31 particles per cell with d_f=15 mm. The total weight of the fuel is 1.48 kg. The trigger cell is added at the bottom, which is filled with saturated steam at 14.8 MPa. The fluid temperature, cover gas pressure are specified per given condition.

3.2.2 Analysis Results

After a very short initialization period, the trigger cell is activated to start the explosion calculation. The duration of the explosion calculation is 6 ms. The plot for the pressures measured at each pressure transducers for KROTOS-44 is shown in Fig.5. The calculated pressure is shown in Fig. 6.

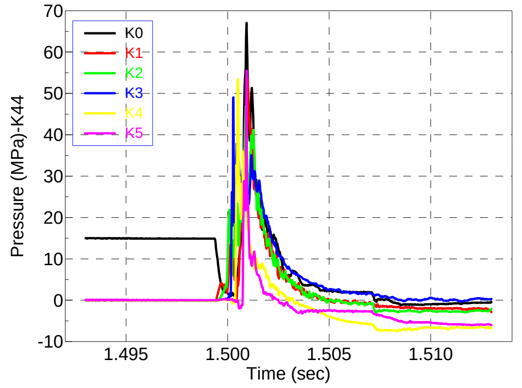


Fig.5 Dynamic pressure - measured

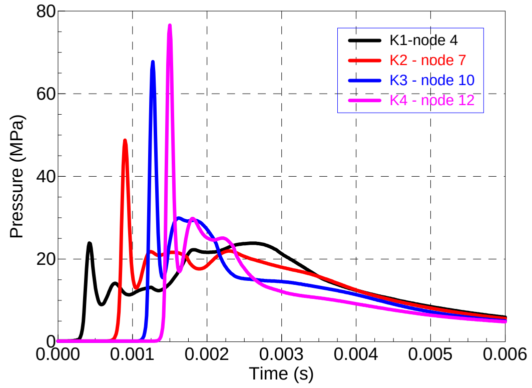


Fig.6 Dynamic pressures – calculated

The impulse on the vessel wall can be calculated from the time integral of the dynamic pressure on the wall in Figure 5. The value up to the maximum has physical meaning. The shape and magnitude of the measured impulse and calculated impulse are nearly the same. Both curves reached 90 KN.s in 4 ms. It suggests that the explosion model in TEXSA-V has a good predictability for an analytical experiment like KROTOS-44.

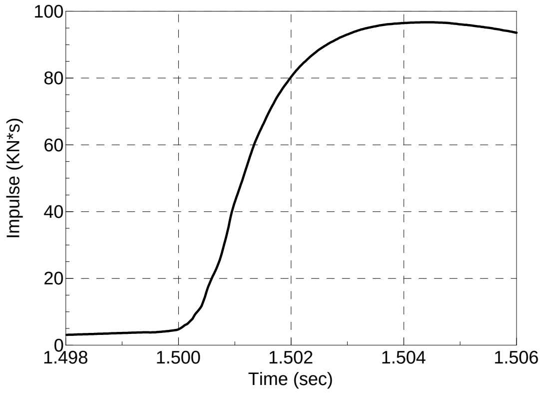


Fig.7 Impulse on the Wall (Measured)

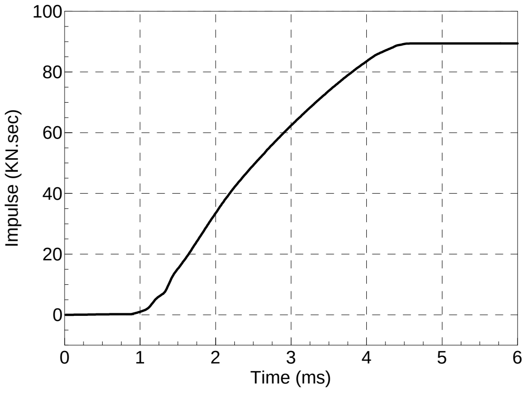


Fig.8 Impulse on the wall for (Calculated)

3.3 Analysis of FARO L-33

In this test 100 kg of corium melt (80% wt UO_2, 20%wZrO_2) at 3073 K were poured by gravity into a test section which contains 531 kg of water and whose depth, temperature, and pressure are 1.62 m, 294 K, and 0.41 MPa respectively. Major parameters of the FARO L-33 test are listed in Table 3. The test section is contained in a FAT vessel. The test configuration is shown in Fig. 4. An external trigger was applied at 1.12 s, which resulted in energetic steam explosion. The maximum pressure measured on the wall of the test section was 10.5 MPa.

There are two ways to calculate the steam explosion load for this test. The first one is to simulate the whole phase of the experiment including the pre-mixing phase and explosion phase together. Alternative approach is starting the calculation from given pre-mixture condition. Here, the second approach is taken to exercise the TEXAS-V explosion model separately. The pre-mixture condition was given from the OECD/SERENA project, which is briefly summarized in Table 3.

3.3.1 The input model for TEXAS-V

The input model for FARO L-33 has 44 nodes for the simulation of the facility. It has 34 nodes for the test vessel, which has 2.3 m height and 10 nodes, whose size is 0.1 m each, on the top to simulate the cover gas region. The area of the nodes for test vessel is 0.344 m^2

There is certainly a multi-dimensional effect in the FARO L-33 tests, because the pre-mixture, whose height is 1.7 m and diameter is 30 cm, is formed only near the center region of the test section. The initial void fraction of the test vessel was taken as 0.05 assuming uniform distribution. However, as the TEXSA-V allows only one-dimensional nodes, uniform distribution of the fuel and void is assumed. This deficiency can be augmented by a parametric study on the size of the mixture zone.

Uniform melt fraction of 0.026 in the pre-mixture was simulated by particles at size d_f=3.6 mm distributed the cell. The total weight of the fuel was 25 kg. Uniform void fraction of 0.05 was assumed in the pre-mixture. The trigger cell is added at the bottom, which is filled with saturated steam at 14 MPa.

3.3.2 Analysis Results

After a very short initialization period, the trigger cell was activated to start the explosion calculation. The duration of the explosion calculation is 6 ms. Plots for the pressures measured and calculated at each pressure transducers for FARO L-33 -44 are shown in Fig.9 and Fig. 10.

In this calculation, the key parameters are chosen as the same as those of KROTS-44 simulation. However, as can be seen from the plots, the calculated pressure is ten times bigger than the measured pressure. The other computer code also over-predicted the pressure by using the default code settings [10]. In order to match the data, key effects such as heat transfer and fragmentation parameter s had to be more or less arbitrarily reduced. The fundamental difference is the material. Possible physical explanations are freezing of the melt during premixing and hydrogen production during pre-mixing, which was observed in FARO tests. However, as there was certainly a tendency that the corium is hardly explosive, it is possible that there could be other effect not listed above. Further investigations are necessary to draw conclusion.

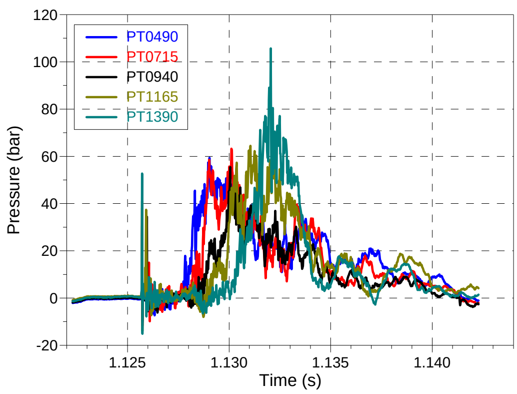


Fig.9 Dynamic pressure - measured

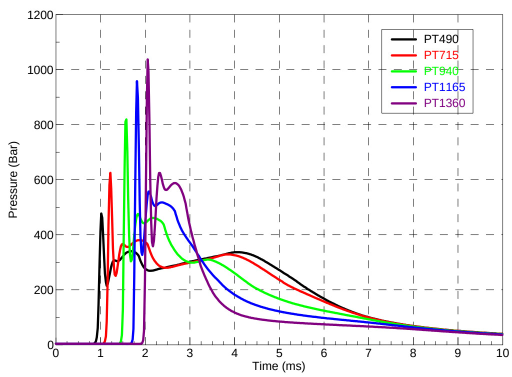


Fig.10 Dynamic pressures – calculated

3.4 Analysis of TROI-13 and TROI-34

Korea Atomic Energy Research Institute (KAERI) launched a research program on the steam explosion named “Test for Real cOrium Interaction with water (TROI)” in 1997. After preliminary tests using ZrO_2, experiments using a mixture of ZrO_2 and UO_2 [11] were performed. About 4 ~ 9 kg of corium melt (80% wt UO_2, 20%wZrO_2) jet is delivered into a sub-cooled water pool at atmospheric pressure. Spontaneous steam explosions were observed quite repeatedly. It was reported that TROI-13 experiments resulted in a dynamic pressure of 7 MPa. The fact that reactor material resulted in a spontaneous explosion is a very important observation, as it deviated from the observations of previous experiments. The configuration of recent TROI experiment is shown in Fig. 11. Fig. 12 is a typical snap shot of fuel coolant interaction in TROI. It was measured by a high-speed video.

It was decided from the OECD/SERENA meeting to perform a blind test for code simulation in TROI. In addition to TROI-13. The test was performed at almost the same initial and boundary condition as those of TROI-13 except using a external trigger. Table 2 summarizes the major parameters of those two experiments. In the calculation, the major parameters are taken as the same as those of KROTS-44.

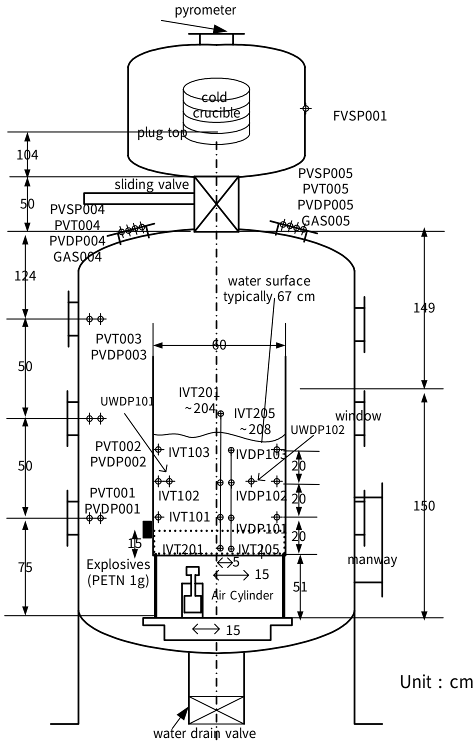


Fig. 11 Configuration of TROI-34 test

Fig. 12 Visualization of Fuel Coolant Interaction

The dynamic pressure sensors, IVDP101, IVDP102, and IVDP103, were flush mounted on the wall of the test section for TROI-13. In TROI-34, hanging dynamic pressure transducers, UWDP101 and UWDP102, were additionally installed near the wall in the water pool. In TROI-34, there are two peaks in the dynamic pressures. The initial peak was due to the dynamic pressure due to external trigger and the second one is due to real steam explosion.

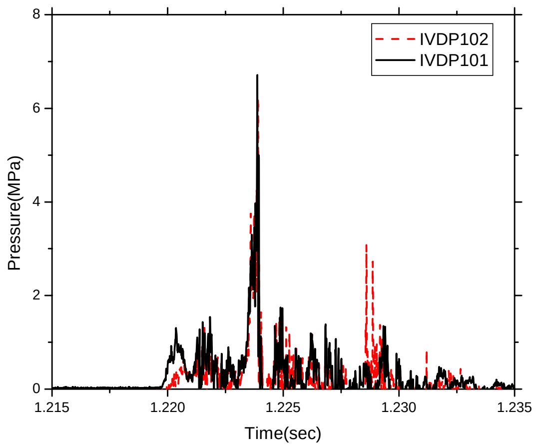


Fig. 13 Dynamic pressure for TROI-13

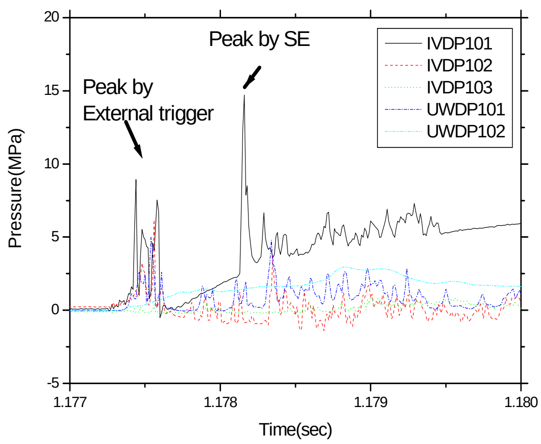


Fig. 14 Dynamic pressure for TROI-34

3.4.1 The Input Model for TROI

The input model for TROI-13 and 34 has 45 nodes for the simulation of the facility. It has 25 nodes for the test vessel, which has 1.5 m height, and 20 nodes, whose size is 0.19 m each, on the top to simulate the cover gas region. The area of the nodes for test vessel is 0.283 m^2

There is certainly a multi-dimensional effect in the TROI-13 tests, because the pre-mixture is concentrated near the center region of the test section as shown in Fig. 12. However, as the TEXSA-V allows only one-dimensional nodes, uniform distribution of the fuel and void is assumed. This deficiency can be augmented by a parametric study.

The initial void fraction of the test vessel was taken as 0.04 assuming uniform distribution. Uniform melt fraction of 0.000636 in the pre-mixture was simulated by particles at size d_f=3.2 mm distributed the cell. The total weight of the fuel was 1.14 kg. The trigger cell is added at the bottom. The basic input data are the same for TROI-13 and TROI-34. Only, the trigger is different. For TROI-13, spontaneous trigger is modeled by activation of steam explosion at each cell initially. In the TROI-34 analysis, a trigger cell filled with saturated steam at 10 MPa is added at the bottom.

3.4.3 The Analysis Results for TROI-13 and TROI-34

The parameters for the explosion model were the same as those used in the simulation of KROTOS-44. Fig. 15 and 16 show the calculated pressure.

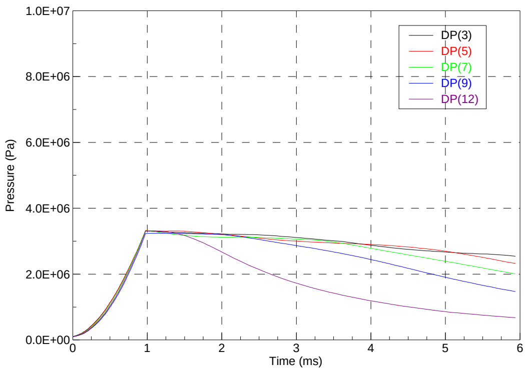


Fig. 15 Dynamic pressure for TROI-13

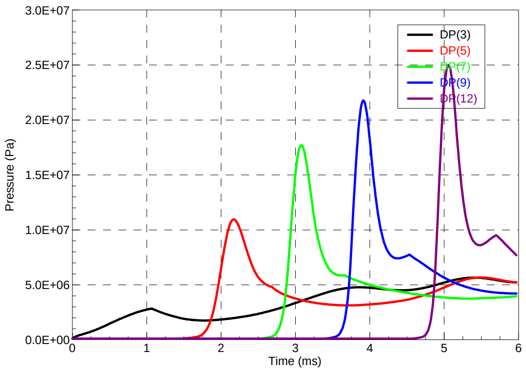


Fig. 16 Dynamic pressure for TROI-34

It is shown that the pressures are in the same order as those of experiments. The case with external trigger showed a nice propagation of explosion wave. However, this behavior was not observed in TROI-34 experiments. In the case of spontaneous steam explosion, the calculated behavior was quite similar to the experimental observations. It was interesting that the calculated pressure was lower than the experimental measurement.

These findings are quite inconsistent with those of FARO L-33. The main difference is the fuel fraction. The fuel fraction is order of magnitude smaller than that of FARO L-33. The low fuel fraction could have resulted in a low dynamic pressure. It can be claimed that TEXAS-V computer code predicts the dynamic pressure in the same order of magnitude for the experiments at very low fuel fraction.

There is another possibility by noting the fact that the void fraction in the interaction region is close to 40% when we convert the level swell measured in typical high-speed video, a typical shape of which is shown in Fig. 12. Since the explosion could not propagate in highly voided region, the explosion occurred near the outer boundary of the interaction zone, where the void fraction is low. Then, the amount of fuel participated in the interaction could be very small. However, it is such a multi-dimensional phenomena that it cannot be easily predicted with existing steam explosion computer codes.

4. Discussions and a Summary

The analyses in this paper were focused on the evaluation of pre-mixing model and explosion model separately. So, the next step should be the evaluation for the adequacy of the computer code for simulating the whole phase of the steam explosion. The present analyses provide a firm corner stone for the integral calculation in the sense that the major parameters for the pre-mixing model and explosion model have been tested and selected from the analyses of the carefully selected experiments.

Still there exist uncertainties, such as, multi-dimensional effect, material effect, freezing phenomena, and hydrogen generation. However, the present analyses demonstrate that the TEXAS-V could be a promising tool in predicting the steam explosion load at reactor scale, as the analyses results with default parameter setting predicted the experimental results reasonably. Also, as a fast running computer code, it allows the user to perform a sensitivity study to evaluate the impact of various uncertainties, which are not clearly understood yet, to provide a conservative envelope for the steam explosion load at reactor condition. It is very essential for the design of preventive measures to avoid or lessen the risk of steam explosion.

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