SAUDI INTERNATIONAL CONFERENCE
ON NUCLEAR POWER ENGINEERING

Proceedings of SCOPE
13-15 Nov. 2023 – KFUPM
Paper 23029

Modelling of Triggering and Steam Explosion Pressure Propagation with Validation Against KROTOS Experiments

Ibrahim Batayneh, Dmitry Grishchenko and Pavel Kudinov
Division of Nuclear Engineering, KTH Royal Institute of Technology
Roslagstullsbacken 21, SE-106 91, Stockholm, Sweden
Batayneh@kth.se, dmitrygr@kth.se, pkudinov@kth.se

Abstract – *Severe accident (SA) mitigation strategy in Nordic Boiling Water Reactors (BWRs) relies on drywell flooding for the ex-vessel scenario. In case of the reactor lower head failure and corium release, the drywell water pool is expected to provide conditions for corium jet fragmentation, quenching, and long-term coolability of the formed debris bed. Ultimately preventing containment failure and release of radioactive products into the environment.*

During corium ***fragmentation*** *in water, a vapor film is formed around the melt preventing direct melt-water contact and limiting the heat transfer between the two liquids. In case of vapor film collapse (****triggering****) an explosive energy transfer from the melt to the volatile coolant may occur. The resulting pressure wave may* ***propagate*** *through the water-corium mixture, escalate and form a shock wave with the potential to challenge containment integrity. Fragmentation, triggering, propagation, and expansion (system relaxation) are the 4 phases of a safety-relevant phenomenon called steam explosion (SE).*

The ultimate goal of this work is to develop a numerical code SEMRA (Steam Explosion Modelling and Risk Analysis) for modelling melt-coolant interactions and assessment of the risk of containment failure. In this paper, we focus on the deterministic part of the code that utilizes improved numerical methods to assess steam explosions and their uncertainty.

Specifically, we address the triggering and propagation of a shock wave generated in a SE scenario. We build a numerically stable code using WENO solver with AUSM+-up schemes to model pressure propagation in a multiphase domain. We compare the results of shock wave propagation obtained using SEMRA code with the experimental simulation from KROTOS facility and with TEXAS-V steam explosion calculations. We discuss the results and their contribution to the enhancement of triggering and propagation modelling in a SE code.

Keywords: Severe Accident, Steam Explosion, Pressure Propagation, SEMRA Code, Trigger Test.

I. Introduction

Steam explosion is a phenomenon of safety importance that arises from the interaction between superheated melt and a volatile liquid coolant. SE is taken into consideration in Nordic BWRs safety analysis, see Fig. 1. SE may occur after the failure of the reactor pressure vessel lower head when corium is released into the flooded drywell. A vapor film forms during the fragmentation process of the melt in water, which isolates the two fluids. If the vapor film collapses, in a process called triggering, the two fluids come in direct contact and an explosive transfer of energy may lead to the formation of a supersonic shock wave that propagates through the drywell pool causing significant mechanical loads on the containment structures and possible containment failure.

Several codes were developed throughout the years to analyse both in-vessel and ex-vessel steam explosion.

Ex-vessel SE was extensively studied in our previous work [1]. TEXAS-V SE code is currently the main code being used to analyse the risk of SE by both the USNRC and for Nordic BWRs.

Texas-V code being developed in the 90s is subject to numerical issues that affect calculations and are impossible to resolve without a complete code overhaul. This motivates the need for a new in-house numerically updated and a stable code, which is currently being developed at KTH. In this work, we compare the triggering and pressure propagation modules of the new under development Steam Explosion Modelling and Risk Analysis 'SEMRA' code with those in TEXAS-V and KROTOS experiment.

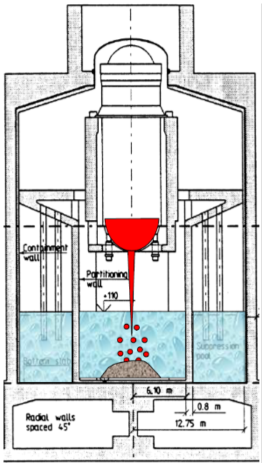

Fig. 1: Nordic BWR Ex-Vessel steam explosion

As a first step, a 1D single phase solver for pressure propagation is developed and compared with the trigger pressure propagation results from TEXAS-V SE code and KROTOS trigger test experiment. In section 2, we introduce the numerical methods used in SEMRA pressure propagation module. In section 3, we validate the pressure propagation code against a validation shock tube problem and in section 4, we compare SEMRA code against and KROTOS experiments results and TEXAS-V code. Conclusions and future work are provided in section 5.

II. Numerical Method

The need to estimate SE impulse propagation, in both low and high (supersonic) speeds, calls for the use of a fast, efficient, and a robust numerical scheme. In SEMRA code, AUSM+-up scheme is adopted to solve the 2D compressible Euler equation for a two-phase fluid interaction model. The Euler equation solved is written as follows [2]:

$$\frac{\partial Q_k}{\partial t} + \frac{\partial E_k}{\partial x} + \frac{\partial F_k}{\partial y} = P_k^{int} + S_k, \qquad (1.a)$$

where Q is the conservative variable vector for fluid k, E and F are the inviscid flux vectors in x and y directions respectively, P^{int} is the fluid interface pressure and S is the source term.

The parameters in the vectors are:

$$Q_k = \begin{bmatrix} \alpha\rho \\ \alpha\rho u \\ \alpha\rho v \\ \alpha\rho E \end{bmatrix}_k \qquad E_k = \begin{bmatrix} \alpha\rho u \\ \alpha\rho u^2 + \alpha P \\ \alpha\rho uv \\ \alpha\rho uH \end{bmatrix}_k$$

$$F_k = \begin{bmatrix} \alpha\rho v \\ \alpha\rho vu \\ \alpha\rho v^2 + \alpha P \\ \alpha\rho vH \end{bmatrix}_k \qquad P_k^{int} = \begin{bmatrix} 0 \\ P^{int}\dfrac{\partial\alpha}{\partial x} \\ P^{int}\dfrac{\partial\alpha}{\partial y} \\ -P^{int}\dfrac{\partial\alpha}{\partial t} \end{bmatrix}_k$$

$$S_k = \begin{bmatrix} 0 \\ \alpha\rho g_x \\ \alpha\rho g_y \\ \alpha\rho g_x u + \alpha\rho g_y v \end{bmatrix}_k, \qquad (1.b)$$

where α is the volume fraction, u and v are the velocity components, ρ is the density, E is the total energy per unit mass, p is the pressure, p^{int} is the interface pressure, H is the total enthalpy and g_x and g_y are the gravity components in x and y respectively.

In this work, the results from a simplified 1D, single-phase solver are shown as a first approximation of SE loads. Hence, above equations are adopted accordingly and the volume fraction is set to 1 depending on the phase considered.

AUSM+-up scheme is used to calculate the flux term in Eq. (1). The numerical flux equation solved is shown in Eq. (3). The full equations and details of AUSM+ scheme are available in [2]. The Courant-Friedrichs-Lewy 'CFL' condition is limited to values between 0.05-0.63 for stability with an optimal value of 0.5 used in most applications.

$$F_{1/2,L/R} = \frac{\dot{m}_{1/2} + |\dot{m}_{1/2}|}{2}\Psi_L + \frac{\dot{m}_{1/2} - |\dot{m}_{1/2}|}{2}\Psi_R + \alpha_{1/2,L/R}P_{1/2}N, \qquad (3)$$

where L and R are left and right cells respectively, $\Psi = (\alpha, \alpha u, \alpha v, \alpha H)$, $N = (0, n_x, 0)$ and $\dot{m}$ is the mass flux.

All cell interface variables are calculated using the Weighted Average Non-Oscillatory scheme of 5th order 'WENO5'. Details of WENO5 are available in [3, 4].

Since in SE scenarios we are mostly dealing with rather strong supersonic shock waves, a 3rd order Total Variation Diminishing 'TVD' Runge-Kutta 'RK' time evolution scheme is used. Details of TVD RK scheme are available in [2].

Finally, since in this work we are simulating a liquid water single phase shock wave, a Modified version of the Nobel-Abel Stiffened Gas 'MNASG' equations of states are used following the equations available in [5].

III. SEMRA Code Pressure Validation Problems

In the 1D single-phase version of SEMRA code, pressure propagation models are validated against RELAP-7 shock tube problems for gas-gas and liquid-liquid domains. The shock tube parameters simulated in the validation problems are for an adiabatic 10m length pipe discretised with a uniform mesh. A "diaphragm" located at (L=5 m) midpoint separates the initial starting values. At t = 0 s the diaphragm is removed, and the two domains come in contact triggering the generation of three waves: a shock wave, a contact wave, and a rarefaction wave.

The gas-gas shock-tube problem consist of two domains, one at a high pressure of 2 MPa and the other at a low pressure of 1 MPa. An initial temperature of 297 K is set in both domains and an CFL of 0.5 is used with 800 nodes mesh and a total simulation time of 10^{-2} s.

In a liquid-liquid shock-tube problem, water is used in both domains. One domain with a high pressure of 10 MPa and the other at a low pressure of 0.1 MPa. Same initial temperature of 300 K is applied in both domains and an CFL condition of 0.5 is used with 800 nodes mesh and a total simulation time of $1.64 \cdot 10^{-3}$ s.

Results of both validation problems are shown in Fig. 2. SEMRA code is in good agreement with RELAP-7 results with minor differences originating from the differences in the initial pressure and energy values resulting from using different equations of states [6]. WENO5 reconstruction is essential to catch sharp discontinuities when compared to AUSM+ standalone solution.

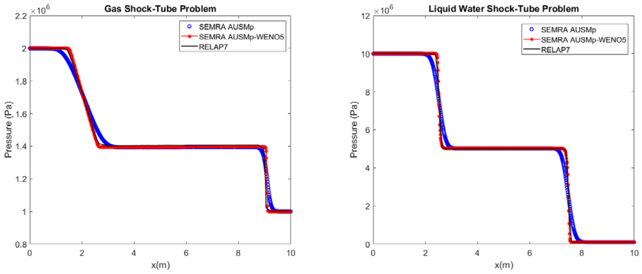

Fig. 2: SEMRA Pressure Propagation Validation against RELAP-7 Shock-Tube problem.

IV. Trigger Pressure Propagation Validation

SEMRA Trigger pressure propagation is validated against KROTOS experimental results. KROTOS test section and pressure transducers k0-k6 locations are shown in Fig. 3. Sensor k0 is at -50 mm and sensor k1 is at 195 mm with 200 mm spacing between each sensor until k6 at 1195 mm). In the triggering test experiment, the water level was increased to immerse k6 transducer having a full water domain for pressure propagation with a total length of 1.2 m. The initial temperature of the water was set to 333 K. In KROTOS trigger test, a 30 cm^3 Argon gas chamber of 15 MPa is used. More information about KROTOS facility and the exact experimental setup is available in SERENA Integrated report [7].

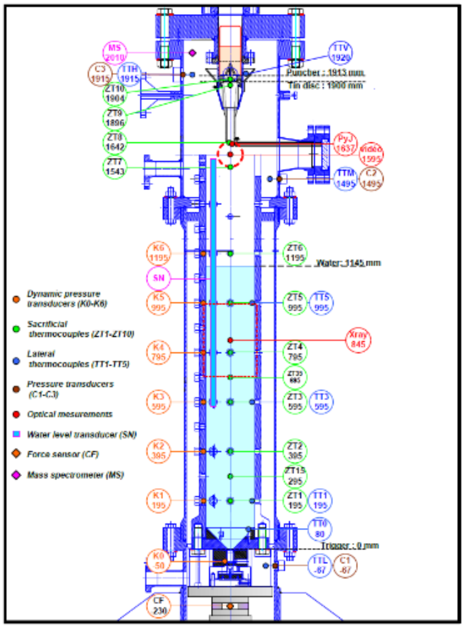

Fig. 3: KROTOS test section showing the positions of the dynamic pressure transducers k0-k6 [7].

Since TEXAS-V code is limited to only liquid trigger cells, this work only compares the trigger pressure propagation resulting from using a liquid water trigger cell (replacing the gas chamber trigger in KROTOS experiments). This was done in both SEMRA and TEXAS-V codes.

TEXAS-V code is a steam explosion modelling tool based on a 1D 3-field transient code (Lagrange field for fuel particles and Eulerian field for gas and liquid). The code has two modules, a premixing module that sets the initial conditions for the explosion module. Details about TEXAS-V code can be found in [8, 9] and TEXAS-V manual [10].

Results of trigger pressure propagation of KROTOS trigger test vs both SEMRA and TEXAS-V codes are shown in Fig. 4. As seen, SEMRA code can apply a continuous trigger pressure in the liquid domain which resembles the effect of a gas trigger cell in KROTOS test section.
On the other hand, TEXAS-V is limited to a water cell discrete single trigger pressure, thus limiting the capabilities of the code in reproducing KROTOS trigger test and only showing a dampening propagation of an initial pressure wave.

SEMRA code calculations of KROTOS trigger test predict dynamic pressures values for sensors k1-k6 that match KROTOS results in maximum peak pressures and pressure evolution trends.

The total time required for the initial shock wave to dissipate through the test section traveling from the bottom sensor (k1) reaching the pressure sensor at the top of the test section (k6) is 0.6 ms. This shows that the updated numerical scheme can estimate the shock wave propagation parameters (Energy, pressure, and speed of sound) accurately matching those parameters in KROTOS trigger test experiment.

A convergence check was conducted by varying both the CFL number and the number of nodes. A CFL number exceeding 0.8 led to solution divergence. Therefore, this study presents results using the recommended CFL value of 0.5 recommended for an explicit AUSM+ solver.

Regarding the number of nodes, SEMRA code effectively captured the sharp pressure increase at the sensor's locations using 400 and 800 nodes, with a slight difference between the two, indicating a satisfactory level of convergence.

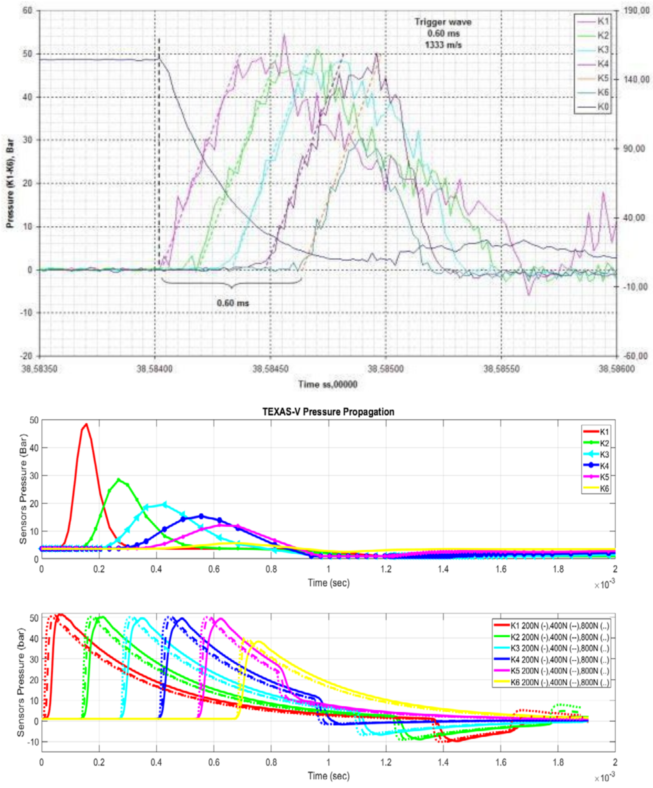

Fig. 4: Trigger Pressure Propagation, KROTOS (Top) [7], TEXAS-V (Middle) and SEMRA (Bottom).

V. Conclusions and Future Work

The objective of this work is to validate a single-phase solver for a new SE code SEMRA. Development of the new code is motivated by the need to improve numerical stability and resulting risk calculations for Nordic BWRs as well as to develop in-house modelling capability that takes into account recent experimental and analytical findings, e.g., SE in stratified configuration, and chaotic nature of triggering.

SEMRA code, with its 1D single-phase solver, was shown to reproduce KROTOS SE trigger test results with good accuracy.

Further work will be focused on expanding SEMRA code to include a 2D, two-phase solver for both explosion pressure propagation and in the premixing and fragmentation module.

Acknowledgments

The work was carried out under the SKC (Swedish Centre for Nuclear Technology) funded research project SEMRA 2019-7.

References

[1] D. Grishchenko, S. Galushin and P. Kudinov, "Failure domain analysis and uncertainty quantification using surrogate models for steam explosion in a Nordic type BWR," *Nuclear Engineering and Design,* pp. Vol. 343. - pp. 63–75., 2019.

[2] K. Kitamura, L. Meng-Sing and C. Chih-Hao, "Extension and Comparative Study of AUSM-Family Schemes for Compressible Multiphase Flow Simulations.," *Commun Computational Physics,* vol. 16, no. 3, pp. 632-674, 2014.

[3] C.-W. Shu, "Essentially Non-Oscillatory and Weighted Essentially Non-Oscillatory Schemes for Hyperbloic Conservation laws.," NASA and ICASE, 1997.

[4] S. Zhang, J. Zhu and C.-W. Shu, "A brief review on the convergence to steady state solutions of Euler equations with high-order WENO schemes," *Advances in Aerodynamics,* p. 1:16, 2019.

[5] J. Chandran and A. Salid, "A modified equation of state for water for a wide range of pressure and the concept of water shock tube," *Fluid Phase Equilibria,* no. 483, pp. 182-188, 2019.

[6] M. O. Delchini, J. C. Ragusa and R. A. Berry, "Simulations of Single and Two-Phase Shock tubes and Gravity Drivren Wave Problems With The RELAP-7 Nuclear Reactor System Analysis Code," Idaho National Labs, Idaho, 2017.

[7] OECD, "OECD/SERENA Integrated Report (Steam Explosion Resolution for Nuclear Applications).," OECD/NEA, 2014.

[8] C.-C. Chu, "One-Dimensional Transient Fluid Model For Fuel-Coolant Interation Anaylsis," Phd Thesis, University of Wisconsin-Madison, 1986.

[9] T. Jian, "Modeling of the Complete Process of One-Dimentional Vapor Explosions," University of Wisconsin_Madison, 1993.

[10] M. Corradini, "Users' Manual for Texas-V: One Dimensional Transient Fluid Model for Fuel–Coolant Interaction Analysis.," University of Wisconsin-Madison,, Madison, 2002.