Development Status and Validation of Nuclear System Analysis Code Using Higher-order Numerical Scheme and Moving Mesh Method

Won Woong Lee [a], Sung Gil Shin [a], Jeong Ik Lee [a*]
[a]*Dept. of Nuclear and Quantum engineering, Korea Advanced Institute of Science and Technology*
291 Daehak-ro, (373-1, Guseong-dong), Yuseong-gu, Daejeon 305-701, Republic of KOREA
Tel: +82-42-350-5869, Fax: +82-42-350-3810, Email: woong.aa@kaist.ac.kr, sgshin@kaist.ac.kr, jeongiklee@kaist.ac.kr
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

In the nuclear system analysis code such as RELAP5, MARS and SPACE, the governing equations are solved by the 1st order numerical scheme in both space and time discretization. The 1st order numerical scheme is very robust and stable. However, the 1st order numerical scheme on the fixed mesh can yield excessive numerical diffusion problem. So, the non-conservative results can be predicted for analyzing transients with steep spatial or temporal gradient of physical parameters. These characteristics are critical drawback in modeling the dramatically fluctuated situation like LOCA (Loss Of Coolant Accident). Therefore, the 1st order numerical scheme on the fixed grid is not desirable during the analysis of accident conditions. So, the high predictive capability and efficient computational cost are required for the advanced nuclear system analysis code.

The authors have been developing a nuclear system analysis code applying the higher-order numerical scheme and the moving mesh method for the advanced system analysis code. In this in-house code, for the higher-order numerical schemes, the 2nd order upwind scheme, centered differencing scheme and Lax-Wendroff scheme are implemented. For the moving mesh method, the moving mesh PDE approach and the monitor functions have been implemented. Thus, this study evaluates preliminarily the performance of the higher-order numerical schemes on the fixed mesh by simulating two phase flow conditions. For the code validation and performance evaluation, MARS-KS code is used for the reference code.

Before evaluating the performance of the higher-order numerical schemes, the developed code using the 1st order numerical scheme, which mimics MARS-KS code solver, is compared under two phase flow conditions. And the higher-order and 1st order numerical schemes are compared in terms of the accuracy and the computational efficiency.

2. Methods and Results

2.1 TWICE code

Fig. 1 shows algorithm of the developing in-house code using the higher-order numerical schemes and the moving mesh method. This code is called TWICE code (Transient Water system analysis code with ICE method) [11]. The spatial discretization, the 1st and 2nd order upwind scheme, centered differencing scheme and Lax-Wendroff scheme are implemented.

Fig. 2 shows the development status of the TWICE code for analysis of two phase flow. In present, the module for solving the two phase two field governing equations are implemented with the higher-order numerical schemes and the moving mesh method. The model and correlations like the wall friction, wall heat transfer, interfacial friction and interfacial heat transfer are being implemented. And the heat structure solver for wall heat transfer is being modified for application of the moving mesh method.

In this study, TWICE code will be validated for simple test case under two phase conditions. And the performance comparison with the 1st order and higher-order numerical scheme will be preliminarily conducted.

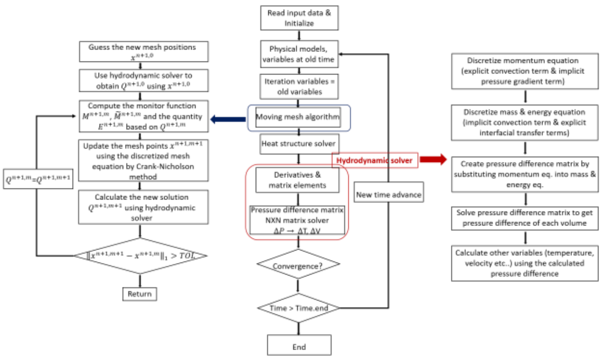

Fig. 1. Algorithm of TWICE code with the moving mesh method

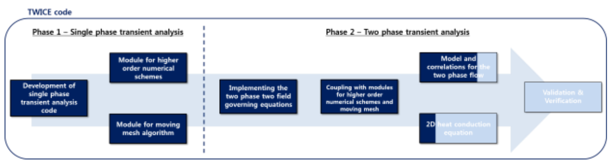

Fig. 2. Development status of TWICE code

2.2 Numerical test case

For validation of TWICE code with MARS-KS code, the flow oscillation test is conducted under two phase conditions. This test consists of a PIPE, an inlet TMDPVOL and an outlet TMDPVOL. Fig.3 shows the nodalization for this numerical test. Table II shows the test conditions. Flow oscillations are induced by a short pressure perturbation at the oulet. The outlet pressure is indicated in Fig. 4 for flow oscillations. The pipe are nodalized with 20, 40 and 80 uniform nodes. The results are compared with pressure, void fraction, mass flow rate of each phase. For modeling this test case, the interfacial friction and heat transfer coefficients use the identical value from MARS-KS code.

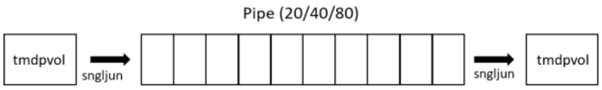

Fig. 3. Nodalization for flow oscillations

	Inlet	Outlet
Pressure [kPa]	50	50
Quality	0.027	0.027
Void fraction	0.9049	0.9049
Liquid velocity [m/s]	1.0	1.0
Gas velocity [m/s]	1.0	1.0

Table II. Flow oscillation test conditions

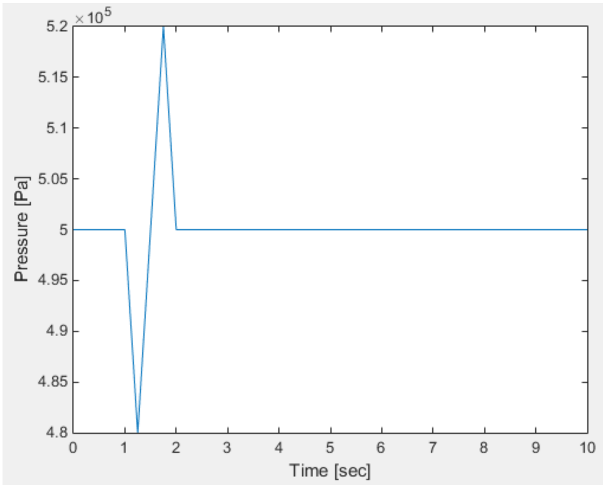

Fig. 4. Pressure changes at outlet for flow oscillations

2.3 Validation

Fig. 5-8 show the validation results of MARS-KS and TWICE using 1st order upwind scheme. with 20, 40 and 80 nodes. The results show the pressure, liquid mass flow rate, gas mass flow rate and void fraction changes at the middle of the pipe. As shown in these graphs, the results show good agreements with MARS-KS and TWICE using 1st order upwind scheme.

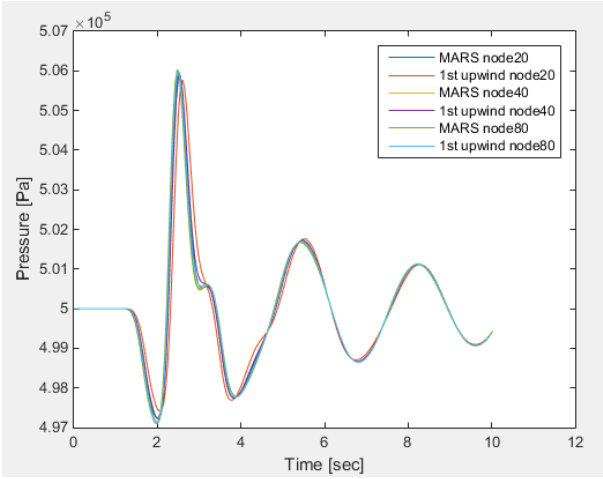

Fig. 5. Pressure changes at middle of pipe

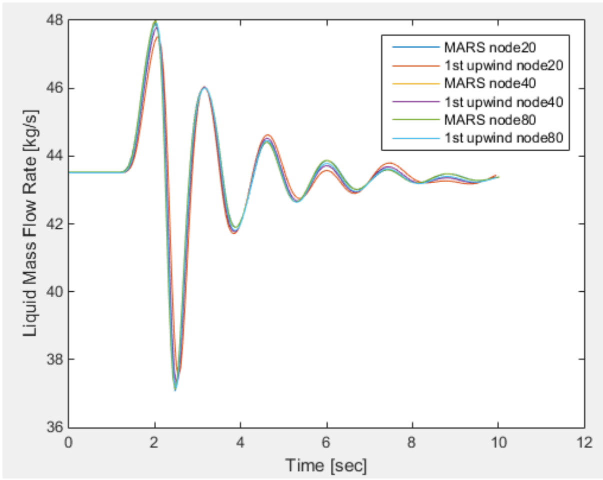

Fig. 6. Liquid mass flow rate changes at middle of pipe

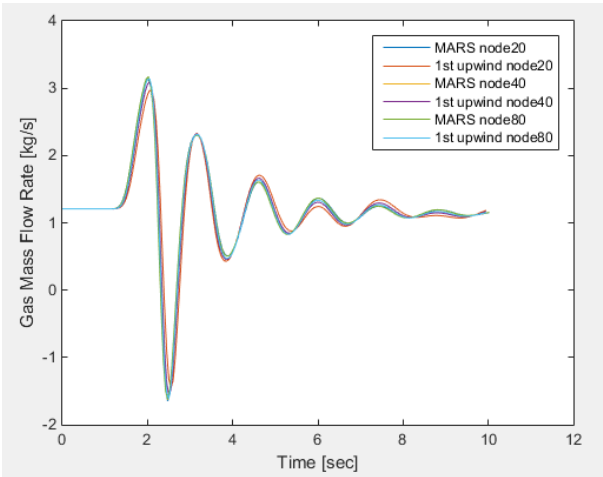

Fig. 7. Gas mass flow rate changes at middle of pipe

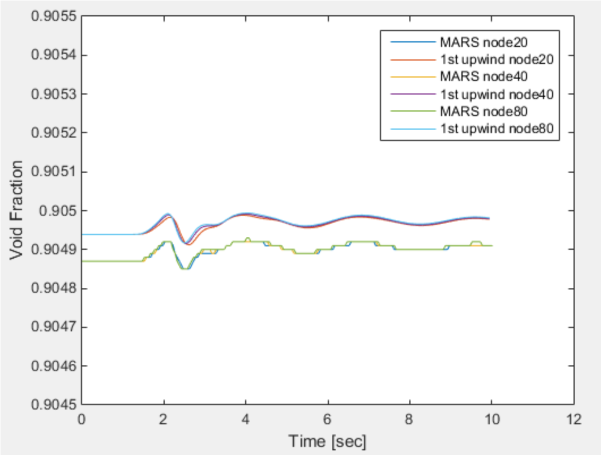

Fig. 8. Void fraction changes at middle of pipe

2.4 Results comparison with higher-order numerical schemes

The results are compared with MARS-KS, TWICE code using 1st order upwind scheme, 2nd order upwind scheme, Lax-Wendroff scheme (LW) and centered differencing scheme (CD) with 40 nodes. Figs. 9-12 show the results of the pressure, liquid mass flow rate, gas mass flow rate and void fraction changes at middle of the pipe using 1st order and other numerical schemes. The results of the higher-order numerical scheme are not much different with MARS-KS and 1st order numerical scheme. Since the interfacial friction coefficient and the interfacial heat transfer coefficients are same with those of MARS-KS, the pressure, velocity fields show little different results. However, the void fraction distribution along the pipe show different results as shown in Fig. 13. In the results of the higher-order numerical schemes, the numerical dispersion problems are occurred near the pipe outlet. This results from the difficulty for application of the flux limiter near the boundary conditions. This test case conducted in this study is open loop. However, this numerical dispersion problem is not occurred in the close loop test cases.

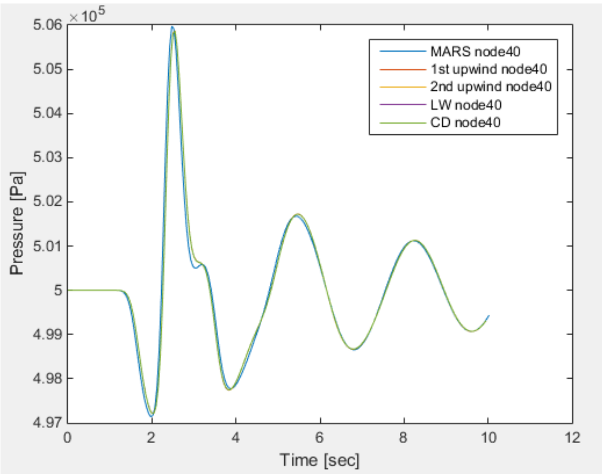

Fig. 9. Pressure changes with 1st order and other numerical schemes at middle of pipe

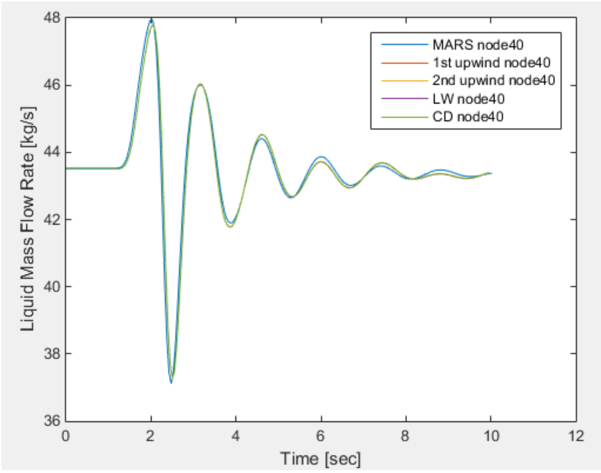

Fig. 10. Liquid mass flow rate changes with 1st order and other numerical schemes at middle of pipe

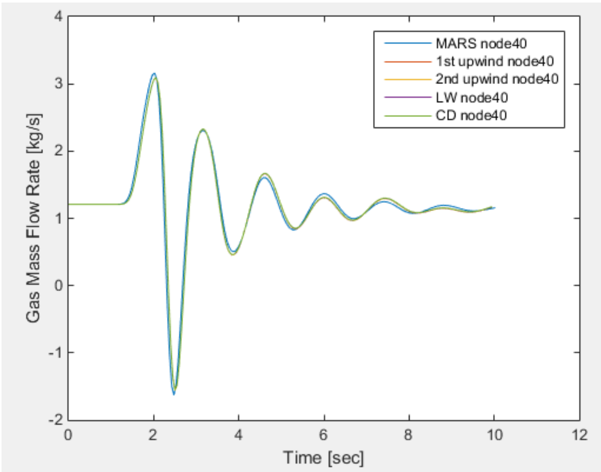

Fig. 11. Gas mass flow rate changes with 1st order and other numerical schemes at middle of pipe

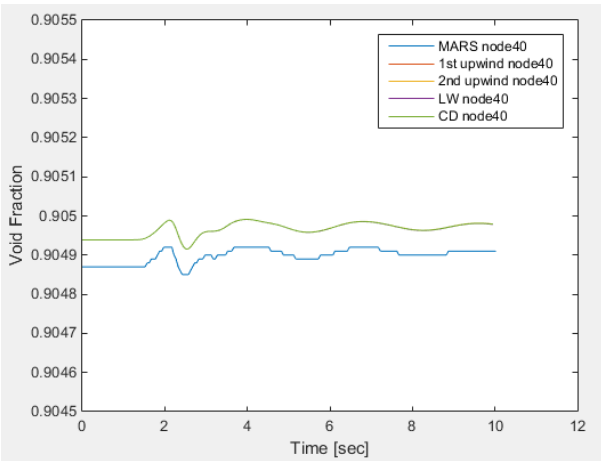

Fig. 12. Void fraction changes with 1st order and other numerical schemes at middle of pipe

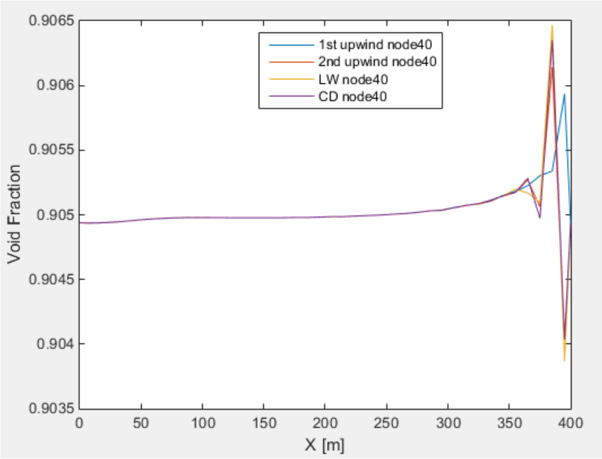

Fig. 13. Void fraction distribution along pipe using 1st order and other numerical schemes

3. Conclusions

This study conducted the valiation of TWICE code using 1st order and higher-order numerical schemes with MARS-KS code for the flow oscillation test. And the results are compared by the pressure, liquid mass flow rate, gas mass flow rate and void fraction changes. For this study, the interfacial friction and heat transfer coefficients use the coefficients from MARS-KS. So, the results between the 1st order and higher-order numerical schemes show little differences. However, in the higher-order numerical schemes, the numerical dispersion problems are occurred due to the difficulty for application of the flux limiter near the boundary conditions. The more detail discussion will be presented during the conference.

For further works, the interfacial friction and heat transfer packages will be implemented. Also, the coupling with the heat structure solver will be conducted. And then, some experiments such as SUBO (SUbcooled BOiling) experiment will be modeled by TWICE code using the higher-order numerical scheme and the moving mesh method. So, the performance evaluation will be conducted in terms of the accuracy and the computational efficiency.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea. (No. 1603010)

REFERENCES

[1] John M. Stockie et al., "A moving mesh method for one-dimensional hyperbolic conservation laws", SIAM Journal on Scientific Computing, Vol.22, p. 1791-1813,

[2] R. Fazio et al., "Moving-mesh methods for one-dimensional hyperbolic problems using CLAWPACK", Computers and Mathematics with Applications, Vol.45, 273-298, 2003

[3] Randall J. Le Veque, " Wave Propagation Algorithms for Multidimensional Hyperbolic Systems", Journal of Computational Physics, Vol. 131, 327-353, 1997

[4] J.H. Mahaffy, "Numerics of codes: stability, diffusion, and convergence", Nuclear Engineering and Design, 145(131-145), 1993

[5] D.R. Liles, Wm. H. Reed, "A Semi-implicit Method for Two-Phase Fluid Dynamics", Journal of Compuational Physics, 26(390~407), 1978

[6] Jae-Jun Jeong, Kwi Seok Ha, Bub Dong Chung, and Won Jae Lee, "A Multi-Dimensional Thermal-Hydraulic System Analysis Code, MARS 1.3.1", Journal of the Korean Nuclear Society, Volume 31, Number 3, pp. 344~363, 1999

[7] H.K.Cho, H.D. Lee, I.K. Park, J.J. Jeong, "Implementation of a second-order upwind method in a semi-implicit two-phase flow code on unstructured meshes", 37(606~614), 2010

[8] H.K. Versteeg, W. Malalasekera, An introduction to computational fluid dynamics, Longman Scientific & Technical, pp. 103~133, 1995

[9] Ercilia Sousa et. al., "On the influence of numerical boundary conditions", Applied Numerical Methematics, 41(325-344), 2002

[10] Ercilia Sousa, "High-order methods and numerical boundary conditions", Computer Methods in Applied Mechanics and engineering, 196(4444-4457), 2007

[11] Won Woong Lee, Jeong Ik Lee, "Performance Comparison of Higher-Order Numerical Schemes Applied to 1D Thermal-Hydraulic System Analysis Code", 2017 Spring KNS