Analysis of Subcooled Water Pressure Transient Behavior During Pipe Blowdown

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1. Introduction

There is a growing interest in nuclear propulsion ships and vessels. As the ship building industry has to strictly manage greenhouse gas emissions, they are looking for efficient and environmentally friendly power generation systems [1]. Since oil and gas prices can become volatile as can be observed recently due to an international conflict, and therefore nuclear power can also play a significant role for this matter [2]. In the case of a ship, internal space and power are the first problems to be considered, and in order to have a high power compared to its size, it is necessary to operate an efficient propulsion system [3].

For the evaluation of structural integrity for the steam generator (SG) in the Pressurized Water Reactor (PWR), the postulated accident such as the main Feedwater Line Break (MFLB) is considered as Design Basis Events (DBE) [4]. From the point of view of structural integrity, the pressure difference between the internals of the SG is a critical parameter because the pressure difference is the only structural load during the MFLB.

Since most of the pipe blowdown studies are aimed at Loss of Coolant Accident (LOCA) of PWR, there are many studies on the sudden change of pressure during the pipe blowdown for high pressure and high temperature above 200℃ [5,6,7]. However, in the case of ships, since the space and weight are limited, it may not receive sufficient feedwater heating before the SG inlet, so the SG inlet temperature may be lower than that of the land-base nuclear power plant SG inlet temperature (~230 ℃). The SG inlet temperature of nuclear propulsion ships is 150℃~170℃ (outlet temperature is 290℃) [8]. In addition, the SG inlet temperature of the SMART pilot plant can become lower as 50℃ [9]. In this study, the pressure transient behavior of subcooled water from 50℃ to 150℃ when the pipe blowdown occurs using RELAP5/MOD3 is investigated.

2. Edward` Pipe Experiment

In this section, the test results and RELAP5 simulation results are compared for the Edward and O`Brien pipe blowdown test condition [10]. There have been many studies in PWR conditions, the most notable of these was the work of Edwards and O`Brien which has been the point of reference for a great deal of subsequent analyses [5].

Fig. 1 shows the RELAP5 nodalization and conditions for Edward` pipe experiment. The structural conditions of this experiment are used in the subsequent RELAP5 simulations. Fig. 2 shows the pressure transient behavior at the pipe exit of the experiment and RELAP5. The RELAP5 result follows the trend of the experiment well and shows a slightly more conservative result.

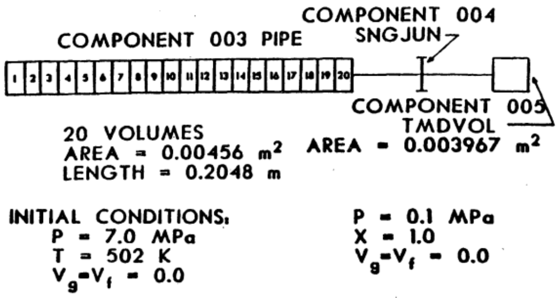

Fig. 1. RELAP5 nodalization and conditions for Edwards` pipe experiment [11]

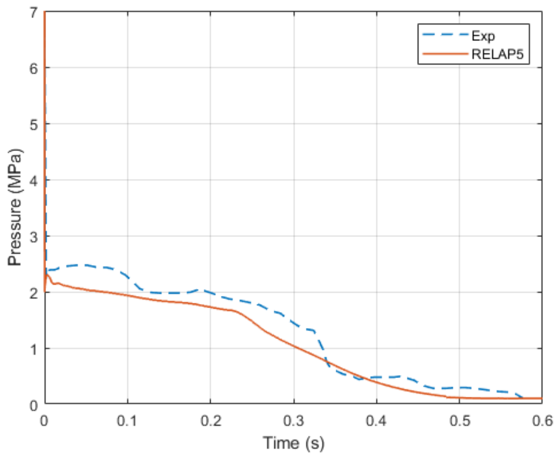

Fig. 2. Comparison of experiment and RELAP5 results at pipe exit (20th node)

3. Pipe Blowdown Case Study

This section presents the simulation results of the pipe blowdown at several conditions using the same structural conditions of the experiment. It is noted that this does not mean Edward and O'Brien conducted experiments at the same conditions, but the authors have simply used the geometry information of the experiment to maintain generality of the obtained results. Table I shows the range of case study. The pressure range was set to include both the pressure of Small Modular Reactor (SMR) and large land-base PWR.

Table I: Temperature and pressure range for case study

	Range
Temperature (℃)	50 ~ 150
Pressure (MPa)	5 ~ 7

Fig. 3 and Fig. 4 show the pressure transient behavior at the pipe exit when the pipe blowdown occurs at initial pressure of 5MPa. At temperatures where the saturation pressure is above 1 atm (100kPa), these results show smooth behaviors. However, at lower temperature cases, the code results show significant fluctuation at the initial stage of discharge. More surprisingly during the fluctuation the pressure in the pipe can become even lower than the boundary volume pressure of 1atm, and shows negative gauge pressure.

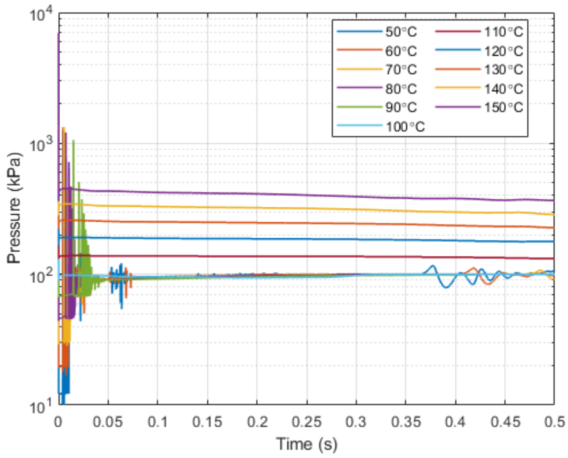

Fig. 3. Pressure transient behavior during pipe blowdown at initial 5MPa (Long term, ~ 0.5sec)

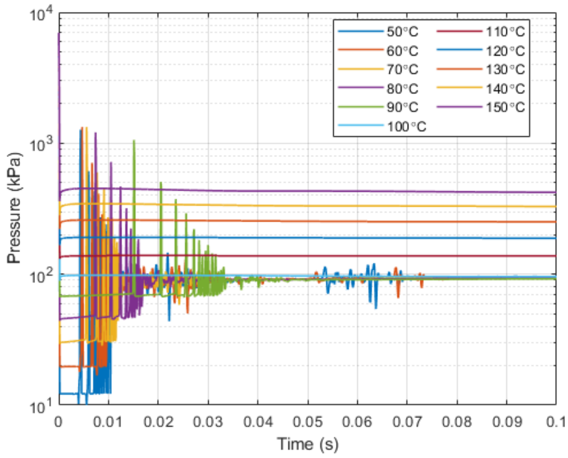

Fig. 4. Pressure transient behavior during pipe blowdown at initial 5MPa (Short term, ~ 0.1sec)

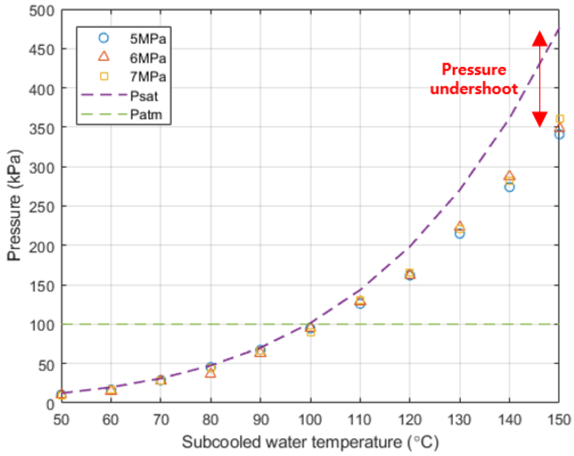

Fig. 5. Pressure undershoot according to subcooled water temperature

The minimum pressure during the pipe blowdown and the saturation pressure are shown in Fig. 5. Subcooled water is suddenly depressurized due to the break, and it passes from subcooled to a superheated state. It finally reaches a pressure (P_n) far enough below its saturation pressure (P_{sat}) [6]. It is called pressure undershoot ($P_{sat} - P_n$). Under pressure undershoot condition, the effect of initial pressure is small, but the effect of temperature is large. It seems that to resolve the pressure undershoot phenomenon, RELAP5 calculation results show that the pressure lower than the saturation pressure of the subcooled water temperature. However, since the saturation pressure at feedwater temperature below 100℃ the pressure in a hydrodynamic volume can be lower than the pressure in boundary volume, which is 1atm.

CHOKEF is a junction quantity in RELAP5 and is a junction choking flag. The value is 0 if the flow is not choked, and is 1 if the flow is chocked. The CHOKEF values for each temperature are summarized in Table II. In RELAP5/MOD3 code manual, it is required that $P_t < P_K$ and either $P_t > P_L$ in order to determine if the flow is choked, otherwise, the flow is considered to be unchoked [12]. P_K is the upstream pressure, P_t is the throat pressure, and P_L is the downstream pressure. For this reason, it is not considered a choked flow at a temperature where the saturation pressure is less than 1atm. Therefore, it is inferred that the choking model is not used when the feedwater temperature becomes smaller than 100℃, and this can cause severe fluctuation at the beginning of the transient.

Table II: CHOKEF value

50℃	0	90℃	0	130℃	1
60℃	0	100℃	0	140℃	1
70℃	0	110℃	1	150℃	1
80℃	0	120℃	1		

Fig. 6 shows comparison of the pressure behavior calculated using RELAP5 and MAKR-KS 1.4 under the same conditions. Although there is a difference in fluctuation frequency, it shows the similar trend, including the negative gauge pressure. In other words, it is not a phenomenon that only occurs in RELAP5.

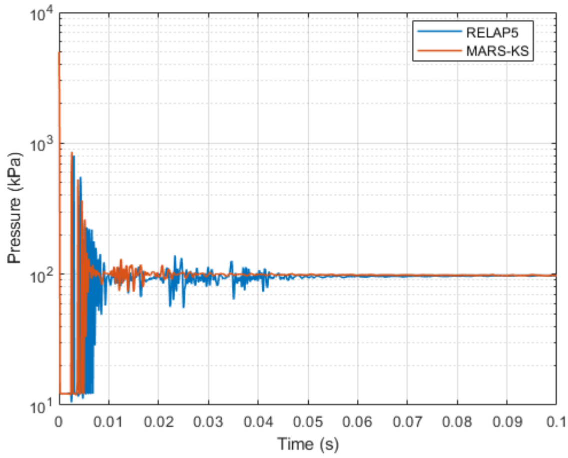

Fig. 6 Comparison of RELAP5 and MAKS-KS results at 50℃ and initial pressure 5MPa

3. Conclusions

In nuclear propulsion ships, there is a possibility that the SG inlet temperature of secondary side may become lower than the large land-base nuclear power plant SG inlet temperature. Thus, it is necessary to evaluate the structural integrity of the SG under this condition when break occurs in SG. For this purpose, pipe blowdown at several different thermal-hydraulic conditions under Edward`s pipe experimental setup geometry was investigated in this study using RELAP5.

At a feedwater temperature below 100℃, the results show that the pressure in the feedwater line can have negative gauge pressure. This is considered to be a result of how RELAP5 handles the pressure undershoot phenomenon. In this case, since the pressure of a hydrodynamic volume can become lower than the boundary volume pressure, which is 1 atm, it is not considered as a choked flow as well. Thus, the choking model is not used when the feedwater temperature becomes lower than 100℃. As a result, the code calculation shows substantial pressure fluctuation at the beginning of the transient. Finally, when compared with the results of MARS-KS, it was confirmed that the results are not unique to RELAP5. Further, experimental studies may require to observe if the calculated fluctuation and negative gauge pressure are actually possible or if it is only a numerical issue.

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