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Dynamic behavior analysis of different pressurizer types on a high-pressure test facility

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HIGHLIGHTS

- The dynamic behavior of Steam, Gas-Steam, and Gas PRZ is evaluated in the WHPCHF facility.
- The peak pressure of different types of PRZs is compared during the same scenario.
- The Gas PRZ has the highest peak pressure due to the lack of non-condensable gas condensation.

ABSTRACT

The pressurizer is a key equipment to ensure the safe operation of pressurized water reactor by maintaining the reactor coolant system pressure within allowed tolerances. Various pressure control systems (Pressurizer) are adopted in industrial applications to satisfy their characteristics. In accordance with the purpose of using nuclear facilities, steam, gas-steam, and gas pressurizer (PRZ) have been used. In nuclear industry, the dynamic behavior of each PRZ is different. Peak pressure is one of the important parameters in choosing the type of PRZ. This study has been evaluated for the University of Wisconsin High-Pressure Critical Heat Flux (WHPCHF) facility as the base loop. Three PRZs are connected to the WHPCHF loop to evaluate their performance during the in-surge scenario. The Peak pressure of the three PRZs is evaluated during transients. The results showed that the use of the Non-condensable Gas (NCG) increases the peak pressure due to the lack of NCG condensation during transient conditions. The use of gas PRZ makes it possible to change the pressure quickly. Also, the pure gas PRZ has the highest peak pressure but has straightforward control logic. The gas PRZ is the best choice for small reactors and high-pressure test facilities.

KEYWORDS
Pressurizer
Dynamic behavior
Peak pressure
Control logic
Test facilities

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1 Introduction

The pressure control system (pressurizer) plays a key role in pressurized water processes. Pressurizer (PRZ) is one of the most important equipments used in the nuclear industry. The purpose of the pressurizer is to keep the pressure constant within the operational limit. On the other hand, the main task of the PRZ system is to control the pressure on the desired limit during transients causing temperature and pressure changes in the system. All of these transients in the main loop affect the PRZ, regulating the pressure and the level (Shoghi et al., 2021). The type of PRZ is selected based on the purpose of the industrial process. PRZs in the nuclear industry are classified into three groups, which include gas, gas-steam, and steam PRZ. Gas PRZs are a group of PRZs used in test facilities, research reactors and, even SMRs. The main part of the gas PRZ is the Non-Condensable Gas (NCG) zone. The presence of the NCG increases the peak pressure due to the lack of NCG condensation during transient and accident conditions. Thus, in the small volume ratio of steam inside the PRZ, it seems that adding gas is not appropriate. Because it increases the peak pressure further and the pressure increases rapidly even during the small transients. Of course, from another perspective, the work of the spray is reduced by adding NCG. Also, the pure gas PRZ has the highest peak pressure but has easy control logic. In other words, the use of gas PRZ makes it possible to change the pressure quickly. The gas PRZ is the best choice for propulsion reactors and high-pressure test facilities. Also, the gas PRZ can be used passively (Shoghi et al., 2021).

Steam PRZs is the most common type of PRZs in the nuclear industry used in most power reactors. On the other hand, The study on the steamgas pressurizer has been rarely done compared to the steam pressur-

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izer because there is only a small number of the nuclear reactors using steamgas pressurizer (Kim et al., 2006). The gas PRZ is very different from the steam PRZ and has been less widely researched than other PRZs (Shoghi et al., 2021). Studies have been performed on the mathematical modeling of PRZs. Mathematical modeling of PRZs well illustrates their dynamic behavior during transient and accident conditions. Pini et al. (Pini et al., 2018) mathematically modeled the steam PRZ for a Pressurized Water Reactor (PWR) and developed a control-oriented model based on the non-equilibrium equations. Zhong et al. (Zhong et al., 2019) used an improved non-equilibrium multi-region model for the accurate prediction of pressure in the steam pressurizer of PWR under transient conditions. Wang et al. (Wang et al., 2019) developed a nonequilibrium three-region pressurizer model for the steam PRZ of PWR. The given model was linearized to introduce the transfer function models of the pressurizer during in-surge and out-surge transients for the controller design of a small pressurized water reactor pressurizer. Moghanaki and Rahgoshay (Moghanaki and Rahgoshay, 2014) used two-region and four-region thermodynamic models for the simulation of a typical PWR pressurizer and benchmarked the calculated results with RELAP5/Mod3 code findings. Baghban et al. (Baghban et al., 2016) employed a simple numerical model based on the non-equilibrium, multi-region model to simulate the pressurizer behavior during transient conditions. Cheng et al. (Cheng et al., 2009) developed a pressurizer model with TRACE code version 5.0 and performed The benchmark of the pressurizer model by comparing the simulation results with those from the tests at the Maanshan nuclear power plant. Hosseini et al. (Hosseini et al., 2020) modeled the thermal-hydraulic behavior of the PRZ by RELAP5 thermal-hydraulic code and coupled the RELAP5 code and MATLAB software to provide a new platform for designing and implementing various intelligent and advanced controllers for PRZ pressure and level in RELAP5 code. Lotfi et al. (Lotfi et al., 2020) simulated the PRZ of VVER-1000 with RELAP5 code. Farman et al. (Farman et al., 2017) performed the study and analysis of the dynamic transient behavior of the pressurizer of PWR. de Oliveira et al. (2013) developed a pressurizer model based on artificial neural networks (ANNs) and developed fuzzy controllers for the PWR pressurizer modeled by the ANN and compare their performance with conventional ones. In addition, many researchers have studied the mathematical simulation for dynamic characteristics of the steam PRZ (Redfield et al., 1968; Baron, 1973; Abdallah et al., 1982; Baggoura and Martin, 1983; Beak, 1986; Wu et al., 2010). The steam-gas PRZ in integrated small reactors experiences very complicated thermal-hydraulic phenomena especially; the condensation heat transfer with NCG under natural convection is an important factor to evaluate the PRZ behavior. Hassan and Banerjee (Hassan and Banerjee, 1996) used the relap5/mod3 thermal-hydraulic code to study the ability of the code to predict Condensation phenomena in the presence of non-condensable gases. Kim et al. (Kim et al., 2008) numerically analyzed gas-steam PRZ's transitions. Wu et al. (Wu et al., 2013) studied transient characteristics of the gas-steam typed pressurizer using the Relap5 code. Lee and Park (Lee and Park, 2013) have researched a thermal-hydraulic system code for transient analysis of a fully-passive integral PWR and presented equations for a gas-steam PRZ. Yoder et al. (Yoder Jr et al., 2014) evaluated the Liquid-Fluoride-Salt test loop that is used an accumulator tank supported by argon gas to control the loop pressure. O'Brien et al. (O'Brien et al., 2017) analyzed the high temperature and pressure test facility that is used an accumulator tank to regulate pressure with supporting nitrogen gas. Xi et al. (Xi et al., 2015) developed mathematical models to study the thermal-hydraulic characteristics of the passive residual heat removal system under ocean conditions. Corradini and Wu (Corradini and Wu, 2015) evaluated the University of Wisconsin High-Pressure Critical Heat Flux (WHPCHF) that is connected to cylinders containing argon gas. Shoghi et al. (Shoghi et al., 2021) first developed mathematical modeling of gas PRZ. The results of the mathematical model are compared with the results of HYSYS. Similar mathematical equations will extend in this paper to simulate the gas PRZ.

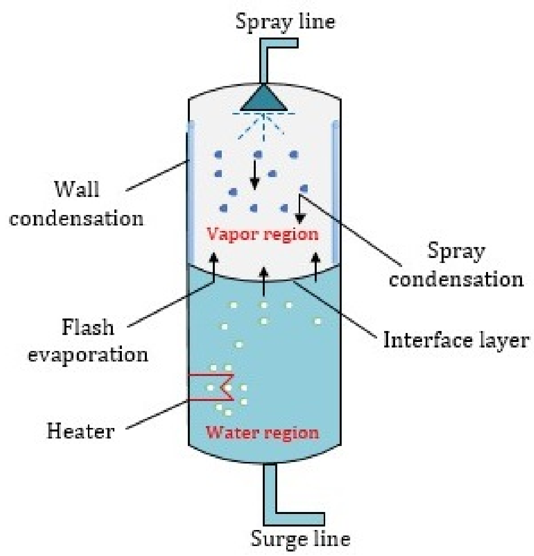

Figure 1: The steam PRZ schematic.

2 Pressurizer system in industrial process

PRZs in the nuclear industry are classified into three groups. Steam PRZ is the most common type of PRZ in the nuclear industry. The steam PRZ operates in equilibrium with a mixture of water and steam. As shown in Fig. 1, the Steam PRZ utilizes two main strategies to control the primary loop pressure within the specified limits. The first strategy is to condense the steam through the cold-water spray to decrease the pressure, and the second strategy is to heat the water with the PRZ electrical heaters to increase the pressure. As shown in Fig. 2, the steam-gas PRZ has been composed based on the non-equilibrium two-region. The steam-gas PRZ uses a single volume consisting of two semi-independent regions, each with special thermodynamic conditions. Another presumption about steam-gas PRZ is that steam and non-condensable gas are combined in the gas region, and mass and energy are transferred between two regions at the interface area. This type of PRZs is also emphasized in a new generation of SMRs, such as the SMART Korean design reactor. In the steam-gas PRZ, the non-condensable gases are applied as controlling actuator mechanisms instead of electrical heaters and sprays (compared with steam PRZ), including the nitrogen and argon, in the steam-gas mixture area.

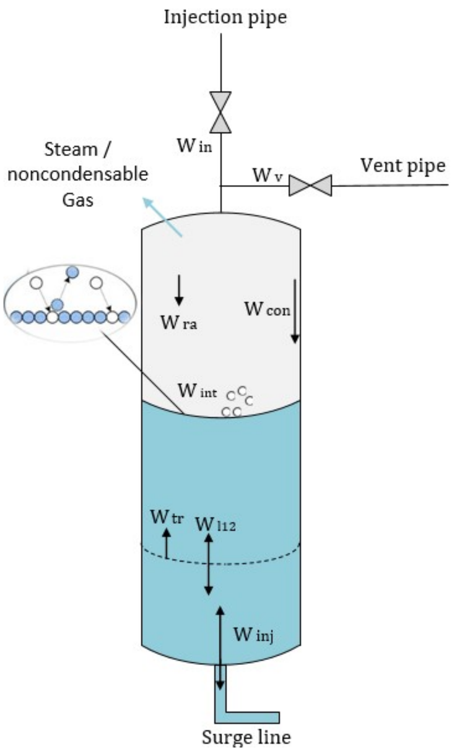

Figure 2: The steam-gas PRZ schematic.

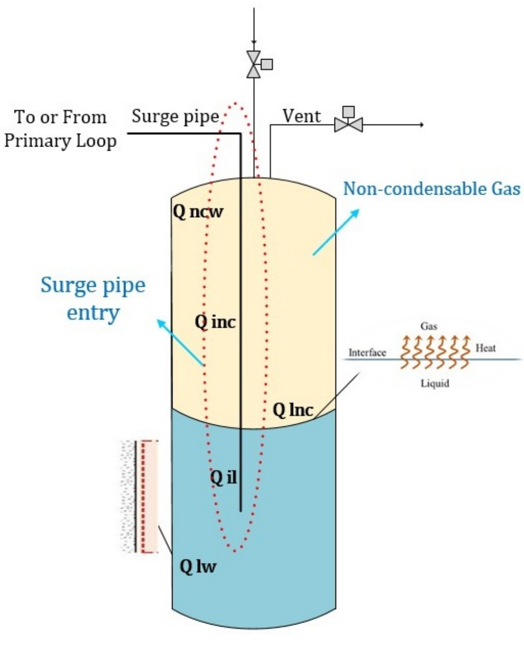

Figure 3: The gas PRZ schematic.

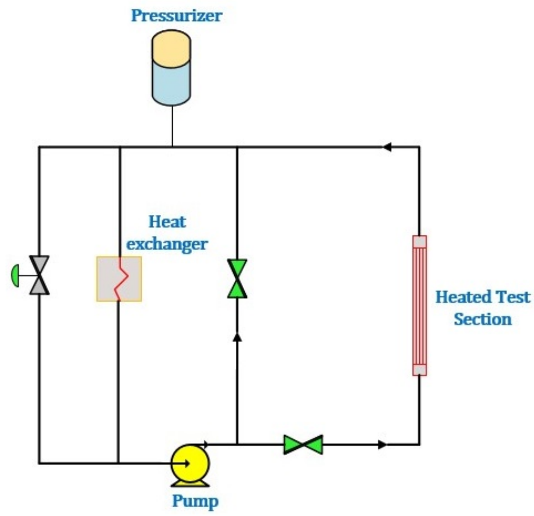

Figure 4: Overview of the main Wisconsin-Madison facility.

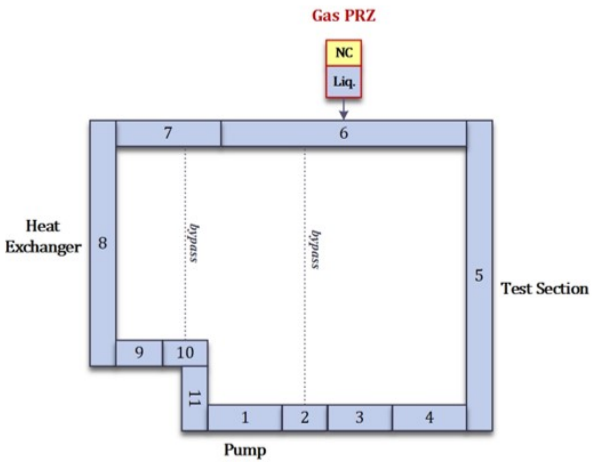

Figure 5: Nodalization of control volumes in the WHPCHF loop.

The gas PRZ (Fig. 3) is another type of PRZ which is controlled by a non-condensable gas that does not mix with the steam. The performance and operation of gas PRZs are different, and less research has been done than other types of PRZs. Therefore, the PRZ is separated into two water and gas regions with different phases and enthalpies of the liquid. In addition, the gas PRZ can be used in the high flux research reactor and SMRs. The working principles of gas PRZs are different from steam PRZs. The gas PRZ separates into two parts, liquid, and non-condensable gas, according to phases and enthalpies of the fluid.

3 Simulated model in HYSYS

Aspen HYSYS is one of the unique tools for chemical processes that are used in various manufacturing processes. Aspen HYSYS is capable of performing many engineering calculations, including mass balance, energy balance, heat transfer, Pressure drops, liquid-vapor balance, mass transfer, chemical kinetics, and more. This program is

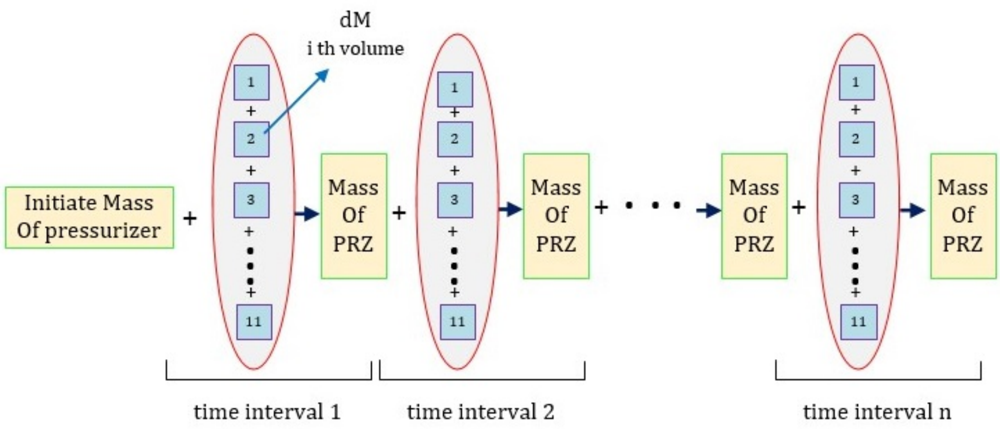

Figure 6: General schematic of the model's performance.

commonly used for steady-state and dynamic simulation, process design, and optimization.

3.1 *WHPCHF facility*

The University of Wisconsin High-Pressure Critical Heat Flux (WHPCHF) facility is specifically designed to obtain CHF data under unique operating conditions. The WHPCHF facility consists of various equipment (Fig. 4); the WHPCHF facility's key equipment is the high-pressure pump, high-temperature test section, heat exchanger, gas PRZ, argon cylinders, and the air chiller. All of the components are integrated with the Aspen HYSYS environment, and the primary loop of WHPCHF is divided into 11 control volumes, as shown in Fig. 5. In each time interval, the total mass changes in the interval are obtained by adding all of the mass changes in control volumes, as shown in Fig. 6.

All three PRZs are simulated in Aspen HYSYS. Each is operated in a similar scenario. It should be noted that the geometry of all three PRZs is similar. the main characteristics of presented PRZs are presented in Table 1.

Table 1: Main characteristics of the presented PRZ.

Parameter	Unit	Value
PRZ Volume	m^3	4.35×10^{-2}
PRZ height	m	2.384
Water Region Volume	m^3	2.376×10^{-2}
PRZ Cross-sectional area	m^2	1.824×10^{-2}

3.2 *Simulated three PRZs (Steam, Gas-Steam, and Gas PRZ) description with Aspen HYSYS*

The Aspen HYSYS software and RELAP5 code are the best options for thermal-hydraulic modeling of PRZ. It should be noted that the RELA5 code has imperfections to model the gas PRZs. In other words, the RELAP5 cannot model the pure NCG region. Thus, the RELAP5 just models the volume with a mixture of water/steam/NCG when the volume of NCG has a low percentage. Therefore, in this study, Aspen HYSYS software is selected to simulate gas PRZ. Aspen HYSYS is one of the unique tools for industrial processes that are used in various manufacturing processes.

It should be noted that the gas PRZ is not defined in the list of Aspen HYSYS equipment. Therefore, a separator has been used to create the geometry of the gas PRZ. Separator boundary conditions are selected according to the WHPCHF gas PRZ boundary conditions. The nodalization of the separator and its boundary conditions are presented in Fig. 7. There are two regions for the steam PRZ (steam and water region). There is steam in the upper part of the PRZ and water (liquid) in the lower part (Fig. 1). Also, there are two regions in the Gas-Steam PRZ (mixed and water regions). In the mixed region, there is a mixture of NCG and steam (Fig. 2). In this study, three PRZs are connected to the WHPCHF loop to evaluate their performance during the same scenario. Because the top region of each PRZ is different, their behavior will also be different (Table 2).

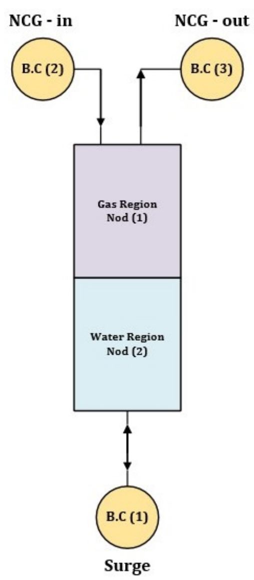

Figure 7: Separator nodalization and boundary conditions.

Table 2: Contents of each PRZ.

PRZ type	Bottom region	Upper region
Steam PRZ	liquid	Vapor
Gas-Steam PRZ	liquid	Vapor-NCG
Gas PRZ	liquid	NCG

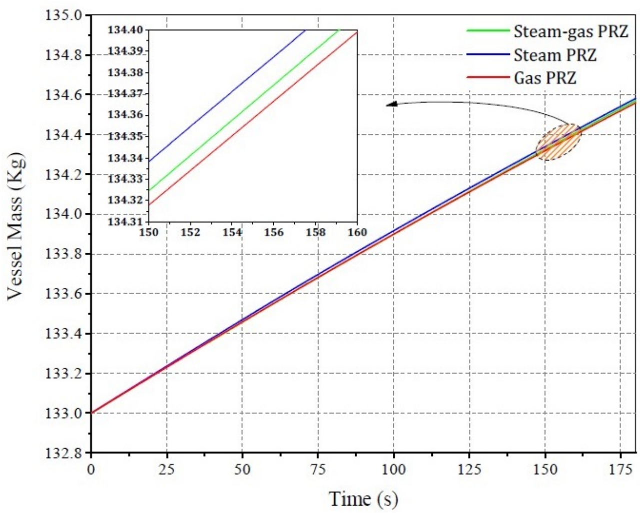

Figure 8: Mass Changes during In-Surge Scenario.

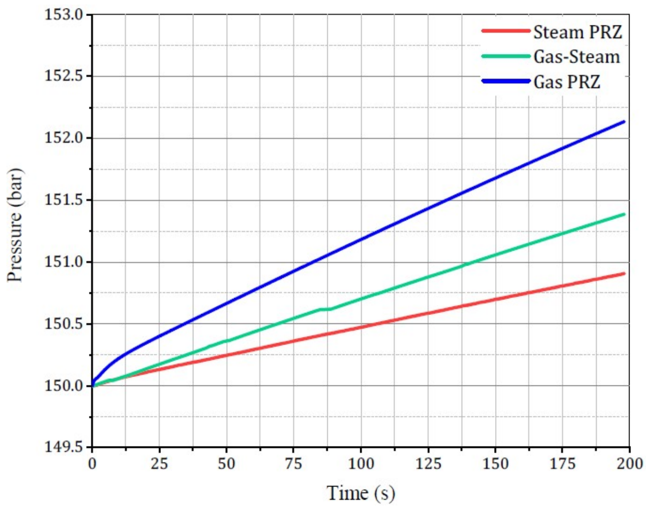

Figure 9: Pressure Change inside the PRZs.

Figure 10: The PRZs comparison is based on their peak pressure and control-ability in transients.

3.3 *In-surge scenario*

A scenario has been implemented to test the performance of each PRZ. During the In-surge scenario, the chiller in the secondary loop removes less heat from the loop and, the heat removed from the primary loop decreases. Therefore, the temperature in the primary loop increases over time. In addition to increasing the temperature, the specific volume inside the main loop increases as a function of specific enthalpy and pressure (Eq. (1)). During this scenario, by increasing the pressure, some water from the primary loop has entered the PRZ.

$$v = f(P, h) \tag{1}$$

In the case of loop malfunction, the specific volume changes in each control volume. Therefore, it changes the mass in each of the control volumes. The mass changes are collected in all control volumes and applied to the PRZ at each time interval (Fig. 6). This scenario is applied to all three PRZs.

4 Results and discussion

During the in-surge scenario, the temperature in the primary loop increases over time. In addition to increasing the temperature, the specific volume inside the main loop increases. During this scenario, by increasing the pressure, some water from the primary loop has entered the PRZ. The comparison of the mass changes inside the different types of PRZs is presented (Fig. 8). During the same scenario (increasing pressure Scenario), the mass input to the steam PRZ is higher than in other PRZs. The gas PRZ also has the lowest value. In general, the pressure in the loop increases with increasing temperature. The upper region of each PRZ has a different content. Figure 9 shows that the pressure in all three PRZs has increased. The pressure changes in the gas PRZ are more than other PRZs. This is due to the presence of NCG inside the gas PRZ (upper region of gas PRZ). This figure shows that the gas PRZ is more sensitive to turbulence than other PRZs. After the gas PRZ, Due to the presence of certain amounts of NCG in the mixture with Steam in upper region of PRZ, Gas-Steam PRZ is more sensitive to turbulence.

It should be noted that the design of the PRZ depends on several factors including the primary loop's inventory and reactor power. In steam PRZ, the volume of the steam is a very critical design parameter that affects the peak pressure. Also, using NCG in the PRZ design (Steam-gas PRZ and Gas PRZ) can be associated with advantages and challenges. Usually, the use of the NCG increases the peak pressure due to the lack of NCG condensation during transient conditions. Thus, in the small volume ratio of steam inside the PRZ, it seems that adding gas is not appropriate. Because it increases the peak pressure further and the pressure increases rapidly even during the small transients. Of course, from another perspective, the work of the spray is reduced by adding NCG. Also, the pure gas PRZ has the highest peak pressure but has easy control logic (Fig. 10). In other words, the use of gas PRZ makes it possible to change the pressure quickly. The gas PRZ is the best choice for high-pressure test facilities. Also, the gas PRZ can be used passively. A summarized comparison between the types of PRZ is shown in Fig. 10. Figure 11 compares the peak pressure in the three PRZs, quantitatively. During the in-surge scenario, in the gas PRZ, the pressure is increased by approximately 2 bar during the scenario and reaches a pressure of 152 bar.

In this study, Gas-Steam PRZ has been selected and different molar fractions have been implemented. The change of pressure in the Steam-Gas PRZ is apparently different when the mole fraction of Argon varies. The peak pressure increases with the increase in Argon mole fraction. This is due to the condensation heat transfer in the presence of NCG, which decreases the heat-transfer coefficient with an increasing mole fraction of NCG. Figure 12 shows the impact of NCG in more detail. During the operation of the PRZ in the loop, the use of the NCG increases the peak pressure due to the lack of NCG condensation during transient conditions. With increasing molar fraction of NCG in the mixed region (from 37% to 57%), the peak pressure increased. The reason for reducing the peak pressure is to reduce the amount of NCG in the steam-gas mixture.

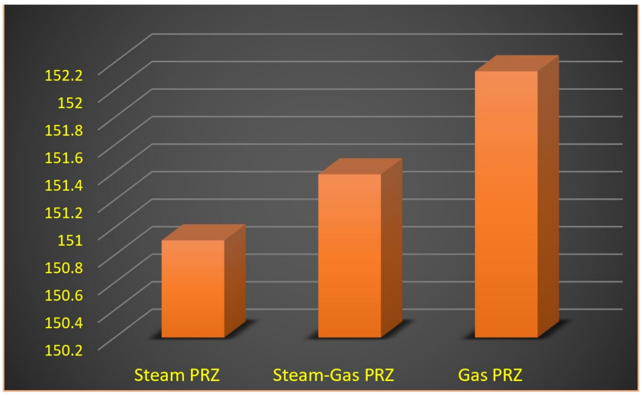

Figure 11: The PRZs comparison is based on their peak pressure in transients.

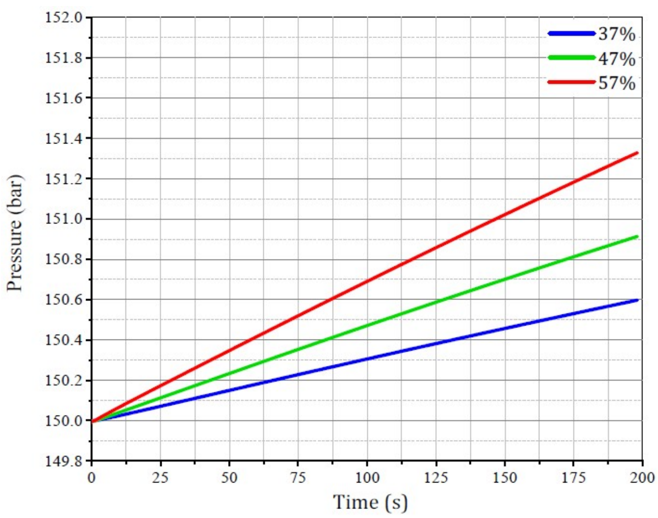

Figure 12: Different NCG Mole Fractions inside Steam-Gas PRZ.

5 Conclusions

The pressure control system (pressurizer) plays a key role in pressurized water processes. PRZs in the nuclear industry are classified into three groups. Steam PRZ is the most common type of PRZ in the nuclear industry. The Gas-Steam PRZ is another type of PRZ that is used in nuclear industries, especially in small modular reactors. The main difference between a Steam and Gas-Steam PRZ is that the upper region of a Gas-Steam PRZ is a mixture of NCG and steam. Gas PRZ is another type of PRZ, which is used NCG in the upper region of PRZ to control the pressure. in this study, three PRZ was connected to the WHPCHF loop to evaluate their performance during in-surge scenario. The pressure changes in the gas PRZ are more than other PRZs. This study shows that the gas PRZ was more sensitive to turbulence than in other PRZs. After the gas PRZ, the steam PRZ was more sensitive to turbulence. The use of gas PRZ makes it possible to change the pressure quickly due to the high peak pressure. The gas PRZ is the best choice for small reactors and high-pressure test facilities because of its controllability. Also, the gas PRZ can be used passively.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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