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Analysis of degassing time of pressurized water reactor pressurizer

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ABSTRACT

The thermal degassing characteristics especially the degassing time of the pressurizer is essential for the design and operation of the nuclear reactor. However, the related studies are rarely published publically. This paper studies the pressurizer thermal degassing characteristics and presents its application to a pressurizer of a typical pressurized water Small and Medium sized Reactor (SMR). Firstly, the steady-state thermal degassing process of the pressurizer is analyzed. A theoretical pressurizer degassing model is developed and verified by comparing with the experiment, which supports the reliability of the model. Secondly, the index of the degassing time is defined and the influencing factors of the degassing time are analyzed theoretically. Thirdly, based on the thermal–hydraulic restrictions of the degassing process of the SMR pressurizer, a degassing time optimization scheme is proposed to optimize the pressurizer degassing time. Through the application of the optimization algorithm, the degassing hydrogen time of the SMR pressurizer is reduced by 10.3% in contrast with the degassing hydrogen time of the SMR pressurizer at its preliminary design value.

1. Introduction

The Small and Medium sized Reactors (SMRs) (Rowinski et al., 2015) are those reactors whose power are lower than 700 MWe, which are more suitable to supply electricity to remote places and to create more distributed energy systems. The SMRs have been focused by many countries. e.g., China is developing a pressurized water reactor which will be placed on a boat and it will become an offshore nuclear power plant for island and offshore platform for electricity generation, sea water desalination and even hydrogen generation (Hu and Guo, 2018).

In the course of operation of a SMR, some fission gases (e.g., krypton and xenon) may dissolve in the reactor coolant as fuel elements become defective. After the shutdown, but before the start of refueling and maintenance operations, the concentration of hydrogen and radioactive gases must be reduced to avoid maintenance personnel being exposed to excessive radiation. Moreover, this reduction will further reduce the possibility of an explosion caused by a potential spark igniting a flammable mixture of hydrogen and air in the containment. Therefore, it is necessary to purify the reactor coolant after the shutdown.

This paper focuses on a typical pressurized water SMR and its degassing method has been chosen carefully. There are various patents (Marie, 1965; Goeldner, 1969; Gramer and Korn, 1974; Kausz et al., 1976; Battaglia and Fleming, 1987; Corpora, 2015) to purify the reactor coolant as shown in Table 1. However, some of the methods require additional equipment and complicated operation. Since the space of a SMR is usually narrow, it is better to use as much equipment which is already present in the reactor installations as possible and to make its purification operation as simple as possible. The method by using reactor pressurizers as thermal degassing apparatus (Gramer and Korn, 1974) is recommended in this paper.

The degassing process is schematically shown in Fig. 1. The pressurizer is connected with the hot leg of the reactor coolant, the cold leg of the reactor coolant and the adsorption device through the surge line, the spray line and the degassing line, respectively. The electric heater remains open during the degassing process. The non-condensable gases (hydrogen and fission gases) dissolved in reactor coolant enter the pressurizer through the spray line. Then the gases may be expelled from the spray droplets to the gas phase space of the pressurizer. The remaining non-condensable gases dissolved in the droplets fall into the liquid phase space of the pressurizer. Some of the gases may enter the gas space again along with the rising bubbles and the remaining flows back to the reactor coolant through the surge line. The mixture of the steam and non-condensable gases is discharged from the gas space to the absorption device through the degassing line. Pure water is supplied to the reactor coolant system through the water supply system. As the process continues, degassing of the reactor coolant can be achieved.

The degassing by the pressurizer has been proven effective (Gramer and Korn, 1974; Caldwell, 1956; Shen, 1988). However, the theoretical analysis of degassing process and the optimization of degassing time are rarely open-published. Caldwell (Caldwell, 1956) did a degassing

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Nomenclature

C_1	concentration of non-condensable gas in spray flow or in reactor coolant (kg/kg(H_2O))
C_2	concentration of non-condensable gas in degassing flow or in gas space (kg/kg(H_2O))
C_3	concentration of non-condensable gas in flow back to reactor coolant or in phase space (kg/kg(H_2O))
C_g	concentration of dissolved gas in solution (kg/kg)
C'	concentration of non-condensable gas in spray and condensate droplets near liquid interface (kg/kg(H_2O))
C''	concentration of non-condensable gas in mixture of steam and gas (kg/kg(H_2O))
G_1	mass flow rate of spray flow (kg/s)
G_2	mass flow rate of degassing flow (kg/s)
G_3	mass flow rate of flow back to reactor coolant system (kg/s)
G_{cs}	mass flow rate of condensate droplets (kg/s)
G_{vap}	mass flow rate of mixture of steam and gas evaporating from liquid interface (kg/s)
G_{10}	maximum spray mass flow rate (kg/s)
G_{20}	maximum degassing mass flow rate (kg/s)
h_{in}	specific enthalpy of inlet spray water (J/kg)
h_{sf}	specific enthalpy of saturated water (J/kg)
h_{sg}	specific enthalpy of saturated steam (J/kg)
K_i	Henry's law constant (Pa^{-1})
M_{H2O}	molar mass of water (g/mol)
M_i	molar mass of non-condensable gas (g/mol)
m_{H2O}	mass of water (kg)
m_i	mass of non-condensable gas (kg)
P	electric heater power (W)
P_0	maximum electric heater power (W)
p_g	partial pressure of dissolved gas in gas phase of the solution (Pa)
p_L	partial pressure of non-condensable in bubbles (Pa)
p_v	partial pressure of non-condensable gas in gas space (Pa)
Q	heat dissipation rate of the total pressurizer through the wall (W)
Q_g	heat dissipation rate of gas phase through the wall (W)
R	time required for total reactor coolant to flow through the pressurizer (s)
S	ratio of degassing mass flow rate to spray mass flow rate
S_0	maximum ratio of degassing mass flow rate to spray mass flow rate
T_d	degassing period defined in Eq. (23) (s)
W	reactor coolant system water mass (kg)
X	factor representing condensation effect of the spray
X_{up}	upper bound of X defined in Eq. (32)
Y	factor representing escape ability of non-condensable gas from the solution
Ω	constraint set defined in Eq. (34)
Ψ	constraint set defined in Eq. (36)
ε	degassing efficiency defined in Eq. (2)
α	ratio of non-condensable gas concentration in gas space to that in liquid space
SMR	Small and Medium sized Reactor

Table 1
Patents for purifying reactor coolant.

Source	Method description
(Marie, 1965)	Separate a small stream of reactor coolant from the reactor coolant system and distill the stream at the reactor operating pressure to form a vapor of primary fluid and a liquid residue. Then return the vapor to the reactor coolant system and discard the residue.
(Goeldner, 1969)	Disclose a vapor compression still system.
(Gramer and Korn, 1974)	Deliver the reactor coolant to the pressure maintenance device wherein the primary coolant is further heated and partially evaporated. Then withdraw the vaporized coolant from the pressure maintenance device together with the gases released from the coolant.
(Kausz et al., 1976)	Disclose a conventional pressurized water reactor coolant radioactive gas disposal system which utilizes a conventional degasser and a separator to separate noble gases.
(Battaglia and Fleming, 1987)	Drain down the reactor coolant system in an unvented condition during the drain-down operation. The step of draining establishes a partial vacuum, which is sufficient to boil the reactor coolant and cause degassing.
(Corpora, 2015)	Pass the reactor coolant over a membrane and extract the gasses by applying a vacuum. Then convey the gases to a nuclear plant waste gas system.

hydrogen experiment and proposed a degassing hydrogen efficiency calculation method. Shen (1988) studied the pressurizer degassing efficiency of both hydrogen and fission gases but the exact expression of degassing efficiency is not given. As for the optimization of the pressurizer, most studies (Xu, 1987; He et al., 2010; Liu et al., 2012, 2014; Wang et al., 2016) are focused on the pressurizer volume and weight.

This paper assesses the capability of doing such research and carries three original works. Firstly, the steady-state degassing process of the pressurizer is analyzed and the theoretical degassing model is developed, which is verified by comparing with the experiment (see Section 2). Secondly, the index of the degassing time is given and the influencing factors of the degassing time are analyzed theoretically (see Section 3). Thirdly, based on the thermal-hydraulic restrictions of the pressurizer degassing process, the degassing time optimization scheme of the pressurizer is given and applied to a SMR pressurizer (see Section 4).

2. Model development and verification

2.1. Model development

The key features and assumptions of the pressurizer degassing process are:

1. The degassing process has been carried out continuously which is further considered to be in a steady state.
2. The water and steam are considered to be in a saturation state.
3. Non-condensable gases distribute evenly in the gas space as well as in the liquid space.

The degassing process of pressurizers is based on the gas dissolution and transport theory, which can be described by Henry's law (Henry, 1803). According to Henry's law, the amount of dissolved gas is