CTMT Depressurization by Reducing Steam and Carbon Dioxide Partial Pressures with a CaO/Ca(OH)₂-based Reaction System

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1. Introduction

The containment of the nuclear power plant, a robust barrier toward the environment, should be kept intact during accident progressions. One of crucial factors that threatens the integrity is over-pressurization. The containment structural intactness shows a direct relationship with the applied internal pressure conditions [1,2]. Also, release rate through the containment is strongly dependent upon the pressure condition [3]. During the early phases after LOCAs(Loss-Of-Coolant Accidents), ejected steam from the RCS(Reactor Coolant System) can increase the internal pressure. Without mitigation systems, the internal pressure radically increases in short time reaching the design limit [4,5]. In addition, when proper remedies do not work in time, accidents change into the severe accident phase. Molten corium during the severe accident progression causes radical non-condensable gas generation during interactions with the concrete(MCCI), which induces pressurization along with the hydrogen. On this basis, several mitigation approaches, like spray, coolant supply systems, severe accident mitigation strategies, hydrogen removal facilities and external actions, are being adopted to suppress the extent of damage by reducing the internal pressure. In this study, a $CaO/Ca(OH)_2$-based reaction system is suggested with preliminary simulations. CaO absorbs steam in the environment, transforming itself into $Ca(OH)_2$; the $Ca(OH)_2$ can be used to capture the emitted CO_2 during the severe accident progression. With the system, prevention of radical pressure increase can be realized in both early phases and late phases after the LOCAs.

2. Methods and Results

The simulation process is divided into two: steam absorption(for the early phase depressurization) and CO_2 absorption(for the late phase depressurization).

2.1 Steam Absorption with CaO

Steam adsorption rate can be described in terms of 'time of complete conversion' and time according to Criado et al. [6]. The complete conversion time is determined by the particle size, environmental conditions (temperature and partial pressure).

$$X_{H_2O}(t) = 1 - \left[1 - \frac{t}{t_{complete}}\right]^3$$

At each time-step, the amount of heat transfer that is made by the exothermic reaction, radiation and heat absorption is considered along with mass change of the elements during steam absorption process.

$$\left[c_{p,CaO}M_{CaO}(t) + c_{p,Ca(OH)_2}M_{Ca(OH)_2}(t)\right]\left\{T_{CaO}(t) - T_{CaO}(t-\Delta t)\right\}$$

$$\varepsilon\sigma A_{CaO}\left[\left\{T_{CaO}(t)\right\}^4 - \left\{T_{steam}(t)\right\}^4\right]$$

$$Q_{exothermic} \times \left\{n_{H_2O}(t) - n_{H_2O}(t-\Delta t)\right\}$$

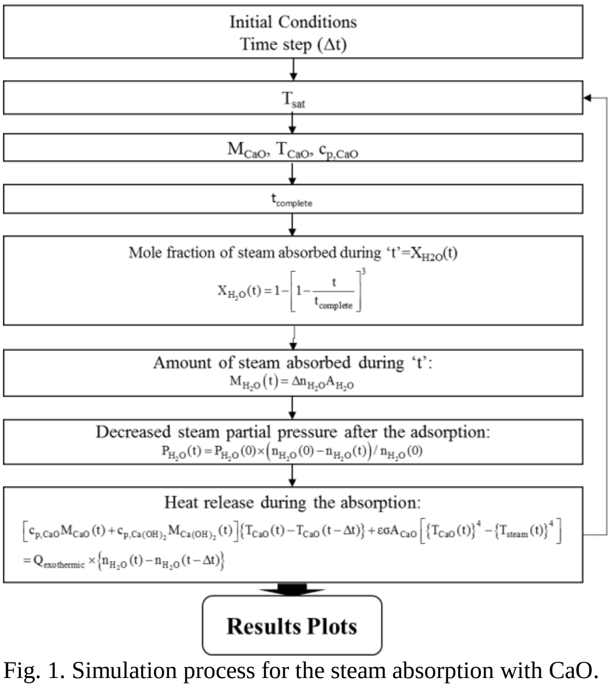

Fig. 1. Simulation process for the steam absorption with CaO.

2.2 CO_2 absorption with $Ca(OH)_2$

The CO_2 absorption rate can be expressed in terms of relative humidity, specific surface area of the $Ca(OH)_2$ particles and the environmental temperature according to Shih et al. [7]. Based on the acquired change rate with time, the amount of mass change can be calculated accordingly.

$$\frac{dX_{Ca(OH)_2}}{dt} = k_1\left(1 - k_2 X_{Ca(OH)_2}\right)$$

Where,

$$k_i = A_i \exp\left(-E_i / RT\right)$$

$$A_1 = 1.11 S_P \left\{-\ln\left(RH\right)\right\}^{-0.96}$$

$$A_2 = 5.31 / S_P \exp\left(0.603 / RH\right)$$

$$E_1 = 17.4\,kJ / mol$$

$$E_2 = -2.9\,kJ / mol$$

$$\left[M_{Ca(OH)_2+CaCO_3}(t) - M_{Ca(OH)_2}(0)\right] = \frac{X_{Ca(OH)_2}(t)\left\{\left(A_{CaCO_3} - A_{Ca(OH)_2}\right) M_{Ca(OH)_2}(0)\right\}}{A_{Ca(OH)_2}}$$

As done in the steam absorption simulation, the amount of heat transfer is calculated at each time-step, and mass change of the consisting elements is tracked to simulate the pressure change.

$$\left[c_{p,Ca(OH)_2} M_{Ca(OH)_2}(t) + c_{p,CaCO_3} M_{CaCO_3}(t)\right]\left\{T_{Ca(OH)_2}(t) - T_{Ca(OH)_2}(t - \Delta t)\right\}$$

$$\varepsilon\sigma A_{Ca(OH)_2}\left[\left\{T_{Ca(OH)_2}(t)\right\}^4 - \left\{T_{CO_2}(t)\right\}^4\right]$$

$$Q_{exothermic} \times \left\{n_{CO_2}(t) - n_{CO_2}(t - \Delta t)\right\}$$

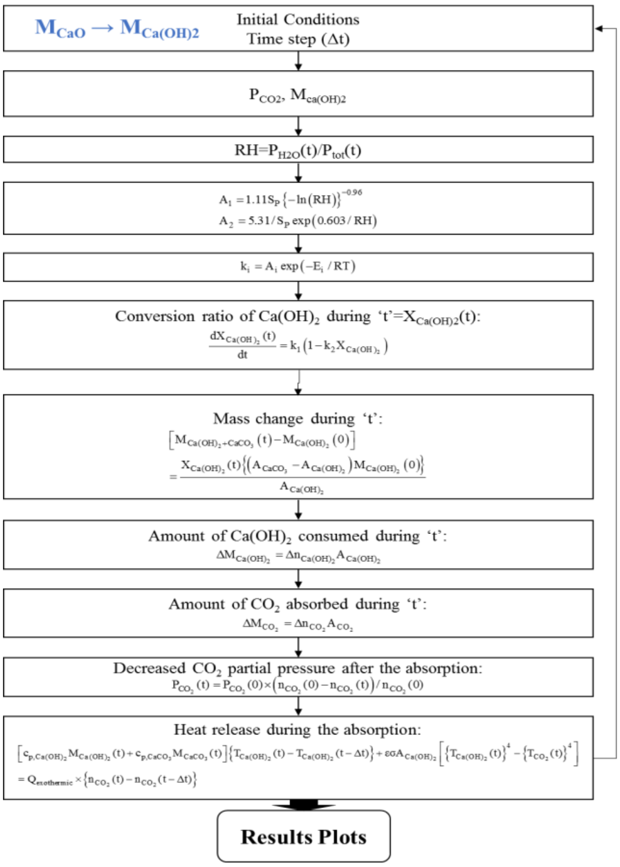

Fig. 2. Simulation process for the CO_2 absorption with $Ca(OH)_2$.

2.3 Steam and CO_2 Partial Pressure with Time

The steam partial pressure radically decreases right after the activation of the system, while the absolute amount of the removed steam is smaller than the silica gel-based system proposed by the research team before [8]. For the CO_2 removal phase, the CO_2 is continuously captured until the saturation states. For both of the absorption process, absolute amount of the initial CaO plays an important role on the overall trends.

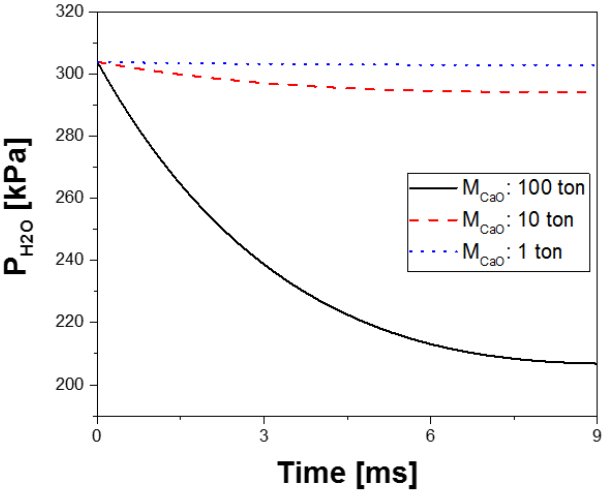

Fig. 3. Simulation of the steam absorption process.

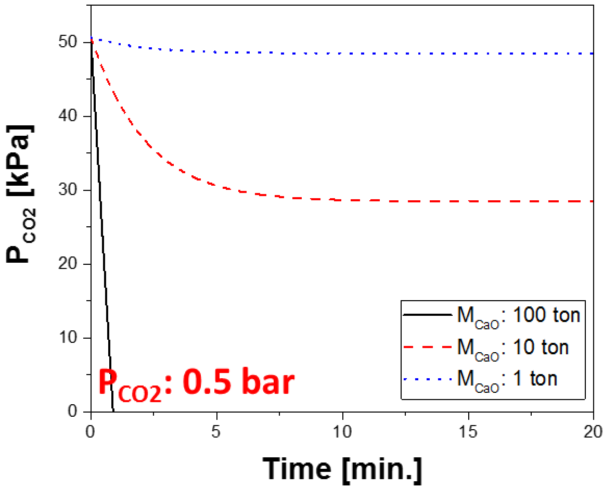

Fig. 4. Simulation of the CO_2 absorption process(0.5 bar).

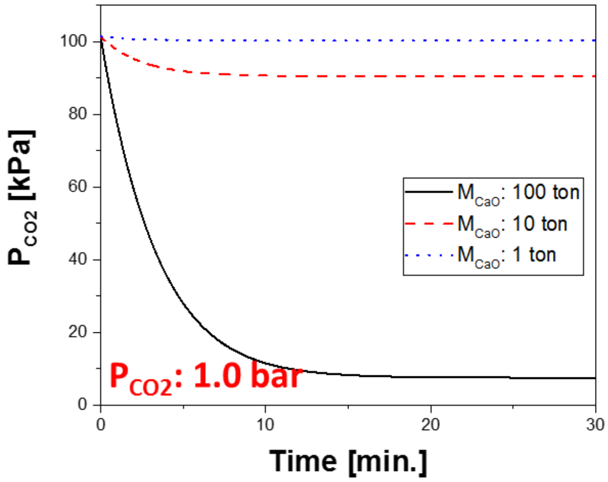

Fig. 5. Simulation of the CO_2 absorption process(1.0 bar).

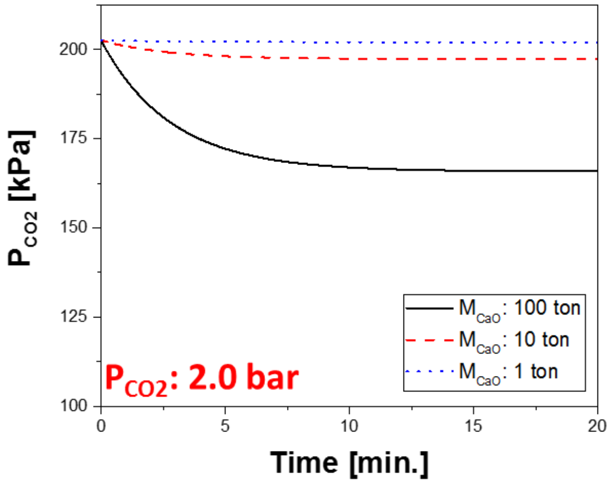

Fig. 6. Simulation of the CO_2 absorption process(2.0 bar).

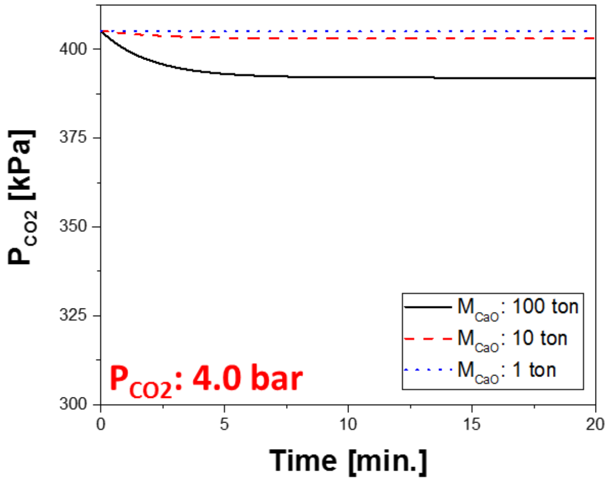

Fig. 7. Simulation of the CO_2 absorption process(4.0 bar).

3. Conclusions

A CaO/$Ca(OH)_2$-based reaction system is proposed and corresponding preliminary simulations have been carried out in this study to mitigate over-pressurization inside the containment. Through the system, excess amount of steam is captured at early phases right after the LOCAs, and CO_2 is captured at late phases after the MCCI. With the system, we can mitigate the accident progression based on easy-applicable technologies. Its low cost and well-known characteristics can provide the potential applicability in the future.

ACKNOWLEDGMENTS

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