Thermal Performance Enhancement of Dry Cask Storage System Using Helium-Based Binary Gaseous Mixture

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1. Introduction

Dry cask storage system (DCSS) is a method to safely and continuously store high-level radioactive waste such as spent nuclear fuels. The dry casks are typically steel cylinders which are either welded or bolted closed. The fuels inside the dry casks are surrounded by a backfill gas. The filling gas cools the fuel rods in the cask primarily before the cask is cooled by ambient air. Helium is one of the most preferred backfill gas for the DCSS because of its low reactivity, radioactivity and high thermal conductivity.

The passive cooling system allows DCSS to be safe and cost-effective method. However, since it is based on natural convection at a low flow rate, there is a disadvantage that the site efficiency is low. In addition, the individual price of the cask is expensive.

It is widely known that the helium shows thermal performance enhancement if heavier gases are mixed. This study proposes the usage of helium-based binary gaseous mixture as an alternative to helium for the backfill gas in order to improve the heat transfer performance in the dry cask based on the computational fluid dynamics (CFD) simulation results. The enhancement in heat transfer performance would help overcome the shortcomings of the dry storage system.

2. Preliminary analysis for the additive gas effects

The additive gas candidates which are appropriate to be filled in the cask with helium were singled out. N_2, CO_2, and inert gases (Ne, Ar, Kr, Xe) were selected because of those low chemical reactivity. The preliminary analysis was performed to verify the possibility of the enhancement of heat transfer performance. For the preliminary-analysis, the figure of merit (FOM) was derived to effectively compare the thermal performance enhancement effect between different conditions.

The derivation of FOM firstly started from the convective heat transfer correlation in a laminar regime for natural convection [1].

$$Nu_L = 0.42 Ra_L^{1/4} Pr^{0.012} \left(\frac{H}{L}\right)^{-0.3} \quad (1)$$
$$(10<H/L<40,\ 1<Pr<2\times10^4,\ 10^4 < Ra < 10^7)$$

Eq. (1) is rewritten by using the definitions of non-dimensional parameters and new correlation (Eq. (2)) only include the four properties of the fluid.

$$h \sim \rho^{0.5} k^{0.738}\, \mu^{-0.238} C_p^{0.262} \quad (2)$$

Finally, the FOM was defined as the ratio of the heat transfer coefficient to compare the thermal performance of the binary mixture case to pure helium case (Eq. (3)).

$$\frac{h_{mix}}{h_{He}} = \left(\frac{\rho_{mix}}{\rho_{He}}\right)^{0.5} \left(\frac{k_{mix}}{k_{He}}\right)^{0.738} \left(\frac{\mu_{mix}}{\mu_{He}}\right)^{-0.238} \left(\frac{C_{p,mix}}{C_{p,He}}\right)^{0.262} \quad (3)$$

From the formula, it can be known that the change of the thermal conductivity and the density will show the largest sensitivity to thermal performance.

Using the FOM, the change of the heat transfer performance of binary gaseous according to the type and mass fraction of the additional gases was confirmed, which was displayed in Fig. 3. Among the gas candidates, xenon and krypton showed the most remarkable improvement in performance. Therefore, those were chosen as final candidates.

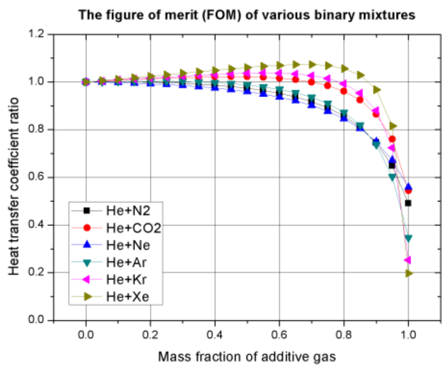

Fig. 1. The change of thermal performance according to the type and mass fraction of additive gases

3. Description of TN24P cask model

In this study, the TN24P model from the previous study was used [4]. Yoo et al.(2010) developed the TN24P model and validated through sensitivity studies. Generally, the porous medium and effective conductivity concept are used to model the fuel assemblies in the dry cask. In the previous study, assemblies were explicitly modeled to get detailed understanding on heat transfer and flow characteristics inside the cask. The reliability of the model was verified through the comparison with the previous numerical and experimental study by Creer et al.(1987) [3]. The models and parameters of the TN24P cask in this study refer to the previous study except material properties [4].

3.1 TN24P model

The TN24P dry cask is a one-piece cylindrical forged steel body for structural integrity and gamma shielding, which is surrounded by a resin layer for neutron shielding. Additionally the body is surrounded by a smooth steel outer shell. A schematic diagram of the TN24P model is shown in Fig. 2. The overall length and the diameter of the body is 5060mm and 2281mm, respectively. The cylinder contains baskets, which are composed of 24 interlocking rectangular borated aluminum made plates. Surry spent fuel assemblies, which have the specification of standard Westinghouse 15×15 assembly design were loaded in the baskets. Among the 225 rods, 20 guide tubes for the control rods and poison rods, and 1 instrument tube are included and the rests are fuel rods. Each of the 24 assemblies emits a different amount of decay heat from 832W to 919W with an average of 860W. The total decay heat in the TN24P cask is 20.6kW. The diameter of the inner cavity is 1455mm and 4150mm height. The thermal hydraulic tests were conducted using three different backfill gases (He, N_2, vacuum) and two different orientations (horizontal, vertical). Among those tests, the test with helium and vertical orientation was selected for the numerical model [2-4].

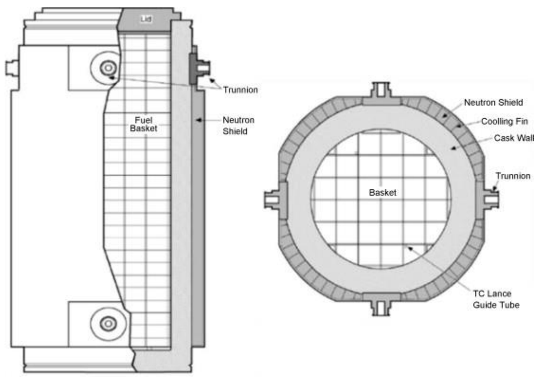

Fig. 2. Overall schematic of TN24P cask model [4]

3.2 CFD Model for the full-scale TN24P cask

3.2.1 Geometry

The full-scale TN24P CFD model was developed and validated using data from the previous study [3]. The grid was generated by GAMBIT software, which is shown in Fig. 3. Assuming symmetric condition, the TN24P model was simulated by its 1/8 section. Two entire assemblies and two half-size assemblies were included. Those are surrounded by an aluminum basket and helium is filled inside. The interior part of the canister was modeled [4].

3.2.2 Numerical models

Numerical models were determined through sensitivity studies. Small model was developed to reduce computational cost for the sensitivity studies. The small model includes the basic components of the metal cask and the geometry was simplified. For the conservative analyses, the heat flux of the small model was adjusted to have a higher PCT and a similar temperature the gradient to real TN-24P cask. Flow regime inside cask was modeled as a laminar flow regime. A SIMPLE method was used for pressure-velocity coupling. In order to simulate the buoyancy-driven flow, pressure scheme was set to be the body-force-weighted scheme. Round-off error was obtained with double precision and radiation was calculated with the discrete ordinates (DO) model in the 4×4 discretized angular space. The numerical models used in the simulation were organized in Table I [4].

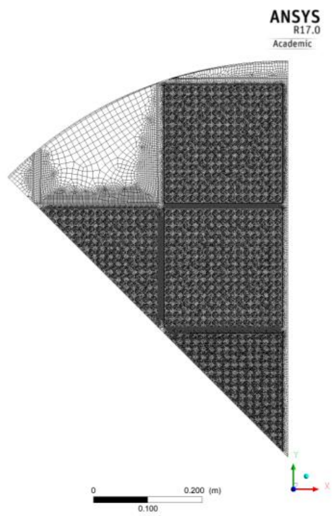

Fig. 3. Mesh generation of the TN24P cask model

Table I: Numerical models for the TN24P [4]

Physical models
Viscous model: laminar
Thermal radiation model: discrete ordinates
-Angular discretization ($\boldsymbol{N_\theta}$×$\boldsymbol{N_\emptyset}$): 4×4
-Pixelation ($\boldsymbol{N_\theta}$×$\boldsymbol{N_\emptyset}$): 3×3
Numerical method
Pressure–velocity coupling: SIMPLE
Discretization scheme
Pressure: Body Force Weighted
Momentum: second order upwind
Energy: second order upwind
Discrete ordinates: second order upwind
Round-off : Double precision

3.2.3 Boundary conditions

Previous studies used fluid properties as polynomial functions of temperature. However, the solid properties were given as constants [3-4]. In this study, properties of fluid and solid were given as polynomial functions of temperature for more explicit simulations. Emittance of the materials was obtained from the previous study [3]. Symmetry condition was applied and temperature distribution was given as a polynomial function of height on the inner wall of the canister [4].

4. Results and discussion

4.1 Pure helium filling gas

The full-scope simulation was conducted with helium backfilled at 1.5atm. In order to acquire converged results, residuals of the continuity and momentum equation were set as 10^{-3}. The residuals of the energy and discrete ordinate intensity were set as 10^{-6}.

The peak cladding temperature (PCT) of the cask was calculated to be 211°C and the position was located slightly higher than the central part of the fuel assemblies because of a low mass flow rate of the helium. Fuel assembly which is closest to the center showed the highest temperature distribution.

The portion of the radiation heat transfer for the total heat transfer was shown to be 23.8%, which is close to a quarter. It can be said that the radiation heat transfer is also an important heat transfer mechanism in the dry cask.

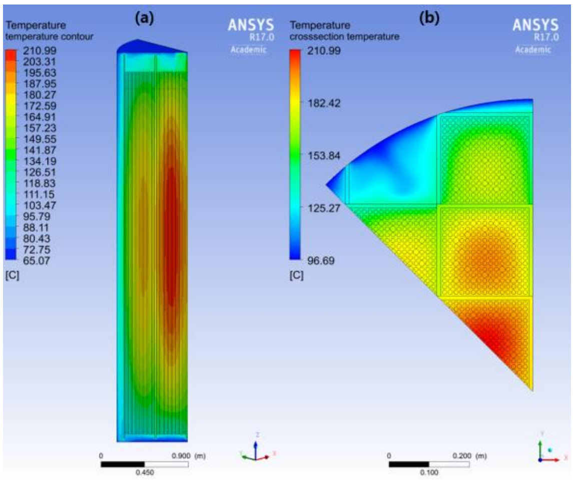

Fig. 4. (a) Overall temperature distribution (b) Cross-sectional temperature distribution at the height of PCT

4.2 Binary gas

At the 1.5atm pressure condition, the PCT increased as the mass fraction of additive gases (xenon or krypton) increase and the enhancement in heat transfer performance wasn't shown, which is demonstrated by Fig.5. As heavier gases are added to helium, generally conductivity decreases and density increases. The increase in density has a positive effect on convective heat transfer. The intensified convection induced by the increased density is shown by the elevation of the height of the PCT displayed in Fig. 6. However, the decrease in conductivity has a negative effect on conductive and convective heat transfer. Therefore, it can be concluded that the effect of the decrease in conductive heat transfer overwhelms the effect of the increase in convective heat transfer. To overcome the decrease in conductive heat transfer, binary gas simulations at higher pressure conditions were performed.

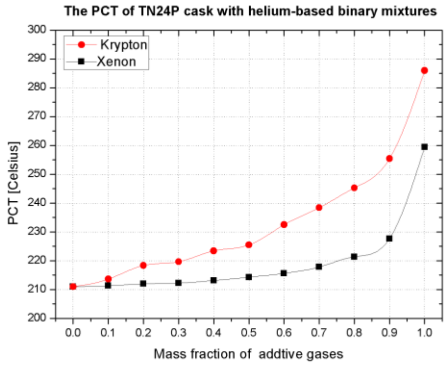

Fig. 5. The PCT variation of the TN24P cask filled with binary mixture in different compositions

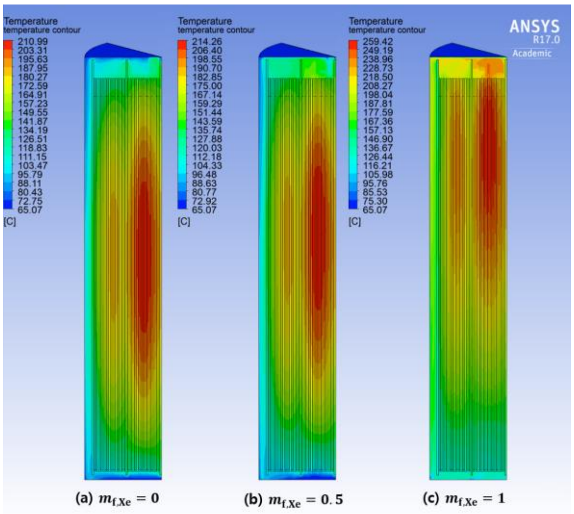

Fig. 6. The elevation of PCT with the addition of xenon to pure helium (a) $m_{f,Xe} = 0$ (b) $m_{f,Xe} = 0.5$ (c) $m_{f,Xe} = 1$

4.3 Binary gas simulation in different pressure condition

The thermal conductivity of the fluid is not sensitive to the change of pressure condition. However, the density change is almost proportional to the pressure change. Therefore, the amount of convective heat transfer is greatly affected by the pressure change. Pressure conditions from 2.5atm to 5.5atm were added and the improvement of the thermal performance was verified, which is shown in Fig. 7 and Fig. 8.

Furthermore, as the overall temperature of the cask decrease, temperature gradient becomes lower. Therefore, the ratio of radiation heat transfer decreases as illustrated in Fig. 9.

For the broad understanding of heat transfer mechanism in the cask, additional calculations with He-Xe mixtures were carried out at lower pressure conditions. When the pressure was lower than 1.5atm, the same trend was maintained with the case at 1.5atm condition . However, the decrease in convective heat transfer makes the trend more steeply. In the case of pure helium, conduction is the main heat transfer mechanism below 1.5atm. Thus, there was no significant difference. However, in the case of pure xenon, decrease in convection was critical and the remarkable increase in PCT was shown (Fig. 7).

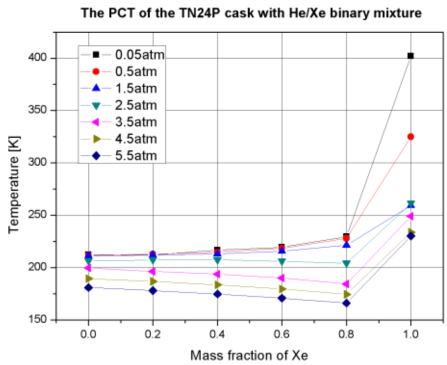

Fig. 7. The PCT of He/Xe mixtures at various pressure conditions

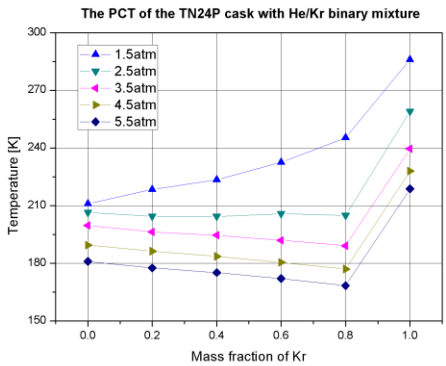

Fig. 8. The PCT of He/Kr mixtures at various pressure conditions

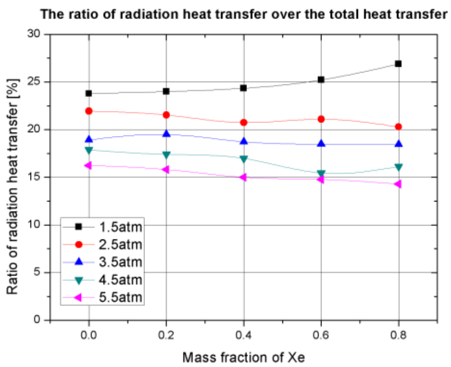

Fig 9. The ratio of radiation heat transfer over total heat transfer of He/Xe mixtures at various pressure conditions

5. Summary

The present study suggests the usage of the helium-based binary gaseous mixtures as an alternative to helium for backfill gas for the enhancement of the heat transfer performance in the dry cask system.

This study was carried out in two steps. Firstly, in order to certify the possibility and reduce calculations FOM pre-analysis was performed. The gas candidates for the additional gas were chosen. Secondly, simulations with binary mixtures in different compositions and pressure conditions were conducted.

When the pressure is less than 1.5atm, the conduction is dominant heat transfer mode. Therefore, the enhancement in convective heat transfer by adding heavier gas cannot be shown. However, when the pressure is above 1.5atm, the dominant heat transfer mechanism change from conduction to convection. The increase in convective heat transfer surpass the decrease in conductive heat transfer and total heat transfer improvement was visually shown by comparing PCT.

Consequently, the enhancement in thermal performance was verified at the pressure from 2.5atm to 5.5atm. The transition in dominant heat transfer mode can be thought of as being between 1.5atm and 2.5atm. It was found that the optimal mass fraction of the additional gas is about 0.8 for xenon and krypton.

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