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Investigation of radiative and convective heat transfer in storage vaults for improving space efficiency

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ABSTRACT

We used computational analysis in order to study the cooling effects of the cylindrical tubes located inside a storage vault for spent nuclear fuel. We considered the effects of the radiative and convective heat transfer on the cooling of the cylindrical tubes based on the non-dimensional maximum permissible surface temperature. We also identified the factors that affect the cooling of cylindrical tubes by investigating the cooling effects with the same heat source as a function of the distance between the tubes, the entrance length, and the tube arrangement. The thermal performance characteristics indicated that a non-uniform staggered tube array could be used in order to improve the storage efficiency of a vault in comparison to the reference uniform in-line tube arrangement, while maintaining the tube surface temperatures at a value below the maximum permissible temperature.

1. Introduction

At the end of 2009, spent nuclear fuel (SNF) had produced a total of approximately 24 hundred thousand metric tons of heavy metals (tHM) around the world and over 90% of that was sitting in interim storage. A total of 10,500 tHM is produced from SNF each year and 80% of that is also sitting in interim storage [1]. In the case of South Korea, the existing capacity to store SNF is reaching saturation and additional interim storage sites are required [2]. Among the various means of interim storage, this study focuses on storage vaults, as their construction costs are relatively low [3,4]. However, storage vault space must be used efficiently in order to store more SNF, because the size of storage vaults is limited. In additional, effective cooling is required, because the surface temperature of the SNF is high due to the decay heat released [5,6]. Therefore, it is necessary to analyze the thermal characteristics of the limited space available in storage vaults by taking into consideration the convective and radiative heat transfer phenomena.

Many researchers have carried out computational analyses of interim storage facilities for SNF. The cylindrical tubes inside a storage vault consist of staggered arrays that are similar in form to a heat exchanger tube tank, which has been examined in many studies. Robinson et al. [7] studied the thermal characteristics of the wet-storage method using computational analysis and verified their computational model. Lee [8] examined the thermal characteristics of cask storage, which is a dry-storage method, using computational analysis. He showed that the internal temperature change in a cask depends on the various sources of decay heat from the SNF, which decreases in value over time. He also demonstrated that the thermal characteristics inside a cask depend on whether He or N_2 is used for the cooling. Fedorovich et al. [9] developed a heat transfer model for both wet- and dry-storage methods. They established the required mathematical modeling using numerical methods and compared their heat transfer correlations with the experimental results.

The studies noted above have focused on the internal heat transfer phenomena of the casks used for the wet or dry storage of SNF. Numerous studies [10–13] have also examined the internal flow and heat transfer inside casks, but there is a limit to how readily these results can be applied to a study focused on the entire area of storage vaults. Zukauskas [14–16], a representative tube-tank researcher, showed that the heat transfer characteristics of the tube bank depend on the orientation of the in-line and staggered arrays. He developed correlations and friction factors as functions of the Reynolds (Re) and Nusselt (Nu) numbers. Khan et al. [17] conducted a parametric study of the in-line and staggered arrays. They developed Nu correlations for various Re, as well as longitudinal and transverse pitches. Many other researchers have also studied the flow and thermal characteristics of tube tanks, but none of their studies have taken radiation into consideration [18–20]. Most of these research papers have only taken the

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Nomenclature

A_{sec}	surface area of the cylindrical tube at each section shown in Fig. 2(b)
C_{ent}	dimensionless entrance length [S_L/D]
C_L	dimensionless longitudinal tube pitch [L_{ent}/D]
C_p	specific heat at constant pressure [J/kg K]
CR_n	ratio of convective to radiative heat transfer rates in Eq. (17)
D	diameter of the cylindrical tube
G_k	generation of turbulent kinetic energy
H	height of the cylindrical tube [m]
$\bar{h}$	area-weighted heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/(m K)]
L	length of the storage module in Fig. 1
Nu	Nusselt number
Pr	Prandtl number
Q	amount of heat released by the cylindrical tubes [W]
Q^*	dimensionless amount of heat released by the cylindrical tubes
Ra	Rayleigh number
S	cylindrical tube pitch
T	temperature [K]
u_i	velocity component in the i-direction [m/s]
x_i	Cartesian coordinate

Greek symbols

μ	dynamic viscosity [N/m^2 s]
ρ	density [kg/m^3]
θ^*	dimensionless temperature in Fig. 3
θ_{allow}	emissivity

Subscripts

comb	combined
ent	entrance
eff	effective
in	storage vault inlet
L	longitudinal
max	maximum
out	storage vault outlet
ref	reference model
T	transverse
t	turbulent
∞	ambient

forced convection into consideration and have ignored the radiative heat transfer. The cylinder tubes in which SNF is stored are cooled by natural convection. However, as the surface temperature is greater than 160 °C, the radiative heat transfer cannot be ignored.

In this study, we took the natural convection and radiative heat transfer into consideration in order to analyze the dependence of the thermal characteristics within a storage vault on the amount of heating. For this purpose, we increased the heat sources within the same storage vault and identified the resulting impact on the process of cooling the cylindrical tubes due to the convective and radiative heat transfer. We also examined the effects of the distance between the cylindrical tubes (C_L), the distance between the inlet tube and the inner wall of the cylinder (C_{ent}), and the arrangement of the cylindrical tubes. We proposed a method to store more SNF by increasing the storage efficiency inside the vault.

2. Mathematical modeling and validation

Fig. 1 provides a schematic diagram of a storage vault. The storage vault has an entrance and exit. Galleries are installed at the

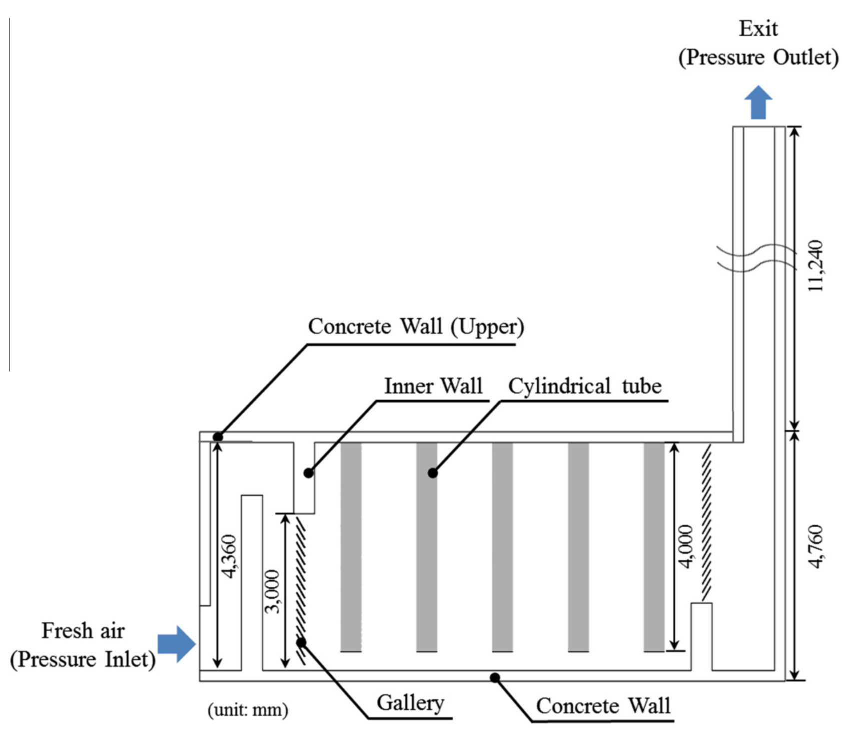

Fig. 1. Schematic diagram of a storage vault.