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<Technical Note>

NATURAL CONVECTION HEAT TRANSFER CHARACTERISTICS IN A CANISTER WITH HORIZONTAL INSTALLATION OF DUAL PURPOSE CASK FOR SPENT NUCLEAR FUEL

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A full-sized model for the horizontally oriented metal cask containing 21 spent fuel assemblies has been considered to evaluate the internal natural convection behavior within a dry shield canister (DSC) filled with helium as a working fluid. A variety of two-dimensional CFD numerical investigations using a turbulent model have been performed to evaluate the heat transfer characteristics and the velocity distribution of natural convection inside the canister. The present numerical solutions for a range of Rayleigh number values (3×10^6~3×10^7) and a working fluid of air are further validated by comparing with the experimental data from previous work, and they agreed well with the experimental results.

The predicted temperature field has indicated that the peak temperature is located in the second basket from the top along the vertical center line by effects of the natural convection. As the Rayleigh number increases, the convective heat transfer is dominant and the heat transfer due to the local circulation becomes stronger. The heat transfer characteristics show that the Nusselt numbers corresponding to $1.5\times10^6 < Ra < 1.0\times10^7$ are proportional to 0.5 power of the Rayleigh number, while the Nusselt numbers for $1.0\times10^7 < Ra < 8.0\times10^7$ are proportional to 0.27 power of the Rayleigh number. These results agreed well with the trends of the experimental data for $Ra>1.0\times10^7$.

KEYWORDS : Natural Convection, Rayleigh Number, Nusselt Number, Heat Transfer Coefficient, Dry Storage Canister, Spent Fuel Assemblies

1. INTRODUCTION

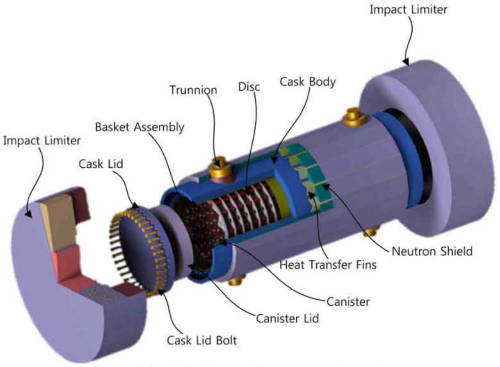
A large increase in the number of casks for transport and/or storage of spent nuclear fuel is predicted in the future. The principal demand for storage or dual purpose (transport /storage) casks for interim storage of spent nuclear fuel prior to reprocess or permanent disposal is expected to be increased. The demand for an increase of interim storage is expected for both on-site and off-site storage facilities. Dedicated transport casks can also be used to transport fuels from spent fuel pools in the nuclear power plants to off-site interim storage, reprocessing, and final disposal sites.

For the purpose of interim storage, a dual purpose metal cask containing 21 spent fuel assemblies is under development by Korea Radioactive Waste Management Corporation (KRMC) in Korea. The major components of this cask consist of a main body made of carbon steel, a stainless steel dry shielded canister (DSC) and stainless steel baskets to contain the spent fuel assemblies as shown in Fig. 1.

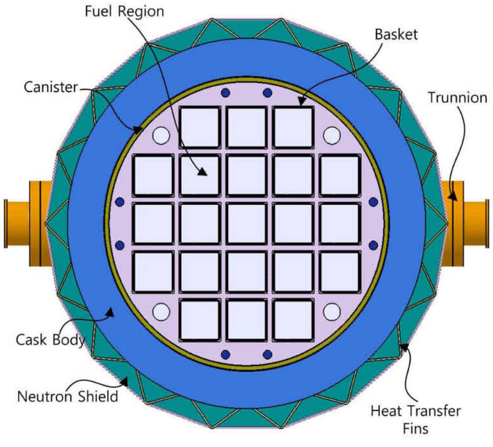
Since this dual purpose cask is used for transport and storage of the spent fuel assemblies, it essentially will be faced with the transport process, including installation on the transport vehicle. During this process, the decay heat generated in the metal cask is removed by conduction, convection and radiation heat transfer. It is well known that the natural convection heat transfer by buoyance driven helium flow within the canister of the cask is a significant heat transfer mechanism when the cask is transported in a horizontal orientation. Special attention is therefore paid to natural convection heat transfer inside the DSC.

A large number of studies on natural convection heat transfer have been performed for simple geometries, both experimentally and numerically.

A good example of the early studies on concentric and eccentric annuli can be found in the papers of Kuehn and Goldstein, in which they employed air and water inside an enclosure formed by two copper-made concentric horizontal cylinders for the experimental procedure and used a finite difference method for the numerical counterpart [1, 2]. The Rayleigh number, based on the gap width, ranged from 2.11×10^4 to 9.76×10^5 and the authors found the fluid to behave in an unsteady pattern for Rayleigh number values higher than 1.0×10^5 [1]. They also presented heat transfer results of the concentric geometry for Rayleigh numbers from 2.2×10^2 to 7.7×10^7 which includes regions of conduction, laminar convection, and partially turbulent convection. Their results showed that the Rayleigh number based on the gap-width was about 10^6 for the turbulence transition. The annulus internal flow was characterized by a turbulent upward moving plum above the inner cylinder and a turbulent downward flow against the outer wall for Rayleigh number higher than the transition value [2]. Macleod and Bishop also performed experimental work and presented several measurements of overall heat transfer rates and profiles of the time-averaged and fluctuations of the temperature field for fully turbulent natural convection [3]. Furthermore, they presented an empirical equation which correlates the heat transfer data that takes into account the Rayleigh number in the range of 2.2×10^2 to 7.7×10^7. Their results indicated that the expansion number ($\beta\Delta T$) should be taken into account, regardless of the Rayleigh number, when predicting the heat transfer rates [3]. The work by Char and Hsu, on turbulence modeling of natural convection in cylindrical horizontal annuli, proposed a comparison of the different turbulence models, suggesting a better modeling practice [4].



(a) Outline of the metal cask



(b) Cross-sectional view of the metal cask

Fig. 1. Dual Purpose Metal Cask Arrangement

Some studies on natural convection heat transfer in an enclosure with more complicated geometry, such as enclosed horizontal rod bundles, have been reported.

Canaan and Klein presented that natural convection heat transfer was experimentally investigated in an enclosed horizontal rod bundle, which characterizes a spent fuel assembly during the transport and some dry storage scenarios. The convective heat transfer correlations had been modified for radiation heat transfer using a numerical technique. They also suggested the conduction and convection regimes, distinguished by a critical Rayleigh number and the convection flow regime was turbulent flow condition [5]. Keyhani and Luo numerically investigated natural convection heat transfer in enclosed horizontal 4×4 arrays of heated rods with constant heat flux dissipation. The results indicated the enclosure Nusselt number increased as the order of the array N was increased from 3 to 9 and the reported correlations could be readily used to estimate the maximum temperatures in the arrays with the order from 3 to 9 [6].

However, most studies were focused on the natural convection within the spent fuel assemblies. Only a few studies have been performed on the natural convection heat transfer in an enclosure with many inner rectangular tubes such as DSC in a spent fuel transport cask.

Nishimura et al. conducted a heat transfer and flow visualization experiment on a one-fifth scale model to simulate a DSC with 24 PWR spent fuel assemblies, then the results of the thermal and fluid flow analysis were compared with the measurements. Their results indicated that the overall heat transfer coefficients were proportional to about a 0.27 power of the Rayleigh number when air is used as a working fluid [7]. Xie et al. performed a numerical investigation on natural convection heat transfer in a horizontally oriented dry storage system to store 24 spent fuel assemblies. The numerical predictions using commercial CFD codes were compared with the experimental data and heat transfer correlations were presented on three regimes of Rayleigh number [8].

The above-mentioned work was conducted for a scale model of actual dry storage containing 24 fuel assemblies with air as working fluid. However, the results of natural convection heat transfer for a scale model has not been compared with the actual dry storage using a numerical approach or other methods.

In our study, a full-sized metal cask model containing 21 spent fuel assemblies is considered as the numerical model to evaluate the internal natural convection behavior