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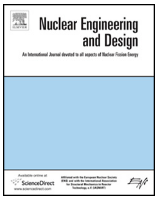

Scaling method for storage vaults based on thermal-hydraulic characteristics

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HIGHLIGHTS

- This study investigated thermal-hydraulic characteristics of storage vault.
- The relationship between heat flux and geometrical length is suggested to analyze scaling analysis.
- The thermal characteristics of the original and scaled storage vaults were in good agreement.
- The simulated results are a good agreement with experimental data.

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ABSTRACT

In this study, natural convection cooling phenomena in storage vaults for spent nuclear fuel were examined. The results revealed a relationship between the geometric length and heat flux of spent fuel cylinders. Such a correlation would be useful in dimensionally scaled storage vaults for experimental investigations of thermal and fluid flow properties. The relationship was applied to five scaled storage vaults, and the resulting thermal and fluid flow characteristics were investigated and compared with those of a full-scale storage vault. The thermal characteristics of the original and scaled storage vaults were in good agreement. The dimensionless temperature, dimensionless resident time, Euler number, and Richardson number were used to compare the behavior of structures with different dimensions, and the obtained data were in agreement within 5.1%. A 1/4-scale storage vault was constructed using the scaling methodology, and the temperature distribution was experimentally measured. The temperature distributions of the measured and simulated structures were found to be in good agreement, demonstrating that the proposed approach is effective for designing scaled-down storage vaults for experimental analyses.

1. Introduction

Recently, the demand for nuclear power has increased in parallel with increasing energy consumption. Consequently, interest in the treatment of spent nuclear fuel has also increased. Because spent nuclear fuel is radioactive, cooling is required to prevent the spent fuel from reaching high temperatures. In this regard, safety is a primary concern. An experimental analysis of storage vaults is expensive, as they are typically very large. However, the safety of such structures may be examined through the use of dimensionally scaled storage vaults. To ensure an accurate analysis from the scaled structures, the relationship between the dimensions and heat flux from spent fuel is required.

There have been a number of reports on the scaling of natural convection for the interim storage of spent nuclear fuel. Ishii and Kataoka (1982, 1984) reported scaling criteria for a natural circulation loop with a single-phase fluid. They assumed one-dimensional natural convection inside a loss-of-fluid test (LOFT) facility. Based on this assumption, the researchers proposed scaling criteria and conducted experiments. Because the working fluid was vaporized inside the LOFT facility, scaling criteria were proposed for a two-phase flow. Kocamustafaogullari and Ishii (1983) reported scaling criteria when considering both natural convection and forced convection, as the flow inside a nuclear reactor is affected by both phenomena. In another study by Kocamustafaogullari and Ishii (1987), a scaling method for internal flow in the cask was suggested by changing the pressure and working fluid.

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Most reports of spent nuclear fuel storage have focused on the type of cask (Ishii et al., 1993; Wataru et al., 2008; Yoo et al., 2010a, 2010b; Yoo, 2011; Hattori et al., 1999). In contrast, we examined the thermal and fluid flow behavior of the storage vault. Some researchers have examined the effect of the type of storage vault used (Sakamoto et al., 2000), and the flow patterns inside a 1/5-scaled vault have been investigated as a function of the Richardson number, *Ri*. However, the number of cylindrical tubes in the 1/5-scaled storage vault differed from that in the original storage vault. If the number of tubes changes, the geometry of the storage vault also changes and with it, the flow patterns and temperature distribution of the storage vault. Therefore, the inner configuration of a scaled-down storage vault must remain similar to that of the original structure to allow for an accurate analysis of the coupled thermal–fluid flow characteristics.

Here, we describe a scaling method that retains thermal and fluid flow characteristics that are similar to those of the original storage vault in terms of the heat flux and geometric length. The thermal and fluid flow characteristics of the original storage vault were first analyzed, and the proposed scaling method was applied to five differently scaled storage vaults using computer simulations. The dimensionless maximum temperature, Richardson number, Euler number, and dimensionless resident time of the scaled storage vaults were compared with those of the original storage vault. After the similarity of the fluid flow patterns and temperature distributions was established, a 1/4-scale storage vault was constructed, and the simulated and measured data were compared.

2. Storage vault geometry and scaling method

2.1. Description of the numerical model

Fig. 1(a) shows a side view of the storage vault. Air flow must pass through a gallery, which is angled to prevent gamma radiation from escaping. The cylindrical tubes or casks containing the spent nuclear fuel are stored by suspending them from the ceiling. As the spent nuclear fuel is radioactive, the tubes constantly release heat energy. For this reason, the working fluid around the cylindrical tubes is heated and subsequently rises due to buoyancy. These convection currents cause air to exit through the chimney, to be replaced by fresh air entering the storage vault. Fig. 1(b) shows the top view of the storage vault. Twenty-two tubes are displayed inside the storage module, which includes the inlet and outlet galleries.

The following assumptions of the thermal and fluid flow behavior of the storage vault were made:

1. The flow inside the storage vault is steady, three-dimensional, incompressible turbulent flow.
2. The properties of the working fluid (i.e., air) are independent of temperature, except for the density.
3. The density of the air is calculated from the ideal gas law (i.e., the working fluid is an ideal gas).
4. The rate of heat release from the cylinders is uniform across the surface and is constant with time.

Radiation heat transfer from the surface of the cylinders was also included, as the temperature of the cylinders will be high. The discrete transfer radiation model (DTRM) was employed here, and the governing equations are as follows (Ansys, 2009; Patankar, 1980; Carvalho et al., 1991; Bianco et al., 2010; Shah, 1979). For continuity we have:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0, \tag{1}$$

where ρ is density and u_i is the velocity in index form. For momentum we have:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left((\mu + \mu_t)\frac{\partial u_i}{\partial x_j}\right) + \rho f_i, \tag{2}$$

where u_j is the velocity in index form, p is the static pressure, μ is the dynamic viscosity, μ_t is the turbulent viscosity, and f_j is the body force in index form. For the turbulent kinetic energy we have the following:

$$\frac{\partial}{\partial x_j}(\rho u_j k) = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + G_k - \rho\varepsilon, \tag{3}$$

where k is the thermal conductivity, G_k is the turbulent viscosity, and ε is the dissipation rate of the turbulent kinetic energy. For turbulent energy dissipation, we have:

$$\frac{\partial}{\partial x_j}(\rho u_j \varepsilon) = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right) + C_1 G_k \frac{\varepsilon}{k} - C_2 \rho \frac{\varepsilon^2}{k}, \tag{4}$$

For conservation of energy, we have:

$$\frac{\partial}{\partial x_j}(\rho c_p u_j T) = k_{eff}\frac{\partial^2 T}{\partial x_j^2} + (\tau_{ij})_{eff}\frac{\partial u_i}{\partial x_j} \tag{5}$$

where T is temperature, k_{eff} is the effective thermal conductivity, τ_{ij} is the stress tensor, and

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \tag{6}$$

$$G_k = 2\mu_t S_{ij} S_{ij} = \mu_t\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)\frac{\partial u_i}{\partial x_j}, \tag{7}$$

$$\sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3, \quad C_1 = 1.44, \quad C_2 = 1.92, \quad C_\mu = 0.09, \tag{8}$$

$$(\tau_{ij})_{eff} = \mu_{eff}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) - \frac{2}{3}\mu_{eff}\frac{\partial u_i}{\partial x_i}\delta_{ij}, \tag{9}$$

and

$$k_{eff} = k_f + \frac{C_p \mu_t}{Pr_t}, \quad \mu_{eff} = \mu + \frac{\mu_t}{0.9}, \tag{10}$$

where μ_{eff} is the effective dynamic viscosity. Since the exterior concrete walls surrounding the storage vault are exposed to air, the heat transfer coefficient calculated from the natural convection correlation reported in reference Cengel (2002) was applied to the exterior walls (Cengel, 2002).

Based on assumption (4), the heat flux at the surface of the spent fuel tubes is as follows:

$$q'' = \frac{H}{A_{\text{tube}}}, \tag{11}$$

where H is the total heat released from each tube, and A_{tube} is the surface area of each tube, expressed as

$$A_{\text{tube}} = \pi r^2 + 2\pi r L_h, \tag{12}$$

where r and L_h are the radius and length of each tube, respectively.

2.2. Scaling methodology

As shown in Fig. 1, spent nuclear fuel is stored in the tubes, which are located inside the storage vault. If the tubes are not effectively cooled, the surface temperature will increase and degradation of cladding may occur. Such degradation is a significant safety issue (Burn et al., 2001) and thus, effective cooling is of utmost importance. For these reasons, regulations in both the US and Japan require that the surface temperature of the tubes should not exceed