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CFD Analysis of Natural Convection on the Outer Surface of the Containment of APWR Model

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ABSTRACT

To improve the safety of nuclear power plants, a modern NPP such as Advance Pressurize Water Reactor (APWR) is equipped with a safety feature called PCCS (Passive Containment Cooling System), where naturally circulating air cools the outer surface of the containment which is used to remove decay heat released inside the containment vessel. The decay heat from the reactor core will be transferred out through the conduction mechanism and the natural convection mechanism on the outer surface of the containment vessel. Then, the hot air that forms in the gap between the containment and its baffles will rose through the chimney located at the top of the concrete building and cold air will enter through the inlet to create a natural circulation cycle. To obtain the effectiveness of the use of baffles, as a comparison, it is necessary to analyze the natural convection heat transfer on the outer surface of a containment vessel that is not equipped with a baffle. In this research, CFD analysis of natural convection on the outer surface of the containment of APWR reactor model has been done. Based on the model developed, the analysis was done to get temperature and convection heat transfer coefficient in the air flow on the containment surface. Heat flux in the containment surface varied from 500 W/m^2 to 2.000 W/m^2 with an increase of 500 W/m^2 intervals. Based on the analysis results, the correlation equations are also proposed in this paper, namely the correlation of natural convection heat transfer for laminar regime on a vertical cylindrical with the heat flux constant in the form $Nu_q = a(Ra_q)^b$.

Keywords:
Computational fluid dynamic analysis; convection heat transfer coefficient; natural convection; passive containment cooling system

1. Introduction

A modern nuclear power plants such as the Advance Pressurize Water Reactor (APWR) or generation III+ reactor is equipped with a passive safety system that do not rely on equipment, in addition to the active safety systems [1]. One of the passive safety systems available on nuclear

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power plant reactor such as the AP-1000 reactor is the passive containment cooling system (PCCS), where naturally circulating air cools the outer surface of the containment which is used to remove decay heat released inside the containment vessel [2-13]. In the PCCS, as shown in Figure 1, the decay heat from the reactor core will be transferred to the outside of the containment vessel by the conduction mechanism through the containment wall and the natural convection mechanism on the outer surface of the containment vessel [10]. Then, the hot air that forms in the gap between the containment vessel and its baffles will rose through the chimney located at the top of the concrete building and cold air will enter through the inlet to create a natural circulation cycle. The existence of the baffle on the outer side of the containment will improve the air circulation. If the rate of heat on the containment walls are still increasing, and cooling air by natural convection heat transfer is no longer effective, the wall temperature will increase further. In these conditions cooling the containment wall will be assisted by water sprayed from the top of the containment.

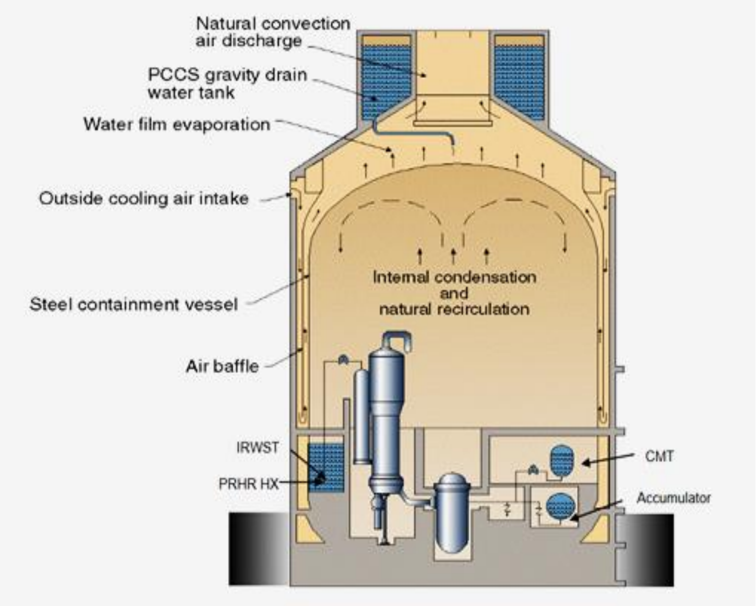


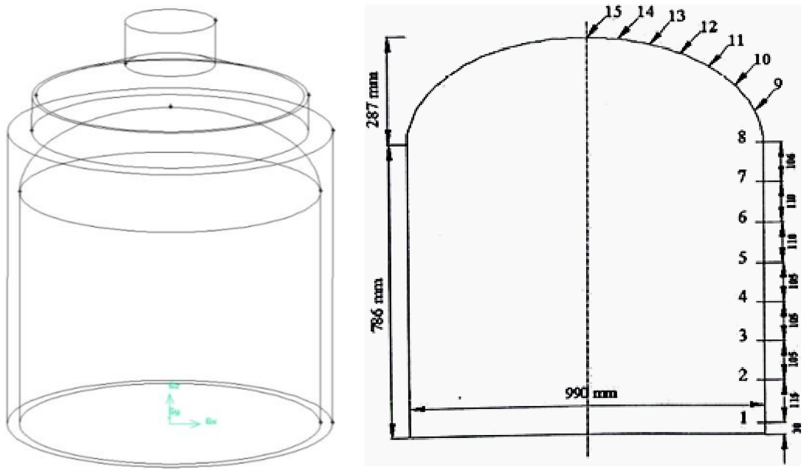
Fig. 1. Passive Containment Cooling System on AP-1000 reactor [10]

In previous studies, preliminary research related to natural convection heat transfer between the containment and its baffle has been carried out, both numerically and experimentally [14,15]. To obtain the effectiveness of the use of baffles, as a comparison, it is necessary to analyze the natural convection heat transfer on the outer surface of a containment vessel that is not equipped with a baffle. One method that can be used in this analysis is computational fluid dynamics [16-26]. Heat, mass, and momentum balance equations are solved with the help of numerical analysis [18,23]. CFD is a powerful technique for study of the complex flow and compared to the experiment, results from CFD can be often obtained in a shorter time and at a lower cost [19,22]. In this research, CFD analysis of natural convection on the outer surface of the containment of AP-1000 reactor model has been done. Based on the model developed, the analysis was done to get temperature distribution and convection heat transfer coefficient in the air flow on the containment surface.

2. Methodology

2.1 Numerical Methods

The size and geometry of the vertical cylinder and an ellipsoidal that used in the current study specifically replicates the size of the containment of AP1000. The containment model was made from stainless steel with dimension of 1/40 of the original AP1000's containment. A sketch of the containment model that used in this study and the position of the surface temperature measurement are shown in Figure 2. The simulation study of this research analyzes the heat transfer in the surface of containment by using a CFD software package (FLUENT). The computational domain covered by the CFD analysis consists of volume between the reactor building and the containment vessel model that filled with the air.



(a) (b)

Fig. 2. (a) Sketch of the containment model and (b) the location of the surface measured temperature

2.2 Boundary and Initial Condition

The heat fluxes on the vertical cylinder and ellipsoidal surface are assumed to be constant and uniform, and the surface of the reactor building components is assumed to be adiabatic. Several other important assumptions are considered in this study, they are

i. The simulation has reached its steady operating condition.
ii. Since the top of containment model is opened to the atmosphere, therefore the pressure at the inlet surface is constant at 1 bar, while pressures at other locations are their hydrostatic pressures.
iii. The air inlet enters the test section at room temperature of 300 K.
iv. The initial velocity of air is 0 m/s.
v. The gravity is 9.8 m/s^2.
vi. Physical properties of air follow its temperature and obtained from Kreith *et al.,* [27] and Holman [28].

2.3 Governing Equations

Governing equations that are utilized in the theoretical study follow the governing equations that are implemented in the CFD. Basically, the equations consist of continuity equation, momentum equation and energy equations [29,30]. These equations can be expressed as following [23]:

Continuity Equation: The continuity equation, or equation for conservation of mass, can be written in the tensor notation as follows:

$$\nabla(\rho\vec{v}) = 0 \tag{1}$$

where, ρ is air mass density and $\vec{v}$ is velocity vector.

Momentum Equation: Conservation of momentum is described by the following equation:

$$\nabla(\rho\vec{v}\ \vec{v}) = -\nabla p + \nabla.\vec{\vec{\tau}} + \rho\vec{g} \tag{2}$$

where, p is the static pressure, $\vec{\vec{\tau}}$ is the stress tensor (described below), and $\rho\vec{g}$ is thegravitational body force. The stress tensor can be expressed as following:

$$\vec{\vec{\tau}} = -\mu((\nabla\vec{v} + \nabla v^T) - \frac{2}{3}\nabla.\vec{v}I) \tag{3}$$

where, μ is the molecular viscosity, *I* is the unit tensor, and the second term on the right hand side Eq. (3) represents the effect of volume dilation.

Energy Equation: The energy conservation equation can be expressed in the following form:

$$\nabla.(\vec{v}\rho(h + \tfrac{1}{2}v^2)) = \nabla.(\kappa_{eff}\nabla T) \tag{4}$$

where, κ_{eff} is the effective thermal conductivity, i.e. the fluid thermal conductivity combined with the turbulence thermal conductivity, κ_t, defined according to the turbulence model being used, and *T* is temperature of the air.

2.4 Parameter of Natural Convective Heat Transfer

The empirical equation for the correlation of natural convection heat transfer, in the form of a Nusselt number (Nu_q) as a function of the modified Rayleigh number (Ra_q) is given in Eq. (5), with x is position measured from the upstream end of the vertical cylinder, while a, b, and c are constants that would be empirically determined from the simulation data [23,31-33].

$$Nu_q = a\left(Ra_q\right)^b \tag{5}$$

The Nusselt number is defined by the following equation,

$$Nu_q = \frac{q^{"}x}{k\,(T_s - T_\infty)} \tag{6}$$

The modified Rayleigh number in Eq. (5) is defined by the following equation,

$$Ra_q = \frac{g\rho\beta\, C_p q^{"} x^4}{k^2 \upsilon} \tag{7}$$

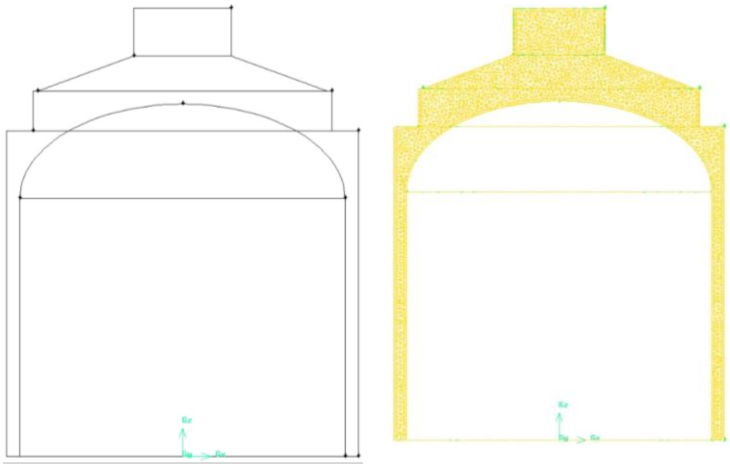
where g is gravity, ρ is density, β is coefficient of expansion, *Cp* is heat capacity, *k* is thermal conductivity, and υ is kinematic viscosity of the air near the cylinder surface. All physical and transport properties (ρ, β, *Cp,* and υ) are evaluated at the film temperature. For the laminar flow and the constant heat flux condition, the value of the modified Grashof number < 10^{11} [28,34-39].

By knowing the geometry of the containment model, all input variables and all measured temperatures, T_s and T_∞, modified Nusselt and Rayleigh numbers for all measurement location can be calculated. The relationship between Nusselt number and Rayleigh number can be determined by linear regression analysis.

2.5 Numerical Procedure

Initially, the air outside of the containment model is at rest. The wall and air are at the same uniform temperature, T = 300 K. At time t = 0, heat is supplied to the outside surface of containment model by means of heat flux imposed along the surface of containment model. It initiates a heat transfer process from the containment surface to the air outside. Heat flux in the containment surface varied from 500 W/m^2 to 2.000 W/m^2 with an increase of 500 W/m^2 intervals.

In the current calculations, the flow and heat transfer are considered three-dimensional. Code CFD-3D, a general-purpose program for simulating laminar and turbulent flows and heat transfer, is used. The schematic of the geometry and the refined mesh is shown in Figure 3 and there are 1,286,300 non-uniformly spaced meshes in the containment model.



(a) (b)

Fig. 3. The schematic of containment model geometry and refine mesh

3. Results

In the discussion of numerical simulation results, emphasis is placed on the temperature fields around the containment model to clarify the heat transfer mechanism. In the present study, the numerical calculations also focused on calculating the surface temperature of the containment model and the air temperature for different heat flux on the surface of the containment model.

3.1 Temperature Distribution

By performing simulations using CFD, it is possible to obtain the surface temperature of the vertical cylinder and the air temperature in the space between the container and its cover. Figure 4 shows the temperature contours of the containment model for a heat flux of 2000 W/m^2. The color bar in this figure shows temperature values in K. Air receives heat from vertical cylinders as it flows upward, so the higher it goes, the higher its temperature. Therefore, the surface temperature of the vertical cylinders must also be higher at higher elevations.

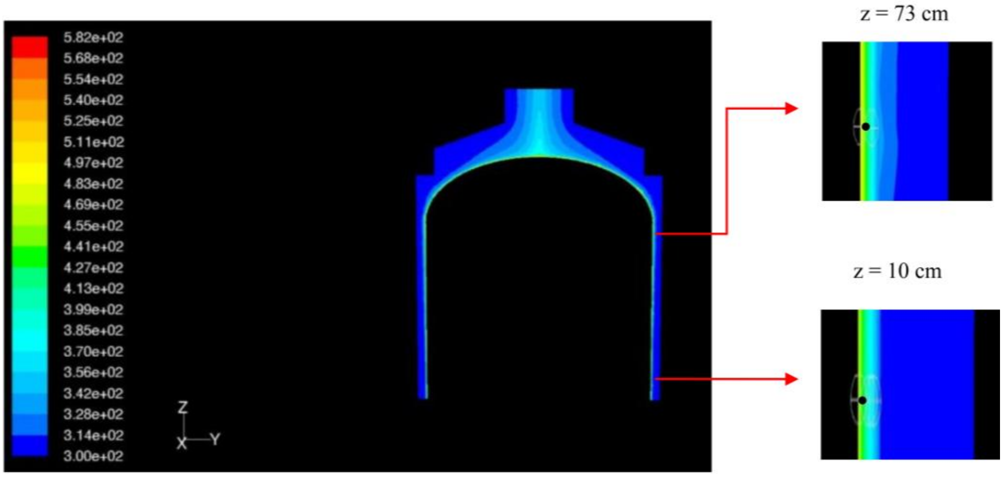


Fig. 4. Temperature contour in the containment vessel model

Figure 5 shows the influences of heat flux on the surface temperature of containment model. For the elevation range (z) > 0.415, the gradient of the surface temperature of containment increased. The result is important to be studied further because it is possible that the transition flow has occurred in the surface of the containment model.

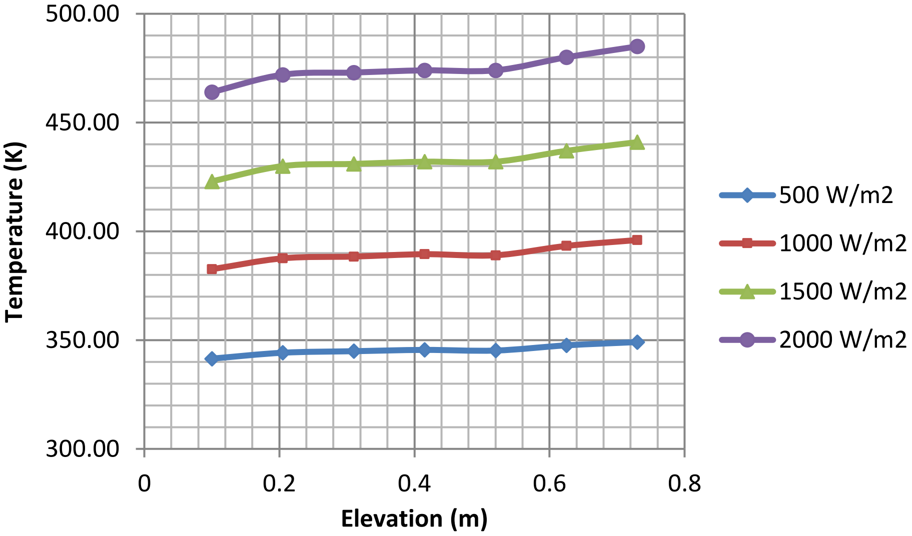


Fig. 5. The influences of heat flux on the surface temperature of containment model

Figure 6 and Figure 7 show the thermal boundary layer growth near the vertical cylinders. The thermal boundary layer is thicker at higher elevations, therefore it can also be expected that heat transfer coefficient tends to be smaller at higher elevations.

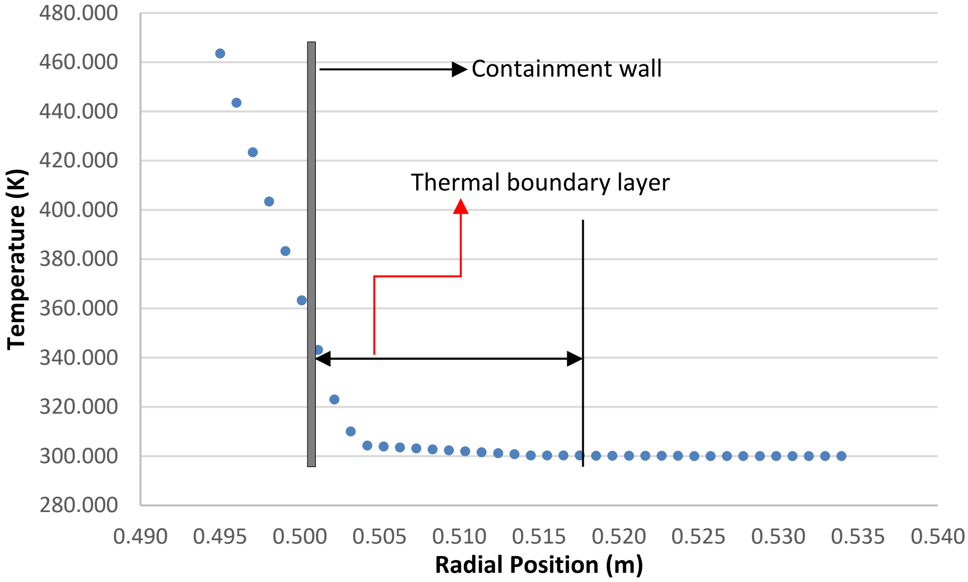


Fig. 6. Distribution of air temperature at z = 10.0 cm

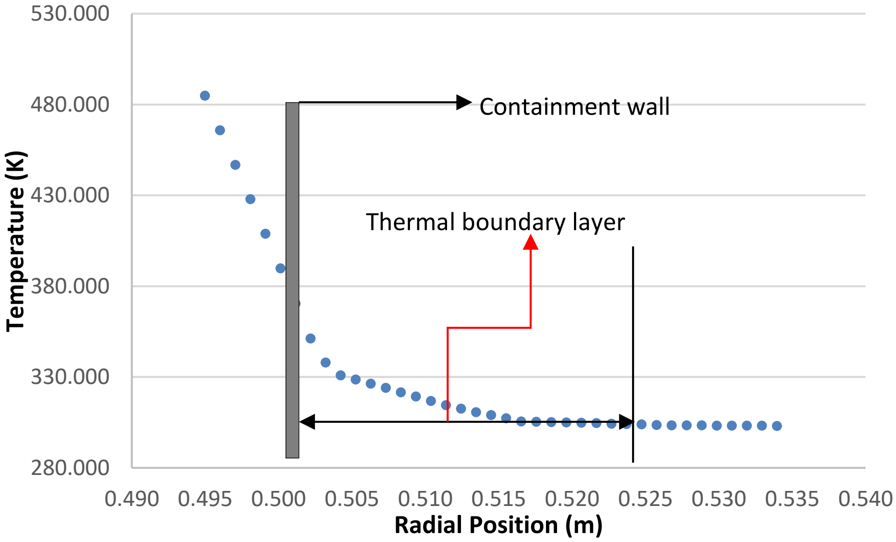


Fig. 7. Distribution of air temperature at z = 73.0 cm

3.2 Heat Transfer Coefficient

Figure 8 shows the heat transfer coefficient (h) on the laminar flow regime with a modified Grashof number range of $2 \times 10^8 \leq Gr^* \leq 8 \times 10^{10}$ or an increment range of $0 \leq z \leq 0.415$. The difference in heat transfer coefficients at various positions is still large. Thus, for laminar flow, the heat transfer coefficient used to determine the correlation is the local heat transfer coefficient. Since the temperature difference continues to increase with increasing altitude, the heat transfer coefficient also continues to decrease with increasing altitude, as shown in Figure 8. For the elevation range (z) > 0.415, it is predicted that the transition flow has occurred in the surface of the model.

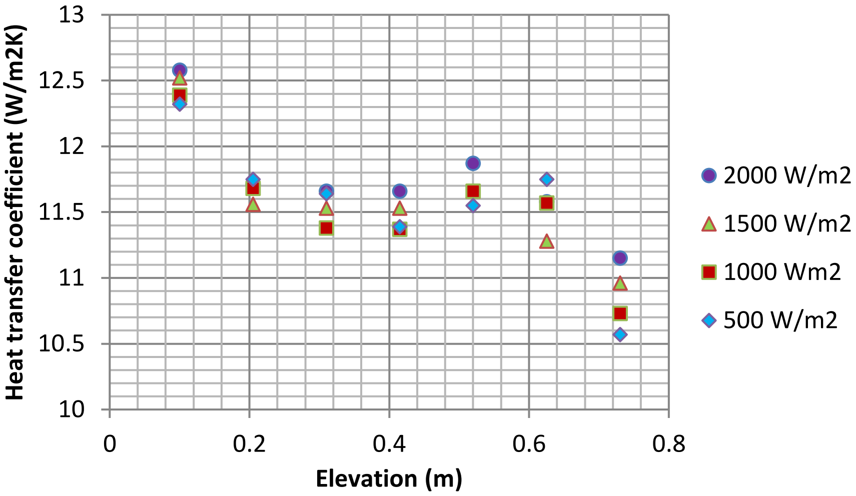


Fig. 8. Heat transfer coefficient for laminar and transition flow with variation of heat flux

3.3 Development of Natural Convective Heat Transfer Correlation

Local heat transfer coefficient on the surface of containment model can be calculated by using Eq. (8).

$$q_c = h_c A (T_{surface} - T_\infty) \tag{8}$$

Heat flux values are given as one of the simulation inputs, surface and free-stream condition temperature values at any observed height can be obtained from the CFD package. Therefore, the local heat transfer coefficient can be calculated. After calculating the local heat transfer coefficients at several elevations, the average value of the heat transfer coefficients can be numerically calculated according to the following equation:

$$\bar{h} = \frac{\int h dA_s}{\int dA_s} \approx \frac{\sum hA_i}{\sum A_i} \tag{9}$$

By using Eq. (5), Eq. (6), Eq. (7), Eq. (8) and Eq. (9), the relationship between Rayleigh number and Nusselt number can be plotted as in Figure 9.

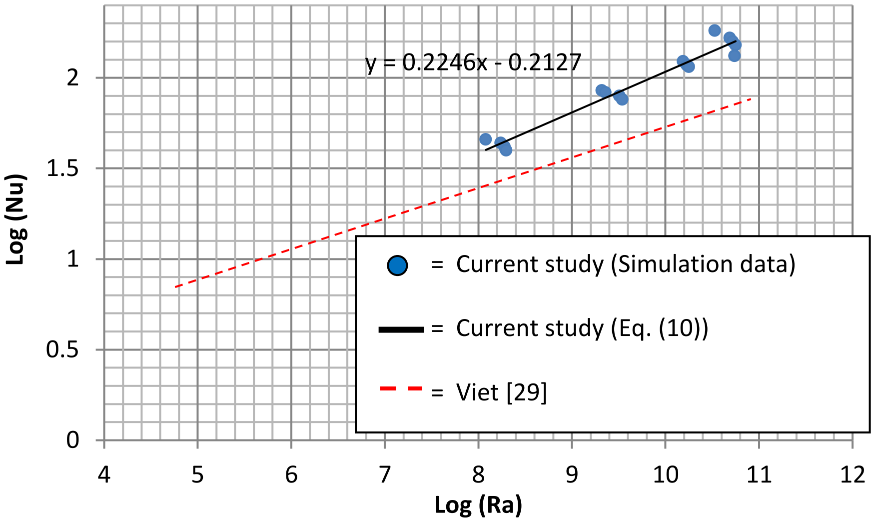


Fig. 9. A new correlation curve for natural convection in vertical cylinder

Based on the data shown in Figure 9, the correlation equation obtained from the current study can be written as

$$\text{Log}\ (Nu) = 0.224\ \text{Log}\ (Ra_q) - 0.212$$

$$Nu = 0.613\ (Ra_q)^{0.224} \qquad (10)$$

for the Rayleigh number range $1.2 \times 10^8 \leq Ra_q \leq 5.6 \times 10^{10}$ or $1.7 \times 10^8 \leq Gr_q \leq 8 \times 10^{10}$.

Figure 9 shows the new natural convection correlation curves for laminar flow regimes in a vertical cylinder using Log Nu and *Log* Ra_q data. The amount of error obtained is less than 10% with the resulting equation: $Nu = 0.613\ (Ra_q)^{0.224}$.

4. Conclusions

Based on the results obtained from the current simulation study, it can be concluded the following important are: temperature distribution around the axial and radial direction of the containment model show that the implementation of the containment model in the current study can simulate the containment vessel that exist in real nuclear power plant. The current study shows that the air flow simulated in this study is in laminar flow regime and a new natural convective heat transfer correlation for the laminar flow regime in the form of $Nu = 0.613\ (Ra_q)^{0.224}$, for the Rayleigh number range $1.2 \times 10^8 \leq \text{Ra}_\text{q} \leq 5.6 \times 10^{10}$ has been obtained from the present study.

Author Contributions

Santiko Tri Sulaksono, Rian Fitriana, Anwar Ilmar Ramadhan, Efrizon Umar, Sidik Permana, Wan Hamzah Azmi contributed equally as the main contribution of this paper.

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