Investigation of the Effective Thermal Conductivity in Containment Wall of OPR1000

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1. Introduction

In nuclear power plant, containment is the last barrier of safety and pressurization of containment can threaten its integrity in case of severe accident. Many computational codes used for analyzing pressure of containment was developed such as CAP (Containment Analysis Package). These computational codes consider concrete conductivity instead of thermal conductivity of containment wall which have special geometry as heat sink [1]. For precise analysis, effective thermal conductivity of containment wall has to be measured in individual NPPs.

Thermal properties of concrete such as thermal conductivity have been investigated as function of chemical composition and temperature. Generally, containment of OPR1000 is constructed by Prestressed (PS) concrete-a composite material. Containment wall of OPR1000 is made up of steel liner, tendon, rebar and concrete as shown in Figure 1. Role of steel liner protects release of radioactive materials so called leak tightness. The effective thermal conductivity of containment wall in OPR1000 is analyzed by numerical tool (CFD) and compared with thermal conductivity models in composite solids. These works can make analysis of pressure and temperature in containment more precisely.

Fig. 1. Geometry of containment wall in OPR1000 (Korean Standard Nuclear Power Plant)

2. Methods and Results

2.1 Thermal properties of concrete

Containment wall of OPR1000 was made for experiment of effective thermal conductivity. Two separate specimens of concrete same with concrete in experiment facility were made in 10cm x 10cm x 2cm. Average of thermal conductivity was measured in 0.7970 W/m·K. Thermal conductivity of concrete is a function of its density [2]. The thermal conductivity of concrete was used 1.6 W/m·K based on the regulation guide. Thermal conductivity of specimens is estimated on account of low density (1852 kg/m^3) than used in NPPs (2400 kg/m^3). Its lower thermal conductivity used in experiment facility is due to its density in Figure 2. The thermal conductivity of concrete was changed by its density as using following equation [2],

$$k_c = 0.0865\, e^{0.00125\rho_{con}} \quad (1)$$

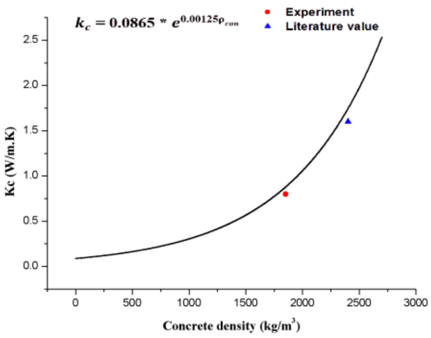

Fig. 2. Concrete thermal conductivity over density

Moreover, various concrete types are categorized by chemical compositions of concrete such as basaltic aggregate concrete (BAS), limestone common sand aggregate concrete (LCS) and limestone concrete (LS) in NPPs. Usually, the Korean nuclear power plant used Basaltic concrete similar with Younggwang unit 3 and 4 [3]. Chemical composition of concrete used in experiment was are analyzed by using XRF (X-ray Fluorescence Spectrometer). Concrete used in experiment is similar to the LCS (Limestone Common Sand) concrete in Table Ⅰ.

Table Ⅰ: Chemical compositions of concretes mostly used in NPP (wt%) [3]

Composition	Experiment	YGN 3&4	BAS	LCS	LS
SiO_2	41.26	55.70	54.84	35.80	3.60
CaO	27.50	15.80	8.82	31.30	45.40
Al_2O_3	8.02	10.30	8.32	3.60	1.60
K_2O	1.97	2.86	5.39	1.22	0.68
Na_2O	0.98	2.04	1.80	0.01	0.08
MgO / MnO /TiO_2	2.25	1.61	7.21	0.69	5.80
Fe_2O_3	4.91	2.60	6.26	1.44	1.20
Cr_2O_3	0.00	0.02	0.00	0.01	0.00
H_2O	12.92	7.23	5.86	4.70	5.94
CO_2	X	2.78	1.50	21.15	35.70
P_2O_5	0.10	-	-	-	-
Total	99.91	100.94	100	100	100

2.2 Models for effective thermal conductivity in reinforced concrete

Models have been proposed for effective thermal conductivity of composite solids. Volume fraction model consider liner plate as in steel fraction z-axis. On the other hand, Maxwell-Eucken model and Rayleigh-parallel model handle steel liner as parallel heat conductor. For analyzing various models, steel volume fraction over individual axis in CFD analysis was investigated in Table Ⅱ.

Table Ⅱ: Steel volume fraction along individual axis in CFD analysis.

Models	Φ_x	Φ_y	Φ_z	Φ
Volume fraction	0.457	0.474	0.069	0.081
Except liner	Φ_x	Φ_y	$\Phi_{z-liner}$	
Volume fraction liner	0.487	0.505	0.008	
Maxwell-Eucken liner				
Rayleigh-parallel liner				

2.2-1 Rayleigh model

Rayleigh model was used for calculating parallel cylinders embedded in composite materials in Figure 3 [4]. Thermal conductivity of cylinders embedded shape is used following equations,

$$\frac{k_{eff,zz}}{k_c} = 1 + \left(\frac{k_s - k_c}{k_c}\right)\Phi \qquad (2)$$

$$\frac{k_{eff,xx}}{k_c} = \frac{k_{eff,yy}}{k_c}$$

$$=1 + \frac{2\Phi}{C_1 - \Phi + C_2(0.30584\Phi^4 + 0.013363\Phi^8)} \qquad (3)$$

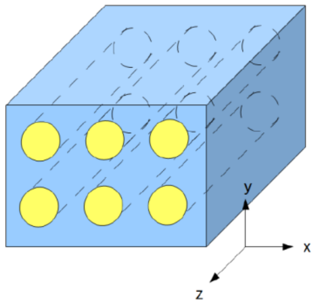

Fig. 3. Schematic of parallel cylinders embedded in composite materials [4].

This model was applied by comparing various models for effective thermal conductivity in containment wall.

2.2-2 Volume fraction model

This model assume that steel liner is uniformly mixed in z-axis. The effective thermal conductivity in volume fraction model is 2.112 W/m·K.

2.2-3 Volume fraction Liner model

Liner plate model considers conduction through steel liner. Heat transfer of containment wall is occurred through two materials. One is steel liner and the other one is concrete including tendon and rebar. Effective thermal conductivity is calculated with thermal resistance in liner plate model.

$$k_a = k_{eff,xx} * \Phi_x + k_{eff,yy} * \Phi_y + k_{eff,zz} * \Phi_{z-liner} \qquad (4)$$

$$k_{eff} = \frac{k_s * k_a(\delta + L)}{\delta k_a + L k_s} \qquad (5)$$

The effective thermal conductivity by this model is 1.893 W/m·K.

2.2-4 Maxwell-Eucken Liner model

Maxwell-Eucken Liner model assumes that rebar and tendon are mixed in concrete isotropic and macroscopically as homogenous composite solids [5]. Liner part is considered by series model individually. The effective thermal conductivity in this model is 1.965W/m·K.

2.2-5 Rayleigh-Parallel Liner model

Rayleigh-Parallel Liner model assumes heat transfer parts as liner, cylinder part and parallel three parts in containment geometry. Rayleigh model apply to cylinder part and parallel model apply to z-axis rebar part. These parts are integrated as series model. Rayleigh-Parallel Liner model equates to following equations,

$$\frac{\delta + L}{k_{eff}} = \frac{\delta}{k_s} + \frac{a}{k_R} + \frac{L - a}{k_p} \qquad (6)$$

$$k_p = k_s\Phi + k_c(1 - \Phi) \qquad (7)$$

k_R was calculated by using Rayleigh model in x–axis equation. Parallel model is used in analyzing k_p for rebar which is same direction of heat transfer. The effective thermal conductivity in this model is 1.894W/m·K.

2.3 Numerical simulation (CFD)

The finite element method (FEM) is frequently used to model heat transfer in composites as well as the effective thermal conductivity. In order to calculate effective thermal conductivity, CFD was used for analyzing a test geometry in containment wall. Unit geometry of containment wall in OPR1000 was applied in Figure 4. Heat flux is 204.4 W/m² in steel liner. The average temperature of steel liner is 417 K. Temperature distribution is distorted due to rebar and tendon inside containment wall as shown in Figure 5.

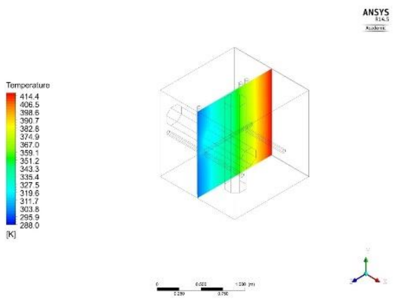

Fig. 4. CFD analysis in containment wall of OPR1000.

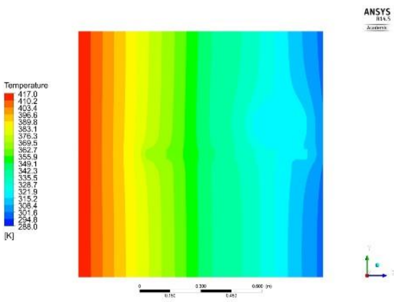

Fig. 5. Temperature distribution in constant heat flux.

The effective thermal conductivity of OPR1000 is 1.898 W/m·K in CFD analysis.

2.4 Results

Various models were compared with CFD result in Table Ⅲ. Rayleigh-Parallel liner model is most fit together with CFD results. The results of effective thermal conductivity in volume fraction model overestimate than that of other models. Other models is relatively well matched with result of CFD analysis.

Table Ⅲ: The effective thermal conductivity in various models and CFD result.

Models and CFD result	Effective thermal conductivity (W/m·K)
Volume fraction model	2.112
Volume fraction Liner model	1.893
Maxwell-Eucken Liner model	1.965
Rayleigh-Parallel Liner model	1.894
CFD result	1.898

3. Conclusions

The thermal conductivity of conventional concrete is lower than regulation value (1.6 W/m·K) because of its low density. The effective thermal conductivity of containment wall of OPR1000 is investigated by numerical analysis (CFD). The thermal conductivity of reinforced concrete is 18.6% higher than that of concrete only. Several models were compared with CFD results. Rayleigh-Parallel liner model agrees well with CFD results. Experiment results will be compared with CFD result and models. CFD result was calculated in low steel volume fraction (0.0809) than that of OPR1000 (0.1043). The effective thermal conductivity in OPR1000 has slightly higher than CFD result because of different volume fraction. Upcoming analysis of containment have to use the effective thermal conductivity in inherent geometry as heat sink. Steel liner, tendon and rebar play an important role in thermal conductivity of containment wall.

Nomenclature

k_c: Concrete thermal conductivity (W/m·K)

k_s: Steel thermal conductivity (W/m·K)

k_R: Effective thermal conductivity of cylinder parts (W/m·K)

k_p: Effective thermal conductivity of z-axis cylinder part (W/m·K)

k_a: Effective thermal conductivity without steel liner (W/m·K)

k_{eff}: Effective thermal conductivity (W/m·K)

Φ_i: i-axis steel ratio in total steel volume (i = x, y)

$\Phi_{z-liner}$: Steel ratio without steel liner in z-axis in total steel volume

Φ : Steel volume fraction in total containment volume

L : Thickness containment wall (m)

δ : Liner plate thickness (m)

a : Sum of total cylinder diameter (m)

ρ_{con}: Density of concrete (kg/m^3)

$k_{eff,ii}$: Effective thermal conductivity as steel volume leaning to i side (i = x, y, z) (W/m·K)

Acknowledgements

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REFERENCES

[1] S. J. Hong et al., "Development of CAP code for nuclear power plant containment: Lumped model", Nuclear Engineering and Design 291, 2015, 47-63

[2] Md Azree Othuman Mydin, "Effective thermal conductivity of foamcrete of different densities", Concrete Research Letters, 2011, Vol.2

[3] K. Y. Shin et al., "Thermo-physical properties and transient heat transfer of concrete at elevated temperatures", Nuclear Engineering Design, 2002

[4] Karol Pietrak et al., "A review of models for effective thermal conductivity of composite materials", Journal of Power Technologies 95(1) (2015) 14-24

[5] Daniel P. Hochstein, "Thermal Conductivity of Fiber-Reinforced Lightweight Cement Composites", Doctor of Philosophy in the Graduate School of Arts and Sciences of Columbia University, 2013