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EXPERIMENTAL INVESTIGATION ON AIR LEAKAGE CHARACTERISTICS OF CONTAINMENTS

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ABSTRACT

Facilities such as nuclear power plants have containments as atomic reactor which are subjected to high internal pressure. The internal pressure induces tensile stress in the containments. The tensile stress can cause generation and propagation of cracks through which the gas contaminated radioactively may leak. Supposing that a potential leakage accident happened, an experimental study on air leakage characteristics of containments was carried out.

Two reinforced concrete specimens which reflect a wall of the containment were manufactured. Then the specimens were subjected to tensile load to generate cracks and air penetration tests were performed. During the air leakage test, the air pressure of inlet and outlet, the flow rate of outlet and the sum of crack widths were measured. The individual factors of the specific crack shape, the wall roughness and the flow coefficient, could be estimated from these experimental data. The factors are expressed as functions in terms of the sum of crack widths by regression analysis. The measured flow rates were compared with the predictive values obtained using the regression curves. Then flow rates according to pressure gradient and crack width were estimated.

It was verified that the predicted flow rates agree with the measured flow rates statistically, that is, the estimated functions predicting the wall roughness and the flow coefficient are suitable. Once the sum of crack widths and inlet pressure of concrete wall are known, thus, the air flow rate can be predicted. The relationship among crack width, pressure and flow rate will serve as a criterion for air leakage characteristics of containments.

Keywords: air leakage test, generation and propagation of cracks, regression analysis, functions in terms of the sum of crack widths

1 INTRODUCTION

As a part of Korea Atomic Energy Research Institute (KAERI) Program, this study has been intended to predict and evaluate the leakage characteristics of containment at potential accidents. The liner is so ductile that the leakage of radioactive material would be prevented well in some duration (Cho, 2005). However, assuming that the liner might be damaged due to any reasons, the air leakage test through the cracked sections of containment wall was carried out. Rizkalla (1984) presented mathematical expression for the flow rate of pressurized air flowing through an idealized crack. During the air leakage tests, several experimental factors are measured and estimated. Using these factors and the given mathematical formula, functional expressions predicting the wall

roughness and the flow coefficient were obtained and the relationship among crack width, air pressure and flow rate was evaluated.

2 AIR LEAKAGE TESTS

To investigate flow rates through cracked concrete wall under various conditions, air leakage tests were planned. Two reinforced concrete specimens were involved in the tests. They represent strips of a concrete wall of containments and their thickness is identical with that of actual containments. The specification of specimens, test apparatus and test procedures are explained in the following sections.

2. 1 Outline of Specimen and Test Apparatus

Length, width and height of the specimen are 2,000mm, 1,200mm and 200mm, respectively. Here, the width of 1,200mm is identical with thickness of a wall of an existing containment. Design strength of concrete is 40MPa. Actual stiffness and ultimate strength obtained through material test are presented in Table 1.

Table 1 stiffness and strength of specimens

Specimen	Stiffness(GPa)	Ultimate Strength(MPa)
RC 1	22.43	32.77
RC 2	24.33	43.76

The cracks would be generated ahead on the surfaces where a loss of cross section exists. The vertical stiffeners on liner are embedded at spacing of 375 mm horizontally in an existing containment. Thus, the stiffeners were installed in the same manner, and it might be associated to create the cracks.

Air tight chamber mounted with gas inlet, outlet, and pressure gauges was manufactured. Surfaces contacting with test specimen were sealed with rubber made of urethane to provide the airproof conditions. In this experiment, nitrogen was used as pressurized air due to stability and economy.

Besides, two static hydraulic actuators and steel block were used to impose tension force on test structure. And strong block was located at the opposite side of specimen to support the specimen. Fig. 1 shows layout of the test structure and air chamber and a complete view of test setup is illustrated in Fig. 2.

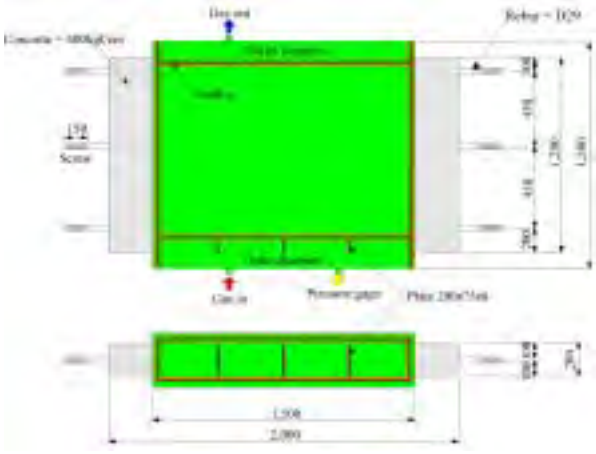


Fig. 1 layout of the test structure

Fig. 2 a complete view of test setup

2.2 Test Procedures

The test procedure can be divided into two steps. At the first step, the test specimen is subjected to tension force by drawing reinforcing bars. Therefore, cracks through the concrete specimen are generated and propagated. The cracked concrete specimen and the measuring device, calipers, are shown in Fig. 3. If the displacement of the actuator reaches the target value, the constant displacement of actuator is maintained. The distance between two reference points is measured and changes of the distance are assumed to be increments of crack width. Then the first step is over.

At the beginning of the second step, the air chamber is attached to the concrete specimen. Pressure gauges are installed at inlet/outlet and flow meters at outlet. Fig. 4 illustrates a pressure gauge and flow meters at outlet. The pressurized air is injected into inlet of the air chamber and the pressure is measured. The pressurized air leaks through the cracks and the air leakage at outlet is measured. After steady-state lasts for a few seconds, the measurement is executed. As the pressure of the air at inlet gets higher, air penetrating operation in former explanation is repeated. When the air pressure at inlet reaches about 6 bar, the second step is finished. These two steps are iterated as the sum of crack widths increases. Air leakage tests were carried out for four cases having different crack widths each specimen at structural testing laboratory of Hyundai Institute of Construction Technology Development.

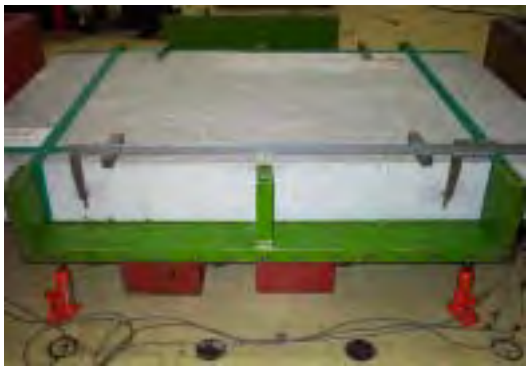


Fig. 3 generation of cracks and measuring device

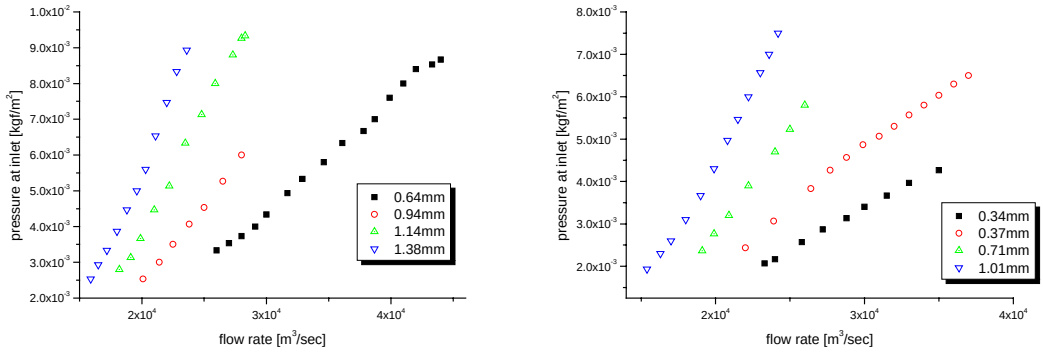
Fig. 4 pressure gauge and flow meters

3 EXPERIMENTAL DATA AND ANALYSIS

Independent variables of the air leakage tests were the air pressure at inlet and the sum of crack widths. Dependent variables were the flow rate and air pressure at outlet. Mathematical expressions explaining the relationship among these variables are introduced. Two experimental factors, the wall roughness and the flow coefficient, were calculated from the analysis using the mathematical formula. Both the wall roughness and the flow coefficient are expressed as functions in terms of the sum of crack widths through regression analysis. Flow rates were predicted with these functions to be compared with measured flow rates statistically. This comparison verifies the reliability of the predictive functions for the wall roughness and the flow coefficient. Following sections explain this procedure in detail.

3.1 Raw Data of the Air Leakage Tests

Two reinforced concrete specimens, RC 1 and RC 2, were subjected to tensile forces and their cracking loads were 472kN and 505kN, respectively. After cracks were generated, the sum of crack widths was measured with calipers and the air penetration tests were performed in cases for the four crack widths each specimen. Crack widths of RC 1 were 0.64mm, 0.94mm, 1.14mm and 1.38mm and those of RC 2 0.34mm, 0.37mm, 0.71mm and 1.01mm. In each case, flow rates and air pressures at gas outlet were obtained according to varying air pressures at gas inlet. The relationship between flow rates and air pressures at inlet of each specimen is shown in Fig. 5. As illustrated in Fig. 5, flow rate and air pressure have positive correlation. However, it could be known by intuition and only qualitative analysis was possible. Therefore, mathematical and analytical formulation was required. An analytical formula is introduced in the following section and used to estimate experimental factors.



(a) RC 1 *(b) RC 2*

Fig. 5 relationship between flow rates and air pressures

3.2 Analytical Formula and Estimation of Experimental Factors

An analytical equation for air leakage based on equation of state for gas and fluid mechanics (John, 1969) had been presented by Rizkalla (1984) and shows relationship among air pressures, flow rates, crack width and other constants as follows.

$$\frac{P_1^2 - P_2^2}{L} = \frac{k^n}{2}\left(\frac{\mu}{2}\right)^n (RT)^{n-1}\left|\frac{P_2 q_2}{B}\right|^{2-n}\frac{1}{W^3} \qquad \text{Eq. 1}$$

In this study, Eq. 1 was slightly modified as:

$$\frac{P_1^2 - P_2^2}{L} = \frac{k^n}{2}\left(\frac{\mu}{2}\right)^n (RT)^{n-1}\left|\frac{P_2 Q_2}{B}\right|^{2-n}\frac{1}{\left(\sum W\right)^3} \qquad \text{Eq. 2}$$

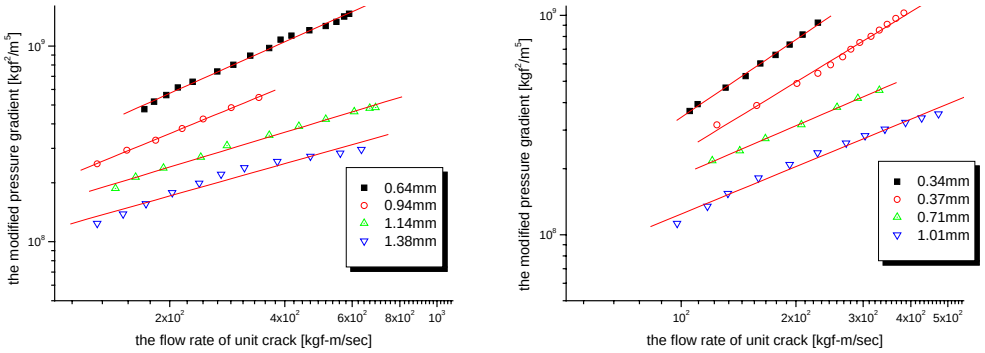
In Eq. 1 and 2, subscripts 1 and 2 mean gas inlet and outlet, respectively. μ is viscosity, 1.76×10^{-5} Pa·s and R is gas constant, 296.5 J/kg·K for nitrogen, respectively. T is the absolute temperature. L is the crack length, 1.2m and B is extent of crack, 0.2m. P is air pressure and W represents crack width. A small letter q means flow rate through individual crack and a capital Q represents the sum of flow rates through all the cracks. k and n are the wall roughness and the flow coefficient respectively and should be determined experimentally.

To estimate the wall roughness and the flow coefficient, Eq. 2 was simplified as

$$P'' = C\left|\frac{P_2 Q_2}{B}\right|^m \qquad \text{Eq. 3}$$

in which P'', modified pressure gradient, represents $(P_1^2-P_2^2)/L$, C is $(k^n/2)(\mu/2)^n(RT)^{n-1}/(\sum W)^3$ and m is 2-n. P_2 can be assumed to be unity(bar), therefore, P_2Q_2/B means the flow rate of unit crack extent. It is noted that the modified pressure gradient and the flow rate of unit crack extent have linear relationship in log scale. The flow rate of unit crack and the modified pressure gradient were calculated with the experimental output data and plotted in log scale as shown in Fig. 6. Linear regression lines of the curves were plotted, and their slopes and intercepts on vertical axis were obtained. The slope and intercepts on vertical axis means constant m and log C, respectively. The flow coefficient n is 2-m and the wall roughness k can be determined using $C= (k^n/2)(\mu/2)^n(RT)^{n-1}/(\sum W)^3$.

The estimated values of the wall roughness and the flow coefficient for the eight crack widths for which the air penetration tests had been performed are listed in Table 2. To predict the flow rates for arbitrary crack width, general expressions of the wall roughness and the flow coefficient in terms of crack width are required. Regression analyses to determine functions for k and n were performed as follows.



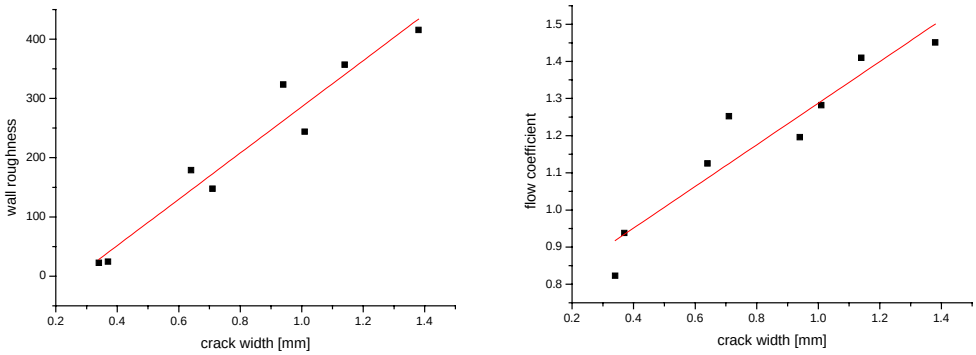
(a) RC 1 *(b) RC 2*

Fig. 6 relationship between the modified pressure gradient and the flow rate of unit crack and linear regression lines

Table 2 the estimated values of the wall roughness and the flow coefficient

Crack width (mm)	Wall roughness, k	Flow coefficient, n
0.34	22.38	0.8228
0.37	24.67	0.9379
0.64	178.98	1.1254
0.71	147.53	1.2524
0.94	323.32	1.1958
1.01	243.91	1.2818
1.14	357.01	1.4095
1.38	415.46	1.4509

The plot of the wall roughness and the flow coefficient versus crack width and their regression curves were depicted in Fig.7 (a) and (b), respectively.



(a) the wall roughness *(b) the flow coefficient*

Fig. 7 the wall roughness and the flow coefficient versus crack width and their regression curves

The mathematical formulae of the regression curves were estimated as below:

$$k(W) = 217336 - 217440 \times e^{(-W/\ 557)} \qquad \text{Eq. 4}$$

$$n(W) = 406557 - 406557 \times e^{(-W/\ 725646)} \qquad \text{Eq. 5}$$

Using these regressive formulae, the wall roughness and the flow coefficient for cases of the eight crack widths for which the air penetration tests had been performed were calculated. The calculated values and the measured pressures were substituted into Eq. 2 and the predictive flow rates were obtained. The reliability of the regressive formulae depends on the comparison of the measured flow rates with the predictive flow rates. The section 3.3 will show the statistical comparison between them.

3.3 Verification of the Regressive Formulae

To examine the reliability of Eq. 4 and 5, the comparison of the measured flow rates with the predictive flow rates was required and the statistical methods were implemented.

3.3.1 Comparison by regression analysis

The graph of the measured flow rates versus the predictive flow rates was plotted in linear scale. Linear regression line through the origin was obtained as depicted in Fig. 8 and the slope of the line was estimated to be 0.964. Here, the standard error and the correlation coefficient were found to be 0.0252 and 0.85, respectively.

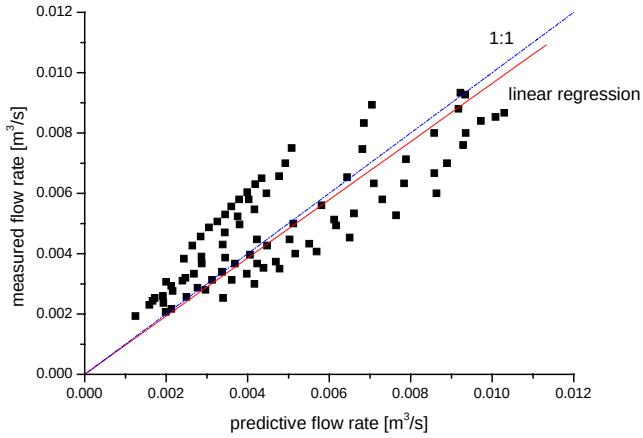


Fig. 8 the measured flow rates versus the predictive flow rates and their linear regression line

3.3.2 Comparison by test of significance

Test of significance was chosen as another implement to verify the reliability of the regressive formulae. In this section, X denotes the difference of the predictive flow rate Q_p and the measured flow rate Q_m, namely, $X= Q_p - Q_m$. If Eq. 4 and 5 predict k and n precisely, the mean value of X gets closer to zero. Thus, the null hypothesis and the alternative hypothesis were determined to be "the mean value of X is zero" and "the mean value of X is not zero", respectively. From the air leakage tests, 86 samples of X were obtained. The mean value and the standard deviation of these samples were calculated to be -0.00014 and 0.001264, respectively. The population standard deviation can be assumed to be same as 0.001264. As shown in Eq. 6, the significance probability should be lager than significance level α not to reject the null hypothesis.

$$2P\left\{\frac{\overline{X} - 0}{0.001264/\sqrt{86}} \le \frac{-0.00014 - 0}{0.001264/\sqrt{86}}\right\} = 2P\{Z \le -1.03\} \ge \alpha \qquad \text{Eq. 6}$$

From the statistic analysis, the significance probability was found to be 0.303. Considering that the common value of significance level is 0.05, the significance probability was so large that the null hypothesis could not be rejected. From the comparisons of two preceding sections, it was concluded that the regressive functions for the wall roughness and the flow coefficient are suitable.

4 CONCLUDING REMARKS

In this study, experimental investigation on air leakage characteristics of containments was carried out. From data of the air leakage tests, the functional expressions for the wall roughness and the flow coefficient were estimated and their reliability was verified statistically. Using these formulae, the relationship among crack width, air pressure and flow rate was evaluated and will serve as a criterion for air leakage characteristics of containments. Further experimental studies with more specimens having various crack patterns will provide more precise predictions.

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REFERENCES

N. S. Cho, and H. T. Kim, (2005), Structural Member Tests of the Prestressed Concrete Containment, KAERI Research Report, KAERI/CM-777/2004.

S. H. Rizkalla, and S. H. Simmonds, (1984), Air Leakage Characteristics in Reinforced Concrete, ASCE, Journal of Structural Engineering, Vol.110, No.5, pp.1149-1162.

J. E. A. John, (1969), “Gas Dynamics”, 2nd ed., Prentice Hall, NJ, 18

