# Literature Investigation of Air/Steam Ingress through Small Cracks in Concrete Wall under Pressure Differences

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**Abstract**

Traditionally within CANDU[2] safety analysis, a loss coefficient of ~2.8 is used to characterize turbulent flow leakage through narrow, sharp-edged cracks into, and out of Steam Protected Rooms (SPRs). In the event of main steam line break (MSLB), the pressure differences observed between SPRs and the surrounding area of the powerhouse range from 0.01kPa to 0.1 kPa. The relatively low pressure differences, coupled with narrow crack sizes, for instance, below 1 mm, may result in laminar flow leakage pathways as opposed to the turbulent variety assumed in analysis. The main purpose of this paper is thus (a) to calculate the loss coefficient for laminar flow through small cracks; and (b) to assess the effect of steam ingress to SPRs when the flow through some or all of the room leakage area is assumed to be laminar. Based on the literature review, the loss coefficient for laminar flow, through 1 mm crack size at 0.1 kPa pressure difference, ranges from 10 to about 65. This value represents an increase in loss coefficient of 3 ~ 22 times the loss coefficient used for SPR safety analysis. The actual volumetric leakage rate is therefore 3 ~ 8 times smaller than the amount previously applied. This paper demonstrates how the traditional loss coefficient used in safety analysis is extremely conservative in the analysis of the SPRs steam ingress phenomenon.

## 1.0 BACKGROUND

Steam Protected Rooms (SPRs) in the containment of a CANDU nuclear generation station (NGS) are designed to ensure equipment that is crucial to safety will be operating during certain postulated events/accidents such as a secondary side main steam line break (MSLB) or feed water pipe rupture [1]. This work is to support the SPR inspection and testing program at OPG.

For turbulent flow with Re>10000, empirical loss coefficients are widely employed in engineering applications with a typical value of 2.7~2.8. Traditionally the leakage of air/steam in and out SPRs has been assumed to be turbulent flow and the openings (cracks/gaps/imperfect door seals/holes around cables or pipes penetrating the wall) were lumped to be a hole or a sharp edged orifice, as shown in Figure 1. So, the loss coefficient of 2.8 has been used for the leakage pathways into and out of SPRs in safety analysis. However, in the postulated scenario of main steam line break (MSLB), the pressure differences between SPRs and the surrounding area of the powerhouse typically ranges from ~0.01kPa to 0.1 kPa. If the crack size is in the order of millimetre, the leakage

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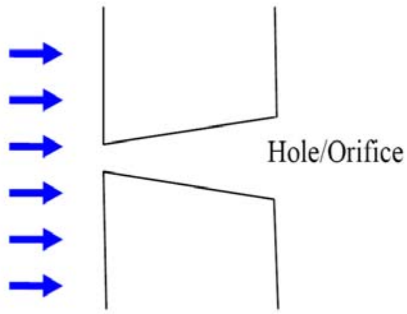


Figure 1: Lumped hole treatment to SPR cracks

would no longer to be classified as turbulent flow leakage. Instead, laminar flow leakage should be accounted for. Therefore mechanism of laminar leakage through a narrow crack in concrete wall needs to be investigated and the wall crack sizes corresponding to the laminar leakage regime needs to be identified. The impairment of the cracks/gaps to the performance of mitigating and safety support systems also needs to be assessed. A literature review thus was performed. In addition to the purposes above, this review was as well intended to provide analytical justification to support visual inspection methods as a means of ensuring adequate SPRs leakage tightness.

## 2.0 CONFIGURATIONS OF LAMINAR FLOW LEAKAGE

To facilitate the search of literature review, representative configurations under laminar flow leakage condition were considered. This section provides three cases classified in terms of pathway straightness and condensation effect.

### 2.1 CASE A: straight pathway of laminar flow through a crack in the SPR concrete wall with smooth surfaces

Figure 2 shows this configuration. This is the simplest case under consideration, featured by a straight pathway with smooth surfaces parallel each other. Note that the condensation effect is precluded in this case. "b" In Figure 2 is the crack size (crack width) in the order of millimetre. The unit of metre will be used in calculations later. "a" is the length of the crack size on the wall. L is the depth of the wall, which is the concrete wall thickness. 8 inches (20 cm) thickness of the concrete wall typically appearing in SPRs was assumed. "$\overline{U}$" is the average velocity passing through the crack.

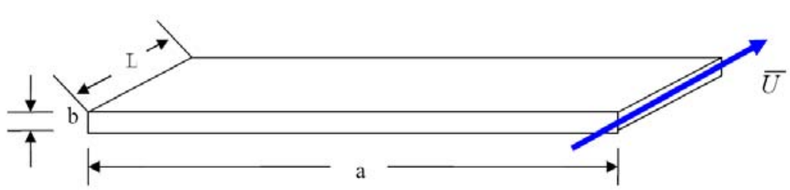


Figure 2: case A

where a: length of cracks on walls, m
b: size of cracks or crack width (b<<a), m

L : wall thickness, m
$\overline{U}$ : average velocity, m/s

### 2.2 CASE B: tortuous pathway of laminar flow through a crack in concrete wall with uneven rough surfaces

In Case B, "a", "L" and "$\overline{U}$ "have the same meanings as in Case A. "b" should be understood as average crack size (crack width) in that uneven rough surfaces is assumed. It should be noted that the actual length that air passes along the wall is larger than the wall thickness, L. This configuration is illustrated in Figure 3. The leakage rate under this configuration, which is not shown in the Figure 3, is Q'.

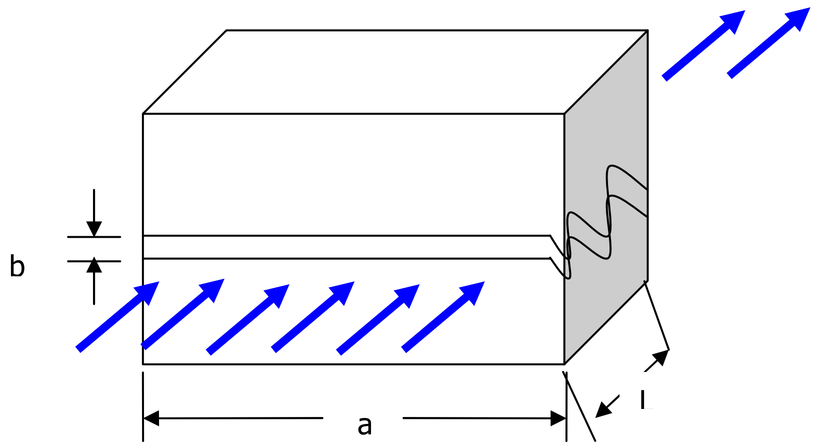


Figure 3: Case B

### 2.3 CASE C: with steam condensation effect, straight pathway of laminar flow through a crack in concrete wall with smooth surfaces

Case C has the same configuration as Case A but with steam condensation effect.

Note that In all four cases, b<<a is assumed.

## 3.0 LAMINAR CASES STUDY BASED ON LITERATURE REVIEW

Base on three cases classified above, the literature review was performed with focus on the laminar flow passing through narrow crack in the concrete wall. Loss coefficient with dependencies of crack size, crack type was derived. In certain cases, some other effects were considered in the derivation, such as mixture of dry air and steam, and occurrence of steam condensation in the crack.

### 3.1 Literature review on Case A: straight pathway of laminar flow through a crack with smooth surfaces

Case A represents a simplest case. The loss coefficient has the following expression in general,

$$K = K_1 + K_2 + K_3 \tag{1}$$

where K: total loss coefficient
$K_1$: entry loss coefficient
$K_2$: loss coefficient through cracks
$K_3$: exit loss coefficient

with

$$K_1 = (0.64 + 38/Re) \quad \text{(Ref. 2)} \tag{2}$$

$$K_2 = \frac{f}{4}\frac{L}{D_h} \quad \text{(Ref. 2)} \tag{3}$$

$k_3$ = 1.0 (Assumed)

where Re: gas apparent Reynolds number

It is well known that

$$f = 96/Re \quad \text{(Ref. 2 and 3)}, \tag{4}$$

$$D_h = \frac{4ab}{2(a+b)} \approx 2b \quad (\because b<<a) \tag{5}$$

$$Re = \frac{\rho D_h \bar{U}}{\mu} \tag{6}$$

μ in Equation (6) is dry air dynamic viscosity in N-s/m$^2$. In Reference 4, the average velocity was approximated by the following expression,

$$\bar{U} = \frac{1}{12}\frac{b^2}{\mu}\frac{\Delta P}{L} \quad \text{(Ref.4)} \tag{7}$$

ΔP is the pressure difference in Pa (d) on the two sides of the wall. For simplicity, the largest possible value of the average velocity is used. The real average velocity would be smaller. In other words, the leakage loss coefficient calculated with the real velocity would be larger and the real leakage rate would be smaller.

Substituting Equation (4) into (3) yields

$$K_2 = \frac{24L}{Re\, D_h} \tag{8}$$

Substituting equations (5), (6) and (7) into formulae (8) yields the following loss of coefficient through a crack with smooth surfaces as

$$K_2 = \frac{72\,\mu^2 \cdot L^2}{\rho \cdot \Delta P \cdot b^4} = \frac{8.08 \times 10^{-10}}{\Delta P \times b^4} \tag{9}$$

In Equation (9), the following assumptions have been made,

- wall thickness of 8 inches (0.2 m)

- environment temperature of 20˚C, for which dry air $\rho$=1.204kg/m$^3$, $\mu$=1.809x10$^{-5}$ N-s/m$^2$
- Re ≤ 2000
- a>>b

Substituting Equations(5), (6) and (7) into Equation(2), and applying same assumptions, yields entry loss coefficient as

$$K_1 = 0.64 + \frac{228\ \mu^2 \cdot L}{\rho \cdot \Delta P \cdot b^3} = 0.64 + \frac{1.26 \times 10^{-8}}{\Delta P \cdot b^3} \quad (10)$$

Substituting (9) and (10) into(1), and assuming $K_3$=1, the total loss of coefficient can be expressed as

$$K=1.64 + \frac{1}{\Delta P}\left(\frac{1.26 \times 10^{-8}}{b^3} + \frac{8.08 \times 10^{-10}}{b^4}\right) \quad (11)$$

Based on the experimental results in Ref. 4, Equation(11) is only applicable for differential pressures lower than 40 kPa (0.4 bar) and crack sizes smaller than 1.3 mm.

The loss coefficients were calculated using this methodology (Equation(11)) as function of crack size (m) under various pressure differences (Pa). The results are presented in Section 4.1.

### 3.2 Literature review on Case B: tortuous pathway of laminar flow through a crack with uneven rough surfaces

This subsection addresses tortuous passage of laminar dry air flowing through a slit/crack with uneven rough surfaces. The methodology is based on review of reference 5. A schematic model configuration is illustrated in Figure 3. The volumetric leakage rate (m$^3$/s) through this type of crack configuration is given by (Reference 5):

$$Q' = a\,(15.3b + 7.56 \times 10^{-3})\frac{b^3 \Delta P}{\mu L} \quad (12)$$

The average velocity has relationship with volumetric leakage rate so it can be calculated by use of Equation (12) as

$$\bar{U}' = \frac{Q'}{cross\,section\ area} = \frac{Q'}{ab} = (15.3b + 7.56 \times 10^{-3})\frac{b^2 \Delta P}{\mu L} \quad (13)$$

Substituting Equation (4) through (6) into (3) gives the expression of $K_2$ in terms of average velocity in Case A,

$$K_2 = \frac{6 \mu L}{\rho b^2 \bar{U}}$$

Similarly, we have $K_2' = \frac{6 \mu L}{\rho b^2 \bar{U}'}$ in Case B. Comparing Case A and B gives

$$\frac{K_{2\_caseB}}{K_{2\_caseA}} = \frac{K_2'}{K_2} = \frac{\bar{U}}{\bar{U}'} \tag{14}$$

Substituting Equation(7) and (13) into (14) yields the ratio of loss coefficients as function of crack size,

$$\frac{K_{2\_caseB}}{K_{2\_caseA}} = \frac{\frac{1}{12}\frac{b^2}{\mu}\frac{\Delta P}{L}}{(15.3b+7.56\times 10^{-3})\frac{b^2\Delta P}{\mu L}} = \frac{1}{12\times(15.3b+7.56\times 10^{-3})} \tag{15}$$

The environment temperature 20˚C is assumed in Equation (14) and (15) in order to compare Case B with Case A under same conditions and to ignore the dependency on dynamic viscosity. Based on experimental results in Reference 5, the above formula (Eq. (15)) is applicable for the following conditions,

- P1 $\geqslant$ 80 kPa(a) or 0.8 bar
- P2 $\leqslant$ 120 kPa(a) or 1.2 bar
- $\Delta$P $\leqslant$ 40 kPa(d) or 0.4 bar
- b $\leqslant$ 0.5 mm, and
- Re $\leqslant$ 100

It shows narrower application conditions in Case B than in Case A. It should be noted that the thickness of the concrete wall used in the experiment of reference 5 was 15 cm. It is assumed that the resultant formula is valid for 20 cm (8 inches) thick wall as well.

Figure 6 shows the comparison of loss coefficients deploying in Case B and in Case A as function of crack size. The results are presented in Section 4.2.

### 3.3 Literature Review on Case C: Case A + condensation effect

This subsection describes the condensation effect of steam from the literature review. In order to quantitatively analyze condensation effect of steam with comparison to no-condensation effect of dry air on the k loss coefficient, the following assumptions are made,

- Mixture is comprised of 50% volumetric steam and 50% volumetric dry air
- Saturated temperature for the mixture, which is 100 C around 1 bar
- The wall thickness is still 8 inches (20cm)
- Differential pressures are same for dry air passage and air-steam mixture passage

In Reference 4, a reinforced concrete panel was mounted by pressurization chambers on both sides. Leakage rates for two components, dry air and steam-air mixture, were measured for upper pressurization chamber of 10, 20, 40 and 80 kPa (0.1, 0.2, 0.4 and 0.8 bar).

The friction loss coefficients for the two components, dry air and steam-air mixture, are termed as $K_{2air}$ (or $K_{2\_case\ A}$) and $K_{2mix}$ (or $K_{2\_case\ C}$), respectively. Starting from basic equations, ΔP= ½ ρK$\overline{U}^2$ and Q=$\overline{U}\cdot$A, one can arrive the following

$$\frac{Q_{mix}}{Q_{air}} = \sqrt{\frac{\rho_{air} K_{2air}}{\rho_{mix} K_{2mix}}} \tag{16}$$

or $$\frac{K_{2\_Case\ C}}{K_{2\_Case\ A}} = \frac{K_{2mix}}{K_{2air}} = \frac{\rho_{air} Q^2{}_{air}}{\rho_{mix} Q^2{}_{mix}} \tag{17}$$

where

$\rho_{air}$ : density of 100°C dry air at a specific pressure
$\rho_{mix}$ : density of air and steam mixture at a specific pressure
$Q_{air}$ : volumetric flow rate of dry air at a specific pressure
$Q_{mix}$ : volumetric flow rate of steam-air mixture at a specific pressure

The density of mixture for the 50%-50% molar mass combination can be calculated by idea gas law as

$$\rho_{mix} = \frac{M_{mix} \cdot P}{RT} = \frac{M_{air} + M_{stream}}{2} \cdot \frac{(P_{atm} + \Delta P)}{R(100+273K)}$$

The molar masses of dry air and steam-air mixture at 100°C is evaluated as 29kg/kmol and 18 kg/kmol, respectively. Reference 4 indirectly gave the experimental measurements of $K_{2mix}/K_{2air}$. Therefore the ratio of volumetric flow rates given in Equation(16) can be calculated. The experimental results and discussions are given in Section 4.3.

## 4.0 RESULTS AND DISCUSSIONS

### 4.1 Case A

By using Equations(9), (10) and (11), the entry loss, friction loss, exit loss and total loss coefficients have been determined as a function of the crack size for a differential pressure of 0.1 kPa(d). The results are presented in Figure 5**.**

From Figure 4, it can be observed that there is a strong correlation between the total loss coefficient (K) and the crack loss coefficient ($K_2$). Therefore, it can be concluded that the dominant contribution to the total loss coefficient is crack loss ($K_2$) rather than entry loss ($K_1$) or exit loss ($K_3$) coefficients when the crack size is less than 1 mm. As noted above, the plots in Figure 5 are for a differential pressure of 0.1 kPa(d), however it is expected that similar conclusions can be drawn for other differential pressures. For a crack size of ~1 mm in width, the total loss coefficient is ~10.

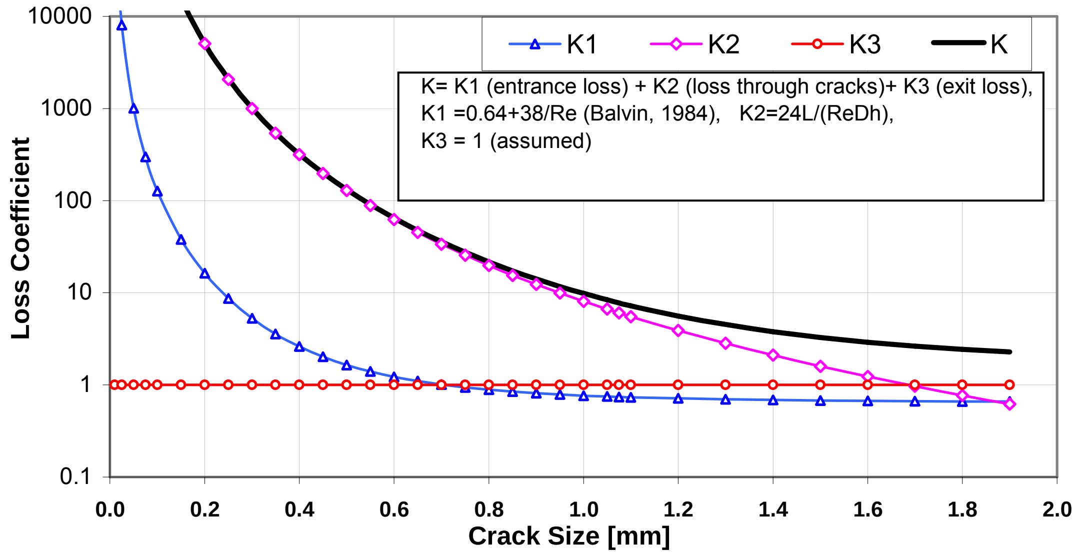


Figure 4: Total Loss Coeff Vs Crack Size at ΔP=0.1kPa
(Laminar Leakage through Two Parallel Smooth Surfaces)

By using Equation (10) the total loss coefficient as function of crack size for different differential pressures has also been calculated. The results are shown in Figure 5. From Figure 5 it can be easily observed that the total loss coefficient is reversely and exponentially proportional to the crack size. The smaller the crack size is, the larger the total loss coefficient, and thus the smaller the leakage rate.

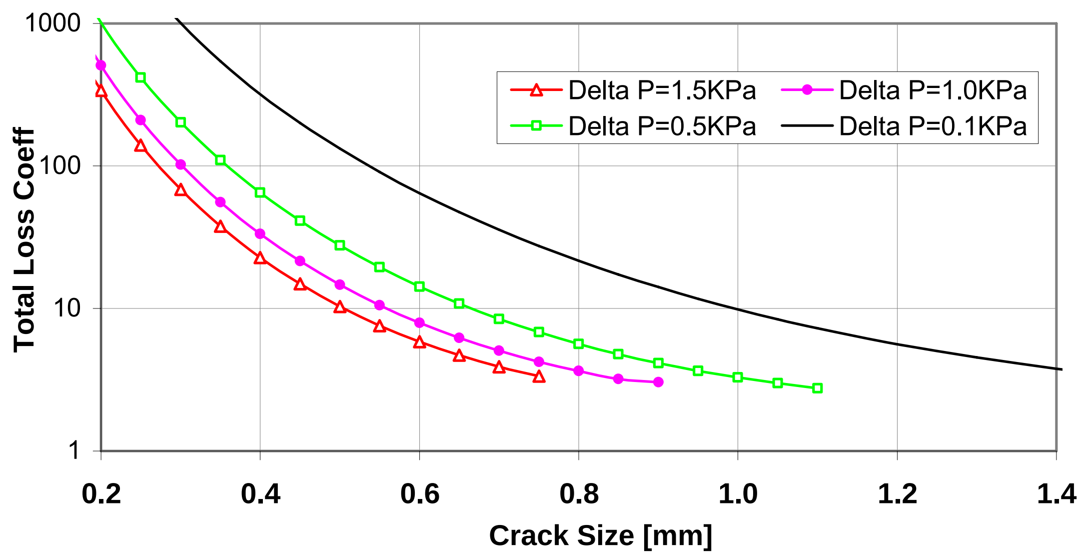


Figure 5: Laminar flow with Smooth Surfaces

As mentioned in Section 3.1, based on data in Reference 4, Equation (10) can be applied for calculating the laminar leakage rate through cracks having sizes of up to 1.3 mm. However, it should be noted that in reality there are no ideal smooth cracks in concrete, so this methodology may still valid for cracks bigger than 1.3 mm.

It should be pointed out that crack depth passing through the concrete wall (differs from the crack length, a, on wall) was treaded as same as the wall thickness in Case A. In addition, the surface roughness was not taken into account in Case A. Given these reasons, the k loss coefficient calculated for Case A is underestimated. Accordingly, the leakage rate with this formula is overestimated.

## 4.2 Case B

According to Equation (15) the ratio of the loss coefficient for tortuous cracks to the loss coefficient through cracks with parallel smooth surfaces as a function of crack size can be plotted as Figure 6. Based on Reference 5, Equation (15) can be applied for calculating the laminar leakage rate through cracks having sizes of up to 0.5 mm.

Figure 6 shows that the loss coefficient is higher for leakage through tortuous cracks, and therefore the leakage rate through tortuous cracks with uneven rough surfaces is lower. For a crack size of ~1 mm in width, the increase in the total loss coefficient due to tortuous cracks with rough, uneven surfaces is by a factor of ~3.6.

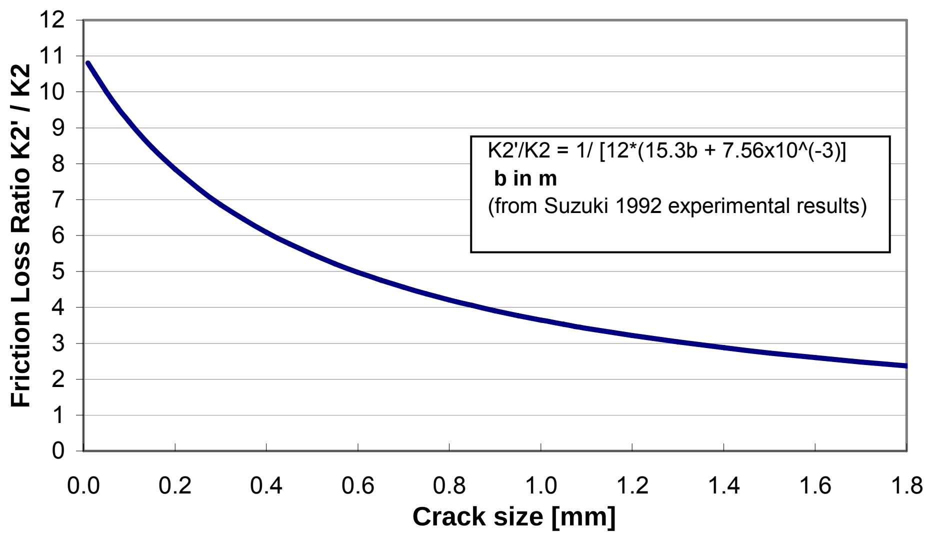


Figure 6: Ratio of $K_{2\_Case\ B}$ to $K_{2\_Case\ A}$

However, the application of crack size may be extended. As mentioned in Section 3.2, the experimental conditions requires pressure difference of 40 kPa(d) and Re⩽100. In fact, given 20 ˚C environment temperature and 0.1 kPa pressure difference, the applicable crack size can up to be 0.7mm to match Re ⩽100. The smaller the pressure difference is, the wilder the crack size is required to match laminar flow condition. The result is derived below for clarity.

$$\left.\begin{array}{l} \left.\begin{array}{l} D_h = \dfrac{4ab}{2(a+b)} = 2b \ \ (\text{Eq.5}) \Rightarrow D_h \infty\ b \\ \mathrm{Re} = \dfrac{\rho D_h \bar{U}}{\mu} \ \ (\text{Eq.6}) \Rightarrow \mathrm{Re} \infty\ D_h \bar{U} \end{array}\right\} \Rightarrow \mathrm{Re} \infty\ b\bar{U} \\ \bar{U} = \dfrac{1}{12}\dfrac{b^2}{\mu}\dfrac{\Delta P}{L} \ \ (\text{Eq.7}) \Rightarrow \bar{U} \infty\ b^2 \Delta P \end{array}\right\} \Rightarrow \mathrm{Re} \infty\ b^3 \Delta P$$

In addition, the author in Reference 5 did not explain how Re =100 was derived. If Re⩽ 400 would have been given, then the applicability of crack size could be extended up to 1.1 mm.

## 4.3 Case C

By using Equation(17), the ratio of the loss coefficient for a mixture of air and steam to the loss coefficient for dry air can be calculated as a function of the volumetric flow rate and density. Figure 8 was plotted by approximating volumetric flow rates from graphs given in Reference 4. Where no value was given in Reference 4, linear interpolation was applied. It should be mentioned that some points are not creditable due to the relatively large uncertainty existed in the estimation of volumetric flow rates from figures in Reference 4, especially those points corresponding to small crack sizes.

From Figure (8) it can be seen that data converges in the crack sizes bigger than 1 mm. The ratio of the loss coefficient with condensation to that without condensation ($K_{2\_Case\ C}$ : $K_{2\_Case\ A}$), is between 2 and 12 for crack sizes up to 1.3 mm, showing that in fact the condensation effect results in a greater loss coefficient. For a crack size of ~1 mm in width, the increase in the loss coefficient due to condensation is conservatively estimated to be by a factor of ~4.

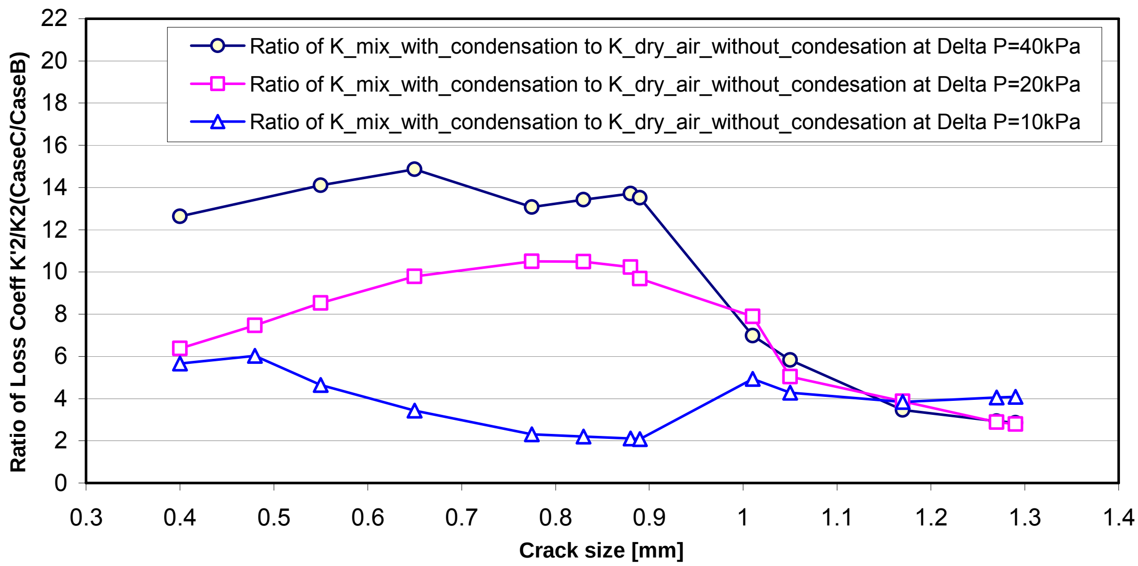


Figure 7: Comparison of loss coefficients with effect of condensation

## 4.4 Summary of Literature Investigation Results

For an 8-inch deep crack in concrete ~1 mm in width and 0.1 kPa pressure difference the laminar flow loss coefficients are given in Table 1.

It should be noted that the literature search only found the data of condensation effect to a small crack for relatively high pressure differences (~10 kPa(d) and up). For smaller pressure differences of ~10-100 Pa(d), which are typical pressure differences between SPRs and the surrounding area of the powerhouse, larger loss coefficients would be expected because more condensation is likely to be retained in the cracks with a smaller pressure gradient. A factor of 4 of increase in loss coefficient to account for condensation in the cracks with smooth surfaces should thus be conservative.

Table 1: Loss Coefficients and Ratio of Loss Coefficient at Crack Size 1 mm

| Pressure | Smooth Surfaces (Case A) | Tortuous Pathway (Case B) | Case A + Steam Condensation (Case C) |
|---|---|---|---|
| | $K_{2\_Case\ A}$ | $K_{2\_Case\ B}$ / $K_{2\_Case\ A}$ | $K_{2\_Case\ C}$ / $K_{2\_Case\ A}$ |
| 0.1 kPa | 10 | 3.6 | 3~4 (1) |
| 1 kPa | 2.6 | 3.6 | 4 (1) |
| 10 kPa | - | 3.6 | 4 |

(1): Expected value

Given that value of 3~4 for Case A with account of steam condensation effect, if Case B combined with steam condensation effect is considered, a minimum value of 6~7 would be expected for the ratio of new $K_2$ to $K_{2\_Case\ A}$ for 0.1kPa pressure difference and 1 mm crack size. In another word, a loss coefficient of at least 60~70 would be expected.

The total loss coefficient for laminar steam flow through narrow, tortuous cracks in 8-inch thick concrete without condensation effect is ~36 for crack sizes of 1 mm. This is 13 times larger than the loss coefficient used for SPR analysis in the Safety Report analysis (2.8 for turbulent flow). If condensation effect is account, which is very likely to occur for steam-air mixture in MSLB scenario, the loss coefficient should be greater than 40 for 1 mm crack passing through 8-inch concrete wall at the pressure difference of 0.1 kPa.

## 5.0 CONCLUSIONS

Based on the results of the review of literature on the laminar leakage through cracks in concrete structures, it can be concluded that:

- The total loss coefficient K is dominated by the friction loss coefficient $K_2$ for crack widths less than ~1 mm;
- The crack size for laminar leakage is recommended to be less than 1.3 mm for a 100 Pa(d) pressure difference;
- The loss coefficient for laminar leakage through tortuous cracks is greater than that through cracks with smooth, parallel surfaces;
- The loss coefficient for laminar leakage with condensation effect is greater than that without condensation effect.

The loss of coefficients ,for 8 inch concrete wall, 1 mm crack size and 0.1kPa pressure difference, were found to be

- About 10 for straight pathway with smooth surfaces (see Figure 5);
- 36 for tortuous pathway with uneven rough surfaces (see Figure 6)
- 30~40 with consideration of condensation effect on straight pathway with smooth surfaces (see Figure 7)

- At least 60~70 (expected) for combination of steam condensation effect and tortuous pathway with uneven rough surfaces.

The volumetric leakage rate is linked to K loss coefficient (see Equation(16) ). Thus the following conclusions can also be drawn for the same condition as above:

- The volumetric leakage rate would be at least 3 times less for cracks with straight pathway and smooth surfaces for laminar leakage than for turbulent leakage;
- The volumetric leakage rate would be at least 6 times less for cracks with tortuous pathway;
- The volumetric leakage rate would be about 5~6 times less for cracks with straight pathway and smooth surfaces, when condensation effect is accounted for.
- The volumetric leakage rate would be expected to be at least 8 times less for cracks with tortuous pathway and uneven surfaces, when condensation effect is accounted for.

Thus it proved that the use of loss coefficient 2.8 was extremely conservative in the past to analyze the SPRs steam ingress phenomenon covering laminar flow cases.

## 6.0 ACKNOWLEDGEMENT

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