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Analysis of Inter-channel Cross Flow Effect on PWR LOCA

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채널간 교차류가 냉각재상실사고에 미치는 영향분석

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Abstract

Predicted in this paper are flow distributions in average and hot channels of the reactor core during small and large break LOCAs. Also estimated based on RELAP5/MOD2 calculations are the effects of cross flow between channels on LOCA analysis results. It has been so far generally accepted that a single average channel is sufficient for small break LOCA core hydraulic modelling. However, based on these calculation results, hot channel modeling (two channel modeling) is found necessary in order to guarantee more reliable and conservative results. In large break LOCA blowdown phase, the hot channel thermal hydraulics is worse than that of average channel in both cases with the without consideration of cross flow.

요 약

소형냉각재상실사고(SBLOCA)와 대형냉각재상실사고(LBLOCA)중에 노심의 Average Channel과 Hot Channel에서의 유량분포를 예측하였다. 아울러 REALP5/MOD2 코드를 사용하여 두 채널사이의 교차류고려여부가 실제사고 분석결과에 미치는 영향을 평가하였다. 현재까지 SBLOCA계산에서는 노심을 한개의 채널로 모델하는 것이 충분하다고 판단되어 왔으나 본 계산결과에 의하면 보수적인 계산을 위해서는 Hot Channel모델링이 필요한 것으로 밝혀졌다. 그러나 LBLOCA Blowdown Phase중에서는 교차류의 고려 여부에 상관없이 Hot Cheannel이 Average Channel보다 보수적인 결과를 가져오며, 교차류의 영향도 미세한 것으로 판명되었다.

1. Introduction

The ECCS(Emergency Core Cooling System) Evaluation Model of 10 CFR 50, Appendix K[1)] requires the calculation of the flow rate through the hot region of the core as a function of time during the blowdown phase of LOCA(Loss of Collant Accident). It is also required for this calculation that cross flow be taken into account between average and hot channels. In conformance with the Appendix K two channels(average and hot channel) have been modeled for large break loss of coolant accident(LBLOCA) blowdown calculation. However, currently only one average channel model is used in small break loss of coolant accident(SBLOCA) calculation. Such a signle channel model has been considered to result in more conservative SBLOCA calculation result compared to the two channel model.

The main purposes of this paper are 1) to predict the core flow distribution during LBLOCA blowdown phase and SBLOCA transient, and 2) to investigate the effect of cross flow between average and hos channels on the core thermal hydraulic behavior during the LBLOCA blowdown phase and the SBLOCA transient.

Included in this paper are brief description of physical phenomena between SBLOCA and LBLOCA, prediction of core flow distribution, calculation results and finally conclusions and discussions.

2. Brief Description on Physical Phenomena of Large and Small Break LOCA

A LOCA transient generally involves RCS(Reactor Coolant System) depressurization, loss of reactor coolant inventory, degradation of core cooling, release of reactor coolant to the containment, and potentially radiological release to the environment. The severity of the consequences depends on the RCS design, the availability of mitigating system, and the break area.

A SBLOCA is characterized by relatively slower RCS depressurization and lower rates of mass transfer within the RCS compared to those for a LBLOCA. Becuase of the slower depressurization, the steam and the liquid are normally separated in RCS for SBLOCA. Therefore phase separation effects dominate both the hydraulic and heat transfer characteristics of the SBLOCA.

A LBLOCA is characterized by three different phases; blowdown, refill, and reflood. During the blowdown phase rapid subcooled depressurization up to a saturation pressure of core occurs in a period shorter than 0.2 second, and then relatively slow depressurization continues until the pressure equalizes between RCS and containment. The period from the end of core bypass (normally shorter or equal to the end of blowdown time) to the time at which emergency core cooling water(ECCW) fills up to the bottom of the core is called the refill phase. Reflood period begins from the bottom of coore recovery(BOCREC) time and the core will be quenched during this period.

The same acceptance criteria are applied for both small and large break LOCA, and the peak cladding temperature(PCT) criterion is one of them. Normally for SBLOCA PCT occurrs in the upper part of the core during the core uncovery period and its severity is dominated by the period of core uncovery. In LBLOCA PCT usually occurrs during the reflood phase.

3. Prediction of Core Flow Distribution

3.1. Flow Distribution without Consideration of Cross Flow between Channels

The total pressure drop along each channel can be described as follows assuming no interaction between channels

$$\pm \Delta p = \pm \frac{1}{2} f \frac{H}{D} \rho_m V^2_m \pm \frac{1}{2} C \rho_m V^2_m + \rho_m g H \quad (1)$$

In this equation the positive sign represents upward, and the negative sign downward flow. Eq. (1) can be rewritten as shown below by the introduction of combined loss coefficient, K:

$$\pm \Delta P = \pm \frac{1}{2} K \rho_m V^2_m + \rho_m g H \quad (2a)$$

$$= \pm \Delta P_f + \Delta P_g \quad (2b)$$

From the fact that loss coefficients can be approximated to be equal in both channels and the definition of dimensionless variables, the following equation is obtained:

$$\frac{\rho_2 V_2}{\rho_1 V_1} = \beta \sqrt{\frac{1-(1-\alpha)\beta}{\alpha \beta}} \quad (3)$$

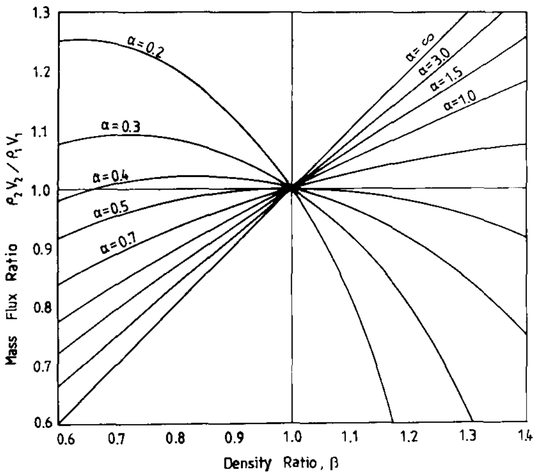

Fig. 1. Mass Flux Ratio as Function of α and β.

where $\alpha = \frac{\Delta p_f}{\Delta p}$ $\quad \alpha < 1$ for upward flow (4a)

$\alpha > 1$ for downward flow

and

$$\beta = \frac{\rho_2}{\rho_1}. \tag{4b}$$

This equation means that the mass flux ratio of hot channel to average channel can be represented as a function of α and β. Eq. (3) is plotted in Fig. 1 for various α's and β's. When α is of lower value than 0.5, the mass flux of hot channel increases with the decrease of density ratio, β. When α is larger than 0.5, the mass flux of hot channel decreases with the decrease of β. Although Eq. (3) is derived from the single phase and the steady state assumption, it can be applied to the slow transient when acceleration term is small compared to other terms.

Typical PWR plant has a α value of ~ 0.8 under normal operating condition (forced circulation by pump), while β is lower than 1.0 because of the higher power desnity of the hot channel than the average channel. Therefore mass flux of the hot channel will be lower than that of the average channel. During the natural circulation period the α value will be lowered to the range of $\alpha < 0.5$ and then the mass flux of the hot channel will be higher than the average channel.

In the LBLOCA blowdown phase, the core flow is in downward direction during the most of period. Therefore mass flux of hot channel will be either higher or lower depending on the density ratio, β.

3.2. Flow Distribution with Consideration of Cross Flow between Channels

With respect to cross flow between channels, one of the most important parameters is the transverse resistance coefficient, K_l. This value has been simply estimated to be the same as the lateral frictional resistance obtained from the data where all flow is assumed to be in the lateral direction in the first efforts. However, it has been found from the experiments[2,3] that the transverse resistance coefficent strongly depends on the inertia effect. The value of K_l is approximated by the following equation as a function of the ratio of lateral velocity to axial velocity, u/V:

$$\left(\frac{K_l}{K_\infty} - 1\right)K_l = \gamma \left(\frac{u}{V}\right)^{-2} \tag{5}$$

where γ is a constant and K_∞ is the value of K_l as (u/V) approaches infinitive.

The consideration of the cross flow tends to equalize the hydraulic parameters between two channels. Therefore the difference in hdraulic parameters between hot and average channel will be reduced compared to those between two channels without considering the cross flow.

4. Calculation Results

Calculations are performed to study that the approach adopted for the prediction of core flow distribution as described in the previous section can be applied in explaining the LOCA transient, and to check using RELAP5/MOD2[4] if the present core channel modellings are appropriate for both SBLOCA and LBLOCA.

Analyses are based on the minimum availability of ECCS equipment required by licensing regula-

Table 1. Initial and Boundary Conditions for Numerical Calculations

Core power	2775 Mwt
Size of hot channel	one fuel assembly
Power shape	top skewed (SBLOCA) 1.55 chopped cosine (LBLOCA)
Hot assembly. peaking factor	1.49
Total peaking factor	2.32
Accumulator pressure	42.4 bar (615 psia)
SI signal	123.05 bar (1784.7 psia) of pressurizer pressure
HPSI pump shut-off head	120.0 bar

tions. Major initial and boundary conditions used in these analyses are listed in Table 1. Effectivenesses of core cooling in both channels are compared by the insertion of two hot rods which are of the same power; one in hot channel and the other in average channel.

4.1. SBLOCA Calculation

Three inch cold leg break is analyzed for two cases, without and with consideration fo cross flow between channels. System nodalization for SBLOCA analysis is presented in Fig. 2.

Calculation results without consideration of cross flow are shown in Fig. 3 to Fig. 5 at the PCT occuring region(upper node of core). As expected hot channel mass flow is calculated to be sufficiently larger than that of the average channel during the natural criculation period. Core uncovery in hot channel occurrs for relatively a short time, and there is no sudden increase of cladding temperature. However, the first and the second core uncoveries occur in the average channel. The first core uncovery is recovered with the clearance of loop seal but the second continues until the end of calculation. With the core uncovery the cladding temperature increases abruptly due to reduction of heat removal until the hat removal improves by the accumulator injection. After the start of accumulator injection, cladding temperature decreases slowly. The reason for no core uncovery in the hot channel is evaluated to be larger mass flow and higher steam production due to higher power density with no interaction between two channels assumed.

Transverse resistance coefficient for cross flow between channels is calculated by Eq. (5). K_∞ is calculated to be 6.78 on the base of lateral flow between two fuel assemblies from the correlation of Idel'Chik[5]. Calculation results with consideration of cross flow are shown in Fig. 6 to Fig. 8. Hot channel mass flow is calculated to be larger than average channel similar to the case of no cross flow but the uncovery of core upper part occurrs at the same time and continues until the end of calculation in both channels. In this case the first core uncovery is not fully recovered with the clearance of loop seal and swell levels in both channels appear the same due to the effect of cross flow. Cladding temperature in the uncovered region of the hot channel is calculated to be higher than average channel because of higher steam temperature due to higher power density of hot channel.

4.2. LBLOCA Blowdown Calculation

Double ended cold leg break (DECLB) blowdown phase is analyzed for two cases; without and with consideration of cross flow between channels. The system nodalization is the same as Fig. 2 except for the steam generator secondary side.

Fig. 9 to Fig. 11 show the analysis results in the central region of the core for the case of no cross flow. During LBLOCA blowdown phase core flow direction reverses because of the lower resistance through core-downcomer-break than through core-steam generator-break. For downward flow, Δp and Δp_f in Eq.(2) have negative signs and α becomes greater than 1.0. As shown in Fig. 10, hot channel void fraction is lower than that of average channel, therefore mean density of hot channel becomes greater than average channel. As shown in Fig. 1 mass flux of hot channel becomes larger than average channel when mean density of hot channel is of greater value than

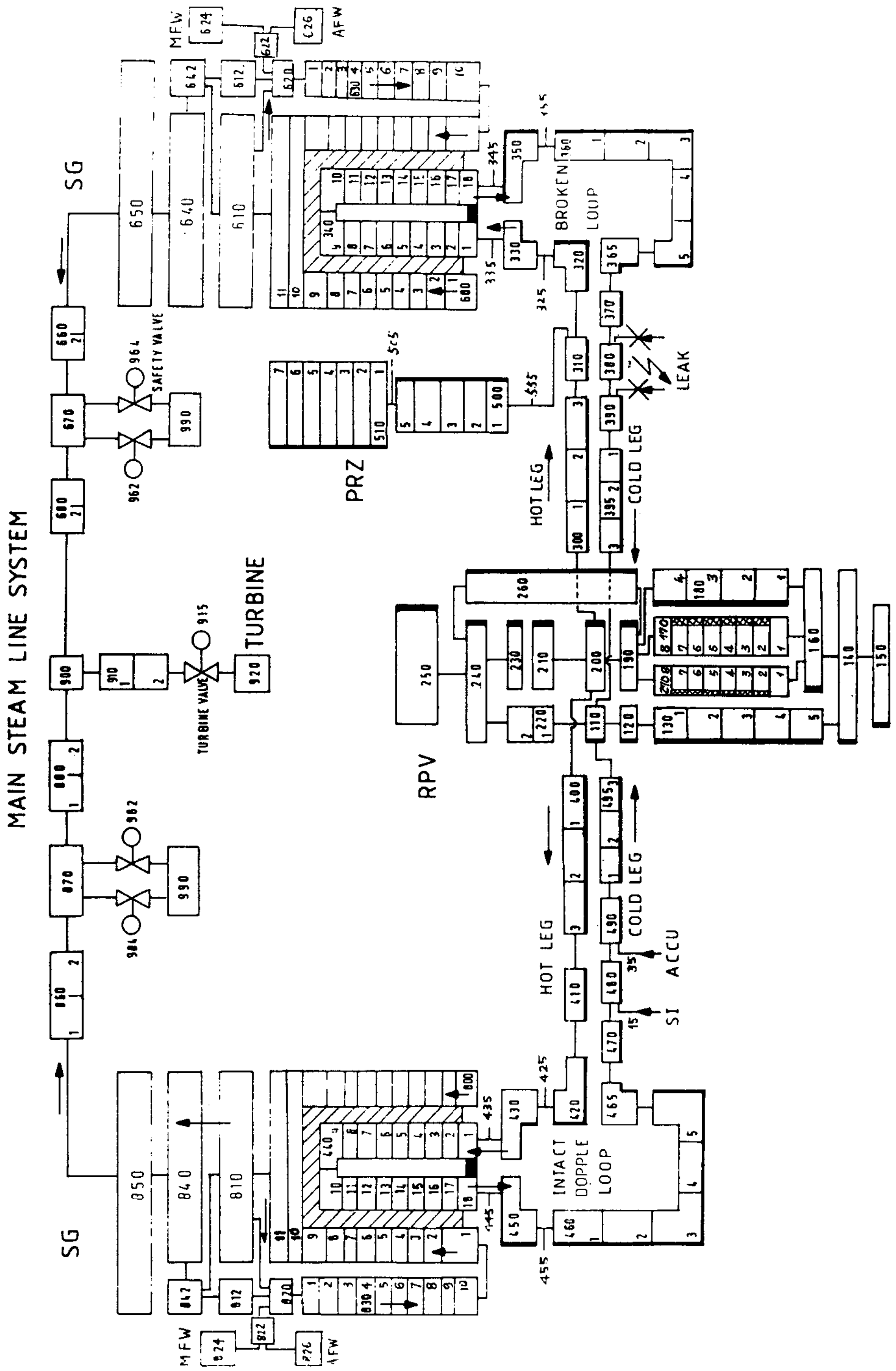

Fig. 2. System Nodalization for SBLOCA Calculation

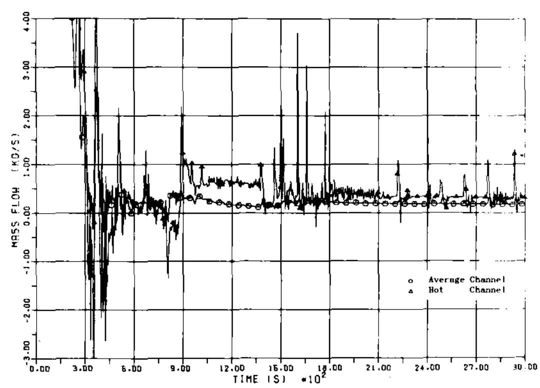

Fig. 3. Mass Flow in SBLOCA without Cross Flow.

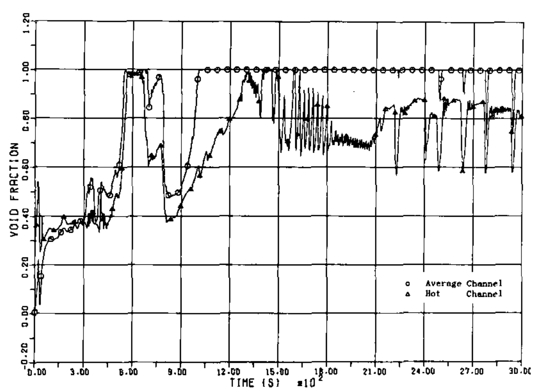

Fig. 4. Void Fraction in SBLOCA without Cross Flow.

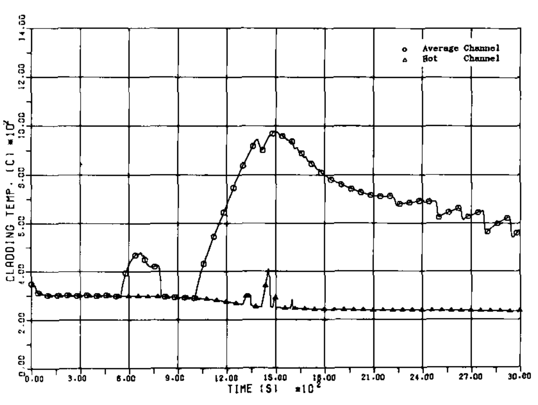

Fig. 5. Cladding Temperature in SBLOCA without Cross Flow.

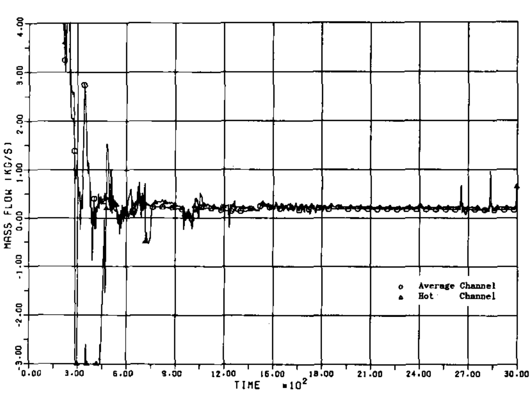

Fig. 6. Mass Flow in SBLOCA with cross Flow.

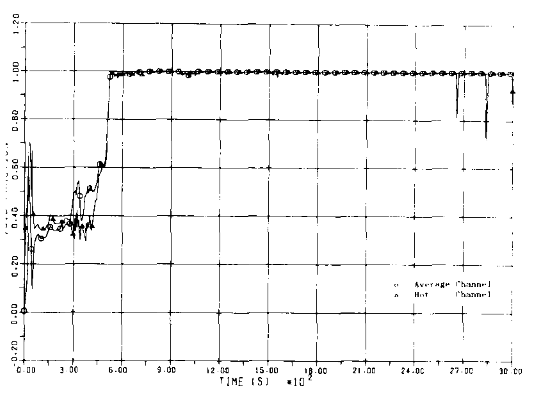

Fig. 7. Void Fraction in SBLOCA with Cross Flow.

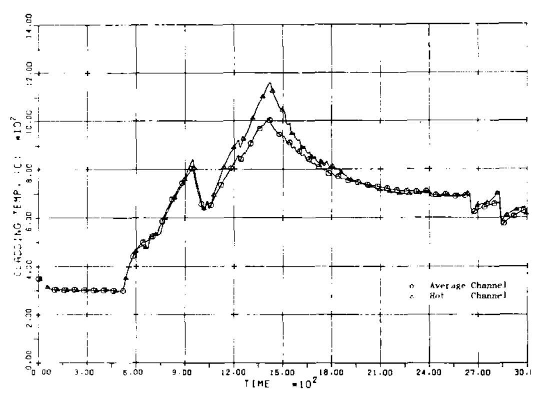

Fig. 8. Cladding Temperature in SBLOCA with Cross Flow.

average channel ($\beta > 1$). During LBLOCA blowdown phase hot channel flow is caluclated to be higher than average channel due to the higher density. Cladding temperature in the hot channel is higher than in the average channel because of the higher steam temperature of hot channel.

Fig. 12 to Fig. 14 show the analysis results for the case with cross flow between channels. All

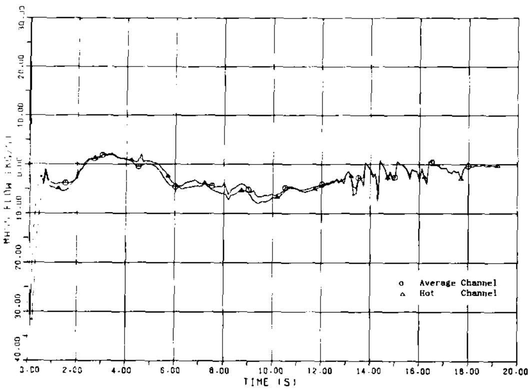

Fig. 9. Mass Flow in LBLOCA without Cross Flow.

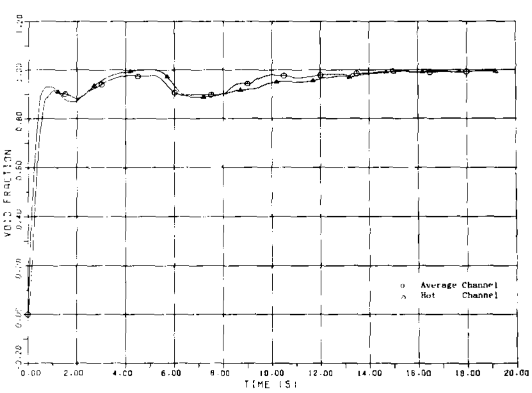

Fig. 10. Void Fraction in LBLOCA without Cross Flow.

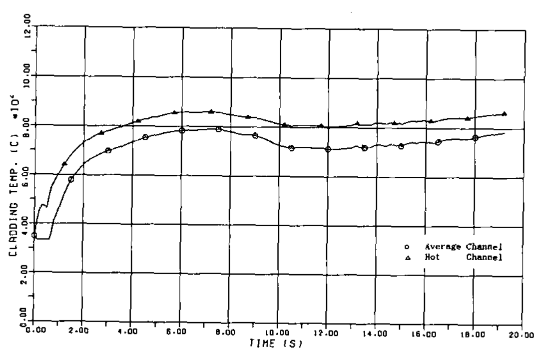

Fig. 11. Cladding Temperature in LBLOCA without Cross Flow.

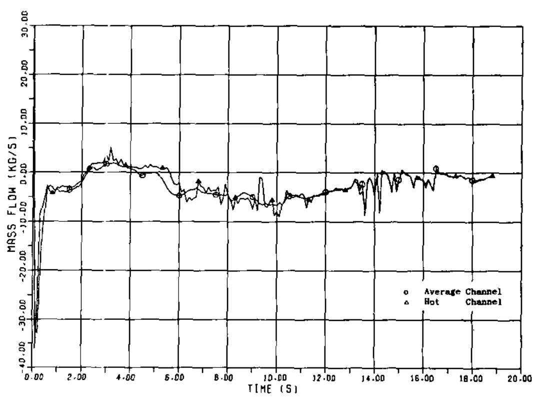

Fig. 12. Mass Flow in LBLOCA with Cross Flow.

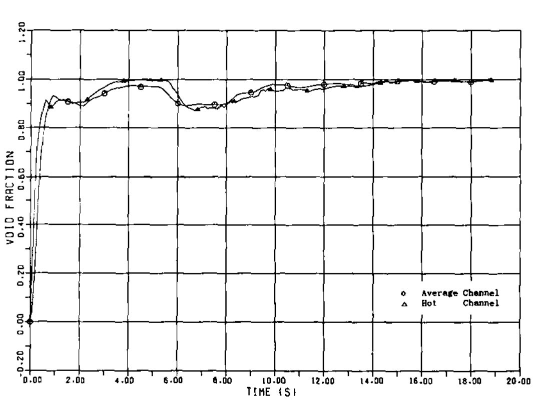

Fig. 13. Void Fraction in LBLOCA with Cross Flow.

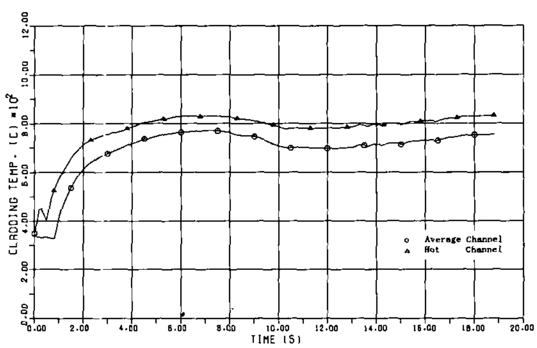

Fig. 14. Cladding Temperature in LBLOCA with Cross Flow.

trends are the same as the case of no cross flow. But hot channel flow has some fluctuation due to cross flow. The reason seems to be relatively small volume of hot channel node compared to average channel node and comparable order of cross low with axial flow of hot channel.

5. Conclusions and Discussions

Based on the study results of the effects of cross flow between average and hot channels on both the LBLOCA and SBLOCA, the following conclusions are reached:

1) With respect to SBLOCA PCT aspect the hot channel thermal hydraulic parameters be either favorable or infavorable compared to those for the average channel depending on the consideration fo cross flow between channels. Without the consideration of cross flow in SBLOCA analysis, the hot channel PCT becomes lower than the average channel due to the attainment of more favorable hot channel hydraulic parameters. This means that no consideration of cross flow between channels may not guarantee the most conservative PCT results in SBLOCA analysis.

2) During LBLOCA blowdown phase, the hot channel parameters are less favorable than those of average channel for both with and without consideration of cross flow. The effect of cross flow between two channels on hot channel thermal hydraulics are small compared to SBLOCA transient.

3) SBLOCA analysis based on single channel core model may not lead to the most conservative PCT result, and requires more careful core modelling such as two channel models to guarantee its conservatism.

Finally, considering the fact that the conclusions arrived at this paper are not based on intensive and detailed calculation results, and that they are to estimate the relative importance of cross flow effects on LOCA calculation results, it is recommended in the future that more extensive and detailed studies be performed to reach the solid and quantitative conclusions.

Nomenclature

ΔP total pressure drop across core, Pa

ΔP_f core pressure drop by losses, Pa

ΔP_g core pressure drop by gravitation, Pa

C factor for evaluation of losses except friction

D hydraulic diameter of channel, m

f friction factor

g graviational acceleration, m/s^2

H channel height, m

K loss coefficient including friction

K_l transverse resistance coefficient

K_∞ constant in Eq. (5)

u cross flow velocity, m/s

V axial velocity, m/s

α ratio of pressure drop by loosses to the total pressure drop (E1. 4a)

β ratio of hot channel density to average channel density (Eq. 4b)

γ constant in Eq. (5)

ρ density, kg/m^3

Subscripts

m mean value in channel

1 average channel

2 hot channel

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