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Counter-Current Flow Limitation at Hot Leg Pipe during Reflux Condensation Cooling after Small-Break LOCA

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Abstract

The possibility of hot leg flooding is evaluated in case of a small-break loss-of-coolant accident in Korean Next Generation Reactor (KNGR) operating at the core power of 3983 MW normally. The vapor and liquid velocities in hot leg and steam generator tubes are calculated during reflux condensation cooling with the accident scenarios of three typical break sizes, 0.13 %, 1.02 % and 10.19 % cold leg break. The calculated results are compared with the existing flooding correlations. It is predicted that the hot leg flooding is excluded when two steam generators are available. It is also shown that the possibility of hot leg flooding under the operation with one steam generator is very low. Therefore, it can be said that the occurrence of hot leg flooding is unexpected when the reflux condensation cooling is maintained in steam generator tubes.

1. Introduction

It is frequently described that the prediction of counter-current flow limitation (CCFL) or flooding in the nuclear power plant system is one of the most important issues for the evaluation of nuclear safety. This is true because the supply of cooling water into the reactor core is limited by the occurrence of CCFL at the upper tie plate, reactor vessel downcomer, pressurizer surge line and hot leg pipe.

It has been known that the CCFL phenomena can be encountered during a large-break loss-of-coolant accident (LOCA) and a small-break (SB) LOCA. During the reflood phase of large-break LOCA, the water accumulated at the inlet plenum of steam generator (SG) can flow back into hot leg and forms a counter-current flow with the steam flow to the steam generator. After the occurrence of a small-break LOCA, the counter-current flow is also expected because the steam can be condensed in steam generator tubes and flow back to the reactor vessel via hot legs. This is referred to as a reflux condensation phenomenon.

Actually, the reflux condensation is one of the effective heat removal mechanisms during a small- break LOCA (Kawanishi *et al.*, 1991). When a small break occurs in reactor coolant system, the decay heat generated in reactor core can be removed by heat transfer to the secondary side of steam generators, the injection of emergency core cooling, and the heat release with break flow. The importance of each heat removal mechanism is dependent on the break size. If the break size is large, the heat is mainly removed by the break flow. However, the cooling via steam generators becomes more important as the break size decreases. This trend is well described in Fig. 1.

The heat transfer through steam generators is achieved by reflux condensation and/or the natural circulation of primary coolant. As shown in Fig. 1, the reflux condensation does not contribute much to heat removal when the break is larger than 1.02 % of cold leg size. However, both reflux condensation and natural circulation become important as the break size decreases.

The occurrence of the counter-current flow limitation under the reflux condensation means the increase of pressure drop across hot leg. This causes the pressure buildup in the upper plenum of reactor vessel and then the shrinkage of liquid level in the reactor core (Lopez de Bertodano, 1994). The reduced core level can result in fuel heatup. Considering the importance of the phenomenon, the possibility of CCFL during SBLOCA is not well arranged up to now. Even though there are a lot of experimental data on CCFL in hot leg pipe, the possibility of hot leg flooding under the accident condition in real plant is rarely evaluated. The main purpose of the present study is to describe the possibility of the CCFL during the reflux condensation cooling in SBLOCA accident scenarios.

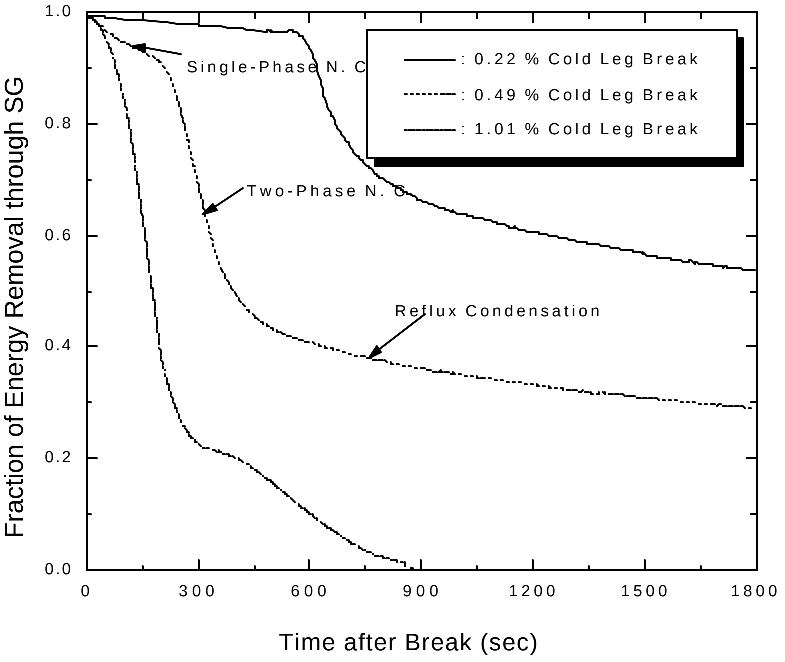

Fig. 1 Fraction of decay heat removed by SGs with the increase of break size.

2. Analysis

The previous studies on reflux condensation reported that various heat removal patterns were observed depending on the thermal-hydraulic conditions in the primary and secondary side of condensing tube. The main flow patterns were the partial reflux condensation mode and total reflux condensation mode. In partial reflux condensation mode, the liquid film is formed along the hot side of condensing tube wall. Usually the partial reflux condensation mode is introduced at a lower steam flow rate. When the steam flow rate is increased up to the flooding limit in tube, a liquid column begins to be accumulated above the two-phase region where condensation occurs. This situation is referred to as total reflux condensation. In addition, many other complicated flow patterns were also observed. Those patterns were expressed as fill and dump mode (Calia and Griffith, 1982), oscillatory mode (Nguyen and Banerjee, 1982), and two-phase thermo-syphoning (Wan *et al.*, 1983). However, Girard and

Chang (1992) showed that the basic mechanisms associated with the reflux condensation are partial reflux condensation and total reflux condensation. They suggested that there exist no oscillatory flow patterns when the tube length is long enough. The l/D ratios of the experiment were 233, 303 and 506. Therefore, it can be said that the complicated oscillatory flow pattern during the reflux condensation in short length system is a part of total reflux condensation (Jeong *et al.*, 1998). The oscillatory behaviors observed with short condensing tube can be considered as transient procedures to another stable stage of total reflux condensation.

For the analysis, it is assumed that the steam generated in the core is condensed completely in SG tubes and drained back to the hot leg pipe. The accumulation of condensate in the steam generator inlet plenum is not taken into account. Therefore, all the condensed liquid flows to the hot leg. The reference plant for the analysis is the Korean Next Generation Reactor (KNGR) which has two steam generators, two hot legs, and four cold legs. The operating core power of KNGR is designed to be 3983 MW. The geometry data for KNGR hot leg and steam generator are described in Table 1.

The quantity of steam generated in the core can be calculated from the decay power and the heat of vaporization for given pressures as described in the following equation:

$$\dot{m}_g = \frac{P_{decay}}{h_{fg}}. \tag{1}$$

The decay heat rate is calculated using 1971 ANS decay heat curve. Now, the vapor and liquid velocities in steam generator and hot leg can be evaluated using the following two equations:

$$j_g = \frac{\dot{m}_g}{A\ \rho_g}, \tag{2}$$

$$j_f = \left(\frac{\rho_g}{\rho_f}\right) j_g. \tag{3}$$

The natural circulation termination time after the break is dependent on the break size. For example, the natural circulation is terminated at about 200 seconds after the break of 1.02 % and the reflux condensation starts at this time. On the contrary, the decay heat begins to be removed by reflux condensation after 2,160 seconds at the break size less than 0.13 % of cold leg. After the initiation of the reflux condensation, the decay power is continuously decreased and the system pressure is also decreased. As a result, the superficial vapor velocity and liquid velocity are continuously changed. The accident scenarios for three typical break sizes are summarized in Table 2. The accident scenario for 0.13 % break is obtained from the experiment performed by Kawanishi et al. (1991). The other two scenarios for 1.02 % break and 10.19 % break are obtained from the design basis accident (DBA) LOCA analysis results for YGN 3&4.

The superficial phase velocities are calculated from the time history of the events for the three scenarios. In Table 3, the calculated vapor and liquid velocities at hot leg and steam generator tube are provided. The evaluated j_g^* and j_f^* are defined as follows:

$$j_k^* = j_k\left(\frac{\rho_k}{gD\Delta\rho}\right)^{1/2}, \tag{4}$$

where k means liquid or vapor phase. Now, it can be evaluated whether the CCFL can be induced in hot leg and steam generator tubes based on the vapor and liquid velocities during the accident scenarios.

Table 1 Hot leg and steam generator data for KNGR

Description	Design data
Hot leg diameter (m)	1.0668
SG tube diameter (m)	0.01692
No. of total SG tubes	12,596
SG tube plugging rate (%)	10
No. of active SG tubes	11,336

Table 2 Typical small-break LOCA scenarios

Case A, 0.13 % break		Case B, 1.02 % break		Case C, 10.19 % break	
Time (sec)	Event	Time (sec)	Event	Time (sec)	Event
244	Reactor trip	203.1	Reactor trip	12.0	Reactor trip
2160	Reflux condensation initiated, P = 8 MPa	-	-	-	-
-	-	219.7	P = 10 MPa	21.4	P = 10 MPa
5545	SG bleed operation started, P = 8 MPa	496.6	Loop seal clearing	62.6	P = 8 MPa
-	-	853.6	P = 8 MPa	70.4	Loop seal clearing
9000	P = 3 MPa	2875.2	P = 3 MPa	124.4	P = 3 MPa

The occurrence of CCFL is usually predicted by the flooding correlation. The correlations for the hot leg flooding were suggested by many researchers based on the experimental results or analytical manipulations. Among these, the correlations suggested by Richter *et al.* (1978) and Ohnuki (1986) are frequently used. In the present study, the following correlation of Richter *et al* is adopted for the prediction of flooding in hot leg pipe:

$$j_g^{*\,1/2} + j_f^{*\,1/2} = 0.7. \qquad (5)$$

In addition, the occurrence of the flooding in a vertical flow path such as steam generator U-tube is predicted with Wallis-type flooding correlation as follows:

$$j_g^{*\,1/2} + m\ j_f^{*\,1/2} = C. \qquad (6)$$

The values of 1.0 for m and 0.85 for C are used in the present study. It is shown that the transition from partial reflux condensation to total reflux condensation due to the occurrence of the flooding at steam generator tubes can be well predicted with these constants (Jeong *et al.*, 1998).

Table 3 Estimated superficial velocities in hot leg and SG tubes

	Time after trip (sec)	% Power	Pressure (MPa)	Hot leg conditions		SG conditions	
				$j_f^{*1/2}$	$j_g^{*1/2}$	$j_f^{*1/2}$	$j_g^{*1/2}$
0.13 % break with 2 SG	1916	1.541	8	0.1045	0.2122	0.1744	0.3541
	5301	1.149	8	0.0903	0.1834	0.1508	0.3060
	8756	0.996	3	0.0699	0.1902	0.1167	0.3173
1.02 % break with 2 SG	16.6	4.6563	10	0.1958	0.3677	0.3267	0.6136
	293.5	2.6084	8	0.1361	0.2762	0.2271	0.4609
	2672.1	1.4028	3	0.0829	0.2255	0.1384	0.3763
10.19 % break with 2 SG	9.4	5.049	10	0.2040	0.3831	0.3404	0.6392
	50.6	3.773	8	0.1637	0.3322	0.2732	0.5544
	58.4	3.651	-	0.1610	0.3268	0.2687	0.5453
	112.4	3.275	3	0.1267	0.3447	0.2115	0.5752
0.13 % break with 1 SG	1916	1.541	8	0.1478	0.3001	0.2467	0.5007
	5301	1.149	8	0.1278	0.2593	0.2132	0.4327
	8756	0.996	3	0.0989	0.2689	0.1650	0.4488
1.02 % break with 1 SG	16.6	4.6563	10	0.2769	0.5200	0.4620	0.8677
	293.5	2.6084	8	0.1924	0.3906	0.3211	0.6518
	2672.1	1.4028	3	0.1173	0.3189	0.1957	0.5322

3. Results and discussion

The data for vapor and liquid velocities given in Table 3 are also shown in Figs. 2 through 5. The flooding correlation is represented as a solid line with no symbol. The solid symbols are the thermal-hydraulic conditions for the three typical small break accidents. The dashed, dotted, and dot-dashed lines mean the complete condensation lines for a specified pressure, 10 , 8 and 3 *MPa*, respectively.

In Fig. 2, the phase velocities in hot leg for the three cases are compared with the flooding criterion when all two steam generators are available for the cooling of primary side. It is evaluated that the hot leg conditions are far below the flooding line even for the 10.19 % break, which is the largest small-break LOCA in KNGR having the break size of 0.5 ft^2. Therefore, judging from this result, there is no possibility of hot leg flooding when there exists the reflux condensation cooling and two steam generators are available. Actually, 10.19 % break is large enough to remove most of the decay heat through the break. In other words, it is difficult that the reflux condensation is to be appeared and the heat removal portion of reflux condensation is very small at the large break size of 10.19 %. As described previously in Fig. 1, the reflux condensation plays important role in smaller breaks less than 1.02 % break.

In Fig. 3, the possibility of flooding in steam generator tubes is checked. Even though the total flow area in steam generator is larger than that of hot leg, it is analyzed that the SG flooding criterion is satisfied and there is some possibility of CCFL during the early period of LOCA with 10.19 % and 1.02 % break size. It should be considered that the hydraulic diameter of steam generator tube is much less than that of hot leg. Therefore, the nondimensional superficial velocities in steam generator tubes can be greater than those in hot leg. This result is observed in some experimental studies on reflux condensation with intentional depressurization of steam generator secondary side. Asaka and Kukita (1995) showed that the steam flow into the SG U-tubes increased after the initiation of depressurization and liquid holdup was resulted from CCFL in SG tube due to the enhanced steam condensation rates. They also reported that there was no indication of CCFL at the SG inlet plenum and hot leg under this situation. This result is consistent with the present calculation described in Fig. 3. The figure shows that the flooding at SG tube is accompanied during the early period of accident with the break size of 1.02 % cold leg. As mentioned previously, the prediction for 10.19 % break can be considered as conceptual estimation because the reflux condensation is not an important heat removal mechanism accompanied with this break size. Though some accident conditions are above the flooding line in Fig. 3, most conditions for the three typical breaks remain within the flooding criterion in SG tube. This means the reflux condensation mode in SG tube is partial or filmwise reflux condensation.

In Figs. 4 and 5, the possibilities of CCFL in hot leg and SG tubes are checked when only one steam generator is available. Figure 4 suggests that the hot leg flooding be introduced with the break of 1.02 % cold leg area. However, it should be remembered that a conservative assumption is adopted in the present analysis. It is assumed that all the heat generated in the core is removed through steam generator. If the heat removal ratio depicted in Fig. 1 is taken into account, it is expected that the hot leg flooding is excluded with the break sizes greater than 1.02 % cold leg. The superficial velocities in Fig. 5 imply that the probability of flooding at SG tubes is very high and total reflux condensation is introduced under this situation. Actually, the assumption of one SG operation for larger break sizes does not have significant meaning. The most important feature to guarantee the normal operation of SG is the supply of auxiliary feedwater into SG secondary side. In safety analysis for KNGR small-break LOCA, the operation of auxiliary feedwater is not taken into consideration for breaks greater than 0.02 ft^2 (0.407 % break). This means that the failure of SG function becomes significant only for small breaks less than 0.407 % break.

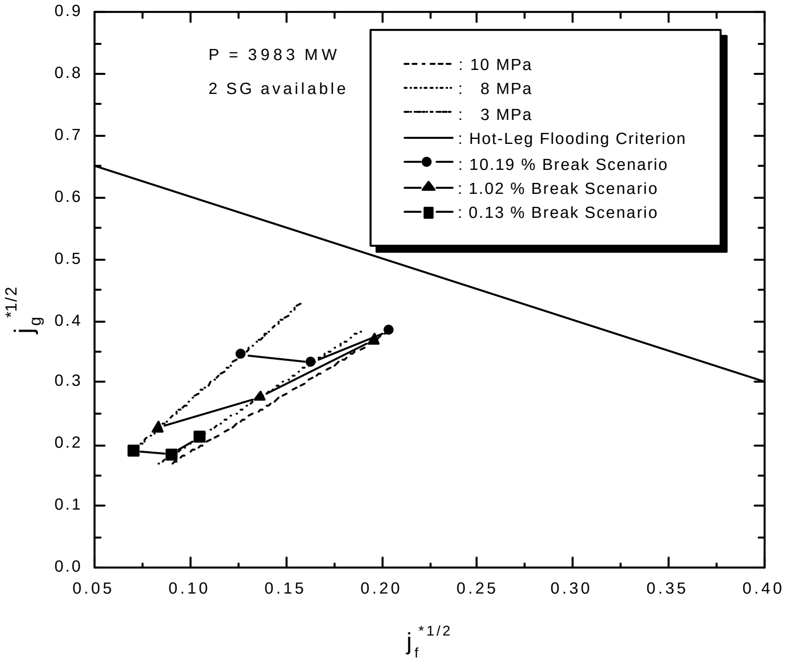

Fig. 2 Superficial velocities in hot leg pipe during small-break LOCAs with 2-SG operation

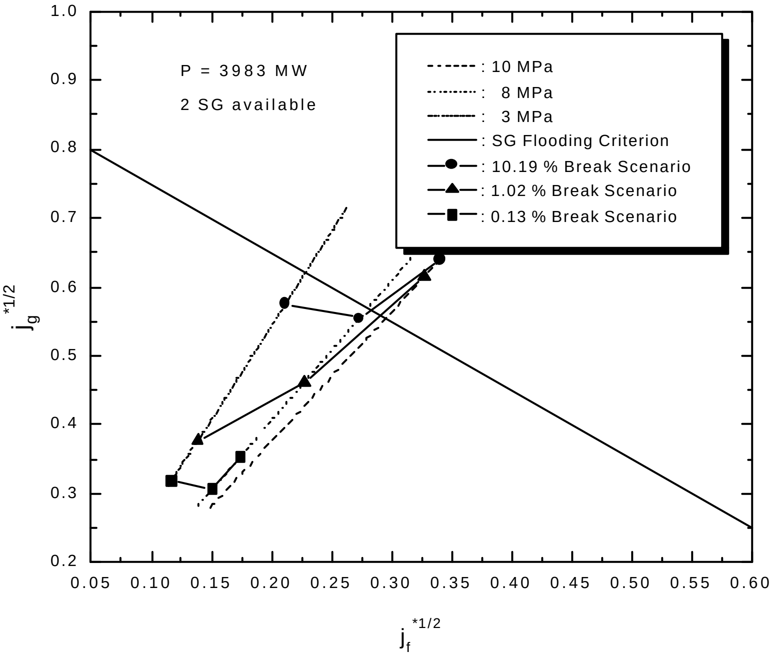

Fig. 3 Superficial velocities in SG tube during small-break LOCAs with 2-SG operation

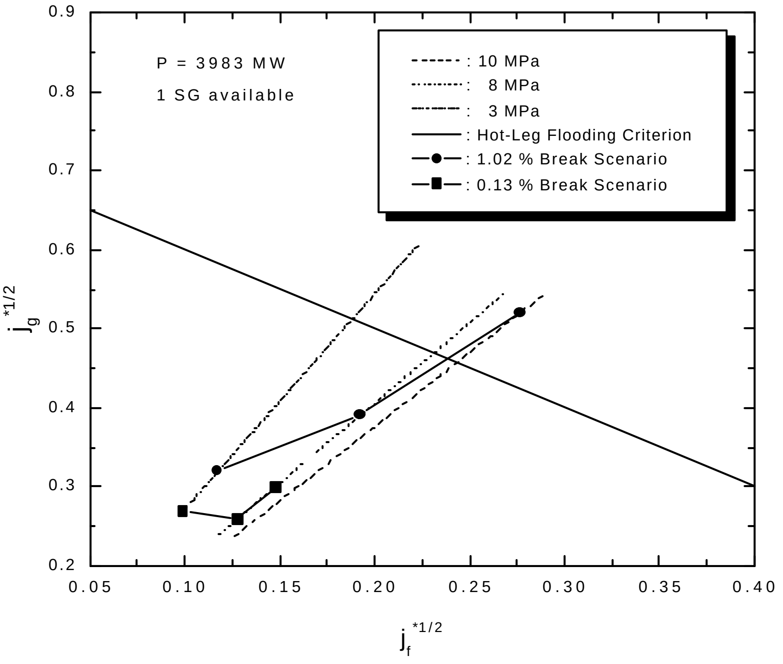

Fig. 4 Superficial velocities in hot leg pipe during small-break LOCAs with 1-SG operation

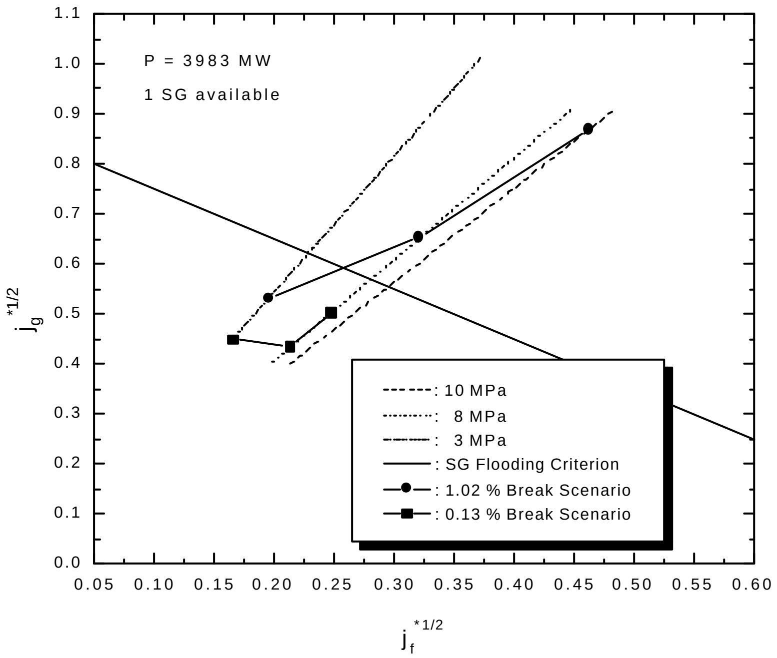

Fig. 5 Superficial velocities in SG tube during small-break LOCAs with 1-SG operation

4. Conclusions

The possibility of CCFL in hot leg and steam generator tubes is estimated with the conservative assumption that all the decay heat is removed through reflux condensation in steam generator tubes. Followings are the main conclusions obtained from the present study:

(1) The CCFL at hot leg is precluded when all the two steam generators in KNGR are available.

(2) The partial or filmwise reflux condensation is a dominant heat removal mechanism with the breaks less than 1.02 % when two steam generators are operable.

(3) It is predicted that the hot leg flooding is possible to occur with the break sizes greater than 1.02 % when only one steam generator is available.

(4) If the reduced heat removal rate through SGs with larger breaks is taken into account, the occurrence of hot leg flooding is improbable.

Through the present study it is validated that the CCFL is expected to occur in SG tubes not in hot legs during the reflux condensation cooling after a small-break LOCA. However, there still remains the possibility of hot leg flooding at the time of the termination of natural circulation after a small-break LOCA, in which some portion of hot leg is filled continuously. Though the prediction of CCFL in hot leg is also required for the modeling of system behavior, the development of accurate correlation on interfacial friction term under counter-current flow condition is more important than CCFL phenomena for the improved prediction of thermal-hydraulic phenomena during small-break LOCA or reflood phase of LBLOCA. The study of Kirmse *et al.* (1995) suggests the importance of interfacial velocity in the prediction of core water level and peak cladding temperature after a small-break LOCA.

References

Asaka, H. and Kukita, Y. (1995) Intentional depressurization of steam generator secondary side during a PWR small-break loss-of-coolant accident. *J. Nucl. Sci. Technol.*, Vol. 32, No. 2, pp. 101-110.

Calia, C. and Griffith, P. (1982) Modes of circulation in an inverted U-tube array with condensation. *J. Heat Transfer*, Vol. 104, pp. 769-773.

Girard, R. and Chang, J. S. (1992) Reflux condensation phenomena in single vertical tubes. *Int. J. Heat Mass Transfer*, Vol. 35, pp. 2203-2218.

Jeong, H. Y., Kim, B. N. and Lee, K. (1998) Thermal-hydraulic phenomena during reflux condensation cooling in steam generator tubes. *Ann. Nucl. Energy*, Vol. 25, No. 17, pp. 1419-1428.

Kawanishi, K., Tsuge, A., Fujiwara, M., Kohriyama, T. and Nagumo, H. (1991) Experimental study on heat removal during cold leg small break LOCAs in PWRs. *J. Nucl. Sci. Technol.*, Vol. 28, No. 6, pp. 555-569.

Kirmse, R., Pointer, W., Sonnenburg, H. G., and Steinhoff, F. (1995) Small-break loss-of-coolant accident analysis for pressurized water reactors with an advanced drift-flux model in ATHLET. *Nucl. Engng Des.*, Vol. 154, pp. 23-25.

Lopez de Bertodano, M. (1994) Countercurrent gas-liquid flow in a pressurized water reactor hot leg. *Nucl. Sci. Engng*, Vol. 117, pp. 126-133.

Nguyen, Q. T. and Banerjee, S. (1982) Flow regimes and heat removal mechanisms in a single inverted U-tube steam condenser. *Trans. ANS*, Vol. 43, pp. 788-789.

Ohnuki, A. (1986) Experimental study of counter-current two-phase flow in horizontal tube connected to inclined riser. *J. Nucl. Sci. Technol.*, Vol. 23, No. 3, pp. 219-232.

Richter, H. J. *et al.* (1978) De-entrainment and counter-current air-water flow in a model PWR-hot leg. NRC-0193-9, US Nuclear Regulatory Commission.

Wan, P. T. *et al.* (1983) Transition conditions from reflux condensation to two-phase thermo-syphoning in steam generator tubes. *Trans. ANS*, Vol. 44, pp. 347-348.