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PWR Hot Leg Natural Circulation Modeling with MELCOR Code

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Abstract

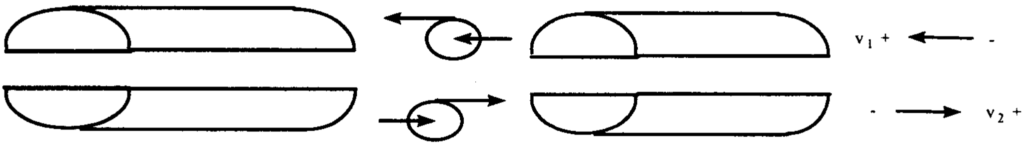
Previous MELCOR and SCDAP/RELAP5 nodalizations for simulating the counter-current, natural circulation behavior of vapor flow within the RCS hot legs and SG U-tubes when core damage progress can not be applied to the steady state and water-filled conditions during the initial period of accident progression because of the artificially high loss coefficients in the hot legs and SG U-tubes which were chosen from results of COMMIX calculation and the Westinghouse natural circulation experiments in a 1/7-scale facility for simulating steam natural circulation behavior in the vessel and in the hot leg and SG during the TMLB' scenrio. The objective of this study is to develop a natural circulation modeling which can be used both for the liquid flow condition at steady state and for the vapor flow condition at the later period of in-vessel core damage. For this, the drag forces resulting from the momentum exchange effects between the two vapor streams in the hot leg was modeled as a pressure drop by pump model. This hot leg natural circulation modeling of MELCOR was able to reproduce similar mass flow rates with those predicted by previous models.

I. Introduction

MELCOR [1] is a fully integrated, relatively fast-running code that models the progression of severe accidents in LWR plants. Previous MELCOR nodalization [2] for simulating the counter-current, natural circulation behavior of vapor flow within the RCS hot legs and SG U-tubes when core damage progress and SGs cease to be an effective heat sink were developed from, and benchmarked against, the calculation results of RCS natural circulation behavior performed by the SCDAP/RELAP5 model [3] which was in turn developed from results of COMMIX calculation [4] and the Westinghouse natural circulation experiments [5] in a 1/7-scale facility for simulating steam natural circulation behavior in the vessel and in the hot leg and SG during the TMLB' scenrio [2]. To model the gas natural circulation behavior, the hot legs were divided into top and bottom halves. The top half provided the flow path for hot vapor to move from the reactor vessel to SGs, while the cooler vapor flowed from the SGs back to the reactor through the bottom half of hot leg pipe. The SG tubes were also separated into two groups. One group was established to allow the hot vapor to flow from the inlet plenum to the outlet plenum, while the remainder provided the flow path for cooler vapor from the outlet plenum to the inlet plenum. The division of tubes into the two groups was based on the results of the Westinghouse 1/7-scale experiments. The form loss coefficients developed for previous MELCOR and SCDAP/RELAP5 nodalizations are, in general, a factor of 10 (to as high as 100) times larger than those suggested by standard hydrodynamic reference [6]. These nodalizations can be used only in the later phase of severe accident and can not be applied to the steady state and water-filled conditions during the initial period of accident progression because of the artificially high loss coefficients in the hot legs and SG U-tubes. The objective of this study is to develop a natural circulation modeling which can be used both for the liquid flow condition at steady state and for the vapor flow condition at the later period of in-vessel core damage.

II. Modeling and Assumptions

The hot leg countercurrent flow between the vessel upper plenum and the steam generator inlet plenum is driven by the density difference between the gases in these volume, and is opposed by drag between the two gas streams in the hot leg. The magnitude of the flow is determined largely by the balance of these forces, although the details of mixing in the steam generator inlet plenum may have a significant effects. The drag force between the two gas streams in the hot leg can be related with the effect of momentum exchange between the two gas streams in the hot leg. For simulating the effect of momentum exchange, opposed "pumps" are introduced into the halves of the split pipe as below [7]. The pressure drop developed by the pump can be made a function of the relative velocity between two streams by using a MELCOR control fuction based pump model ("QUICK-CF"). The positive flow directions of the hot leg top and bottom in the natural circulation nodalization are defined as reversely by user input as below, so each steam flow directions of the hot leg top and bottom will be positive under counter-current flow condition (reverse flow path definition).



The net momentum exchange (interfacial) force between the two gas streams can be expressed as an effective force, F. The force exerted by a pump on the fluid flow is ΔP A_{flow} where A_{flow} is the open flow area of the flow path associated with the pump. The forces exerted by each stream on the other should be equal and opposite, but the area may be unequal. Therefore, the two pumps should be defined as producing pressure boosts of

$$\Delta P_2 = F_{21} / A_{flow\,1} \quad \& \quad \Delta P_2 = - F_{21} / A_{flow\,2} \tag{1}$$

where F_{21} is the net force exerted by stream 2 on stream 1. If F_{21} is related with a net shear force acting on the interfacial area between the two fluid streams in the hot leg with radius of R and length of L, the value will be given by $F_{21} = 2RLF''$ (assuming a reasonably equal split of the total flow area), where F" is the force per unit area. A force balance for steady turbulent flow in a pipe yields

$$\pi R^2 \Delta p = \pi R^2\, 2 f L \rho v |v| / D = 2 \pi R L F'' \tag{2}$$

$$F'' = 0.5 f \rho V |V| \tag{3}$$

where f is a Fanning friction factor. Because the interfacial force between the two fluid streams can be expressed by the relative velocity, v_1-v_2, it is guessed by analogy that

$$F_{21} = 2RL \frac{f}{2} \rho \,(v_2 - v_1)\,|v_2 - v_1| \tag{4}$$

So,

$$\Delta P_{QUICK} = \frac{2RL}{A_{flow}} \frac{f}{2} \rho \,(v_2 - v_1)\,|v_2 - v_1| \tag{5}$$

It is assumed in Eq. (5) that velocities v_1 & v_2 are positive in the same physical direction. The flow areas of the hot leg top and bottom are split as same in the new & previous natural circulation nodalization.

The flow pattern will be co-current at the initial period of accident. By the reverse flow path definition of the natural circulation nodalization, the velocities of two gas streams in the hot leg are similar and opposite, $v_2 \cong -v_1$, then the relative velocity, $v_2 - v_1$, would be zero. So, the QUICK-CF pumps pressure would be negligible at the condition of co-current flow pattern. Therefore, Eq. (5) can be used to the steady state and initial period of accident.

For counter-current flow condition, because velocities v_1 & v_2 are assumed to be positive in the same physical direction by Eq. (5), the relative velocity becomes negative : $v_2 - v_1 = (-v') - v < 0.0$
The interfacial forces exerted by each stream on the other should be equal and opposite by the pump definition of Eq. (1). The mass flow rate can be used instead of flow velocities, v_j. The two QUICK-CF pumps simulating the interfacial drag force are installed oppositely at the middle of hot leg. Thus, the drag forces exerted by the QUICK-CF pumps are given for the counter-current flow condition :

$$\Delta P_1^{QUICK} \cong \Delta P_2^{QUICK} = \frac{F_{21}}{A_j}$$

$$= -2RL\frac{f}{2}\frac{\rho}{A_j}(v_2 + v_1)\left|v_2 + v_1\right|$$

$$= -2RL\frac{f}{2}\frac{\rho_{avg}}{A_j^3}\left(\frac{\dot{m}_{j,2}}{\rho_{j,2}} + \frac{\dot{m}_{j,1}}{\rho_{j,1}}\right)\left|\frac{\dot{m}_{j,2}}{\rho_{j,2}} + \frac{\dot{m}_{j,1}}{\rho_{j,1}}\right| \qquad (6)$$

where an average density, ρ_{avg}, of two flow paths is used. Eq. (6) is used to model the momentum exchange effect between the two gas streams in the hot leg by using the MELCOR control functions.

III. Result and Discussion

The hot leg natural circulation modeling of Eq. (6) was applied to the steam generator tube rupture (SGTR) sequence during severe accident in a Surry 3 loops PWR plant to prove that it can be used both for the liquid flow condition at steady state and for the vapor flow condition at the later period of in-vessel core damage. Previous SGTR analyses [6] used two nodalizations such as once-through & natural circulation models. The oncethrough nodalization represents RCS loop as a simple series of one-dimensional (and therefore, uni-directional flow) hydrodynamic control volumes using standard values of form & wall loss for each flow path, and applied from the steady state condition. The SGTR natural circulation model was similar to the MELCOR TMLB' natural circulation model [2], and applied to the later phase of accident because it did not allow water flow during the steady state & initial phase of accident due to artificially large loss coefficients. It is assumed that the vapor and water flow rates predicted by the previous oncethrough & natural circulation models for the Surry SGTR analysis [6] are correct values, because the Westinghouse test data was not available. The 3 RCS loops were lumped into 2 loops such as loop AB and loop C. Loop AB represents the combined volume and behavior of the 2 intact RCS loops. Loop C represents a single RCS loop containing faulted SG and pressurizer. All flow path data including form & wall loss of the new natural circulation nodalization are assured to be consistent with those of the oncethrough model. The two

QUICK-CF pumps simulating the interfacial drag force are installed oppositely at the middle of hot leg top and bottom of loop AB, and 2 QUICK-CF pumps are installed similarly at loop C. The SGTR sequence analyzed here is initiated by a double ended rupture of one U-tube in the loop C SG. It is assumed that operator actions to depressurize the RCS are not successful and a PORV on the faulted SG is assumed to stick open when the shell side of SG overfills with water. Automatic action of HPSI system is assumed to operate automatically to make up the RCS coolant mass lost through the ruptured tube untill the RWST inventory is depleted.

By the sensitivity study, three friction factors, f=0.6, 0.5, & 0.4, were found to match well with the old natural circulation model. The prediction results of the new natural circulation model (N-QUICK) with the QUICK-CF pumps which model the drag forces between the two vapor streams in the hot leg were compared with those of the oncethrough (Oncethru) and old natural circulation models (NAT) using friction factor f=0.5. Fig. 1 shows the mass flow rates of each model from the upper plenum to hot leg and from the cold leg to reactor downcommer for the intact loop AB and faulted loop C. The new model with the QUICK-CF pumps well matched the mass flow rates at the hot legs and cold legs with the other models. The mass flow rates of new model at the hot leg top and bottom from 100,000 sec to 120,000 sec were similar to those of old model as indicated in Fig. 2. Thus, it was shown that the new model can be used both for the liquid flow condition from steady state and for the vapor flow condition up to the later period of in-vessel core damage for the SGTR sequence, although other important parameter comparisons are not illustrated here.

IV. Conclusion

Previous MELCOR nodalizations for simulating the counter-current, natural circulation behavior of vapor flow within the RCS hot legs and SG U-tubes when core damage progress can not be applied to the water-filled conditions during the initial period of accident progression because of the artificially high loss coefficients in the hot legs and SG U-tubes The drag force resulting from the momentum exchange effects between the two vapor streams in the hot leg was modeled as a pressure drop by pump model using MELCOR code. This hot leg natural circulation modeling of MELCOR was able to reproduce similar mass flow rates with those predicted by previous models. Specially this modeling using the QUICK-CF pump model was powerfull to replace artificially high form & wall loss terms in old model. The objective of this study for developing a natural circulation nodalization which can be used both for the liquid flow condition at steady state and for the vapor flow condition at the later period of in-vessel core damage for SGTR sequence was achieved.

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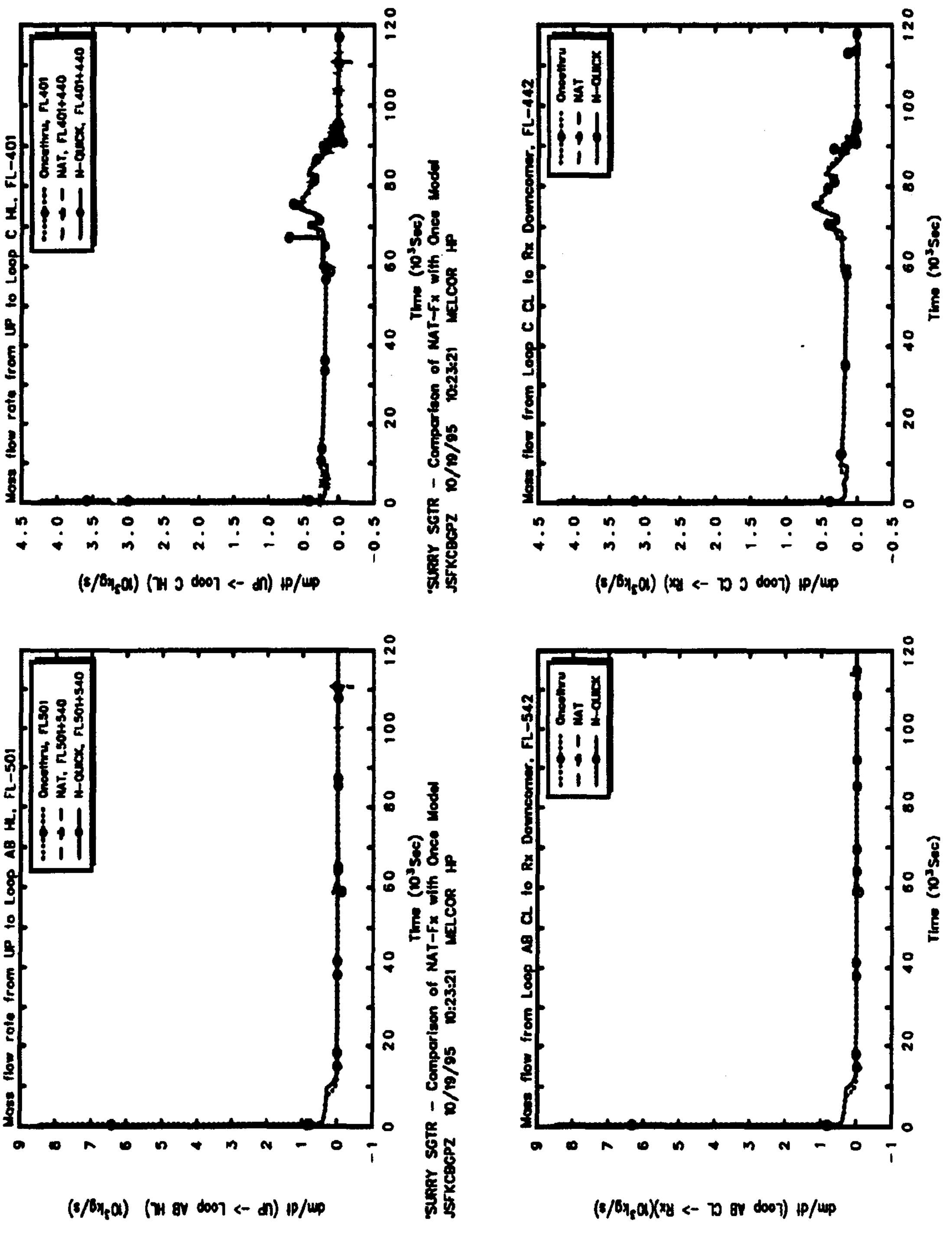

Fig. 1 Comparison of mass flow rates predicted by new model with those by previous models at the hot legs and cold legs

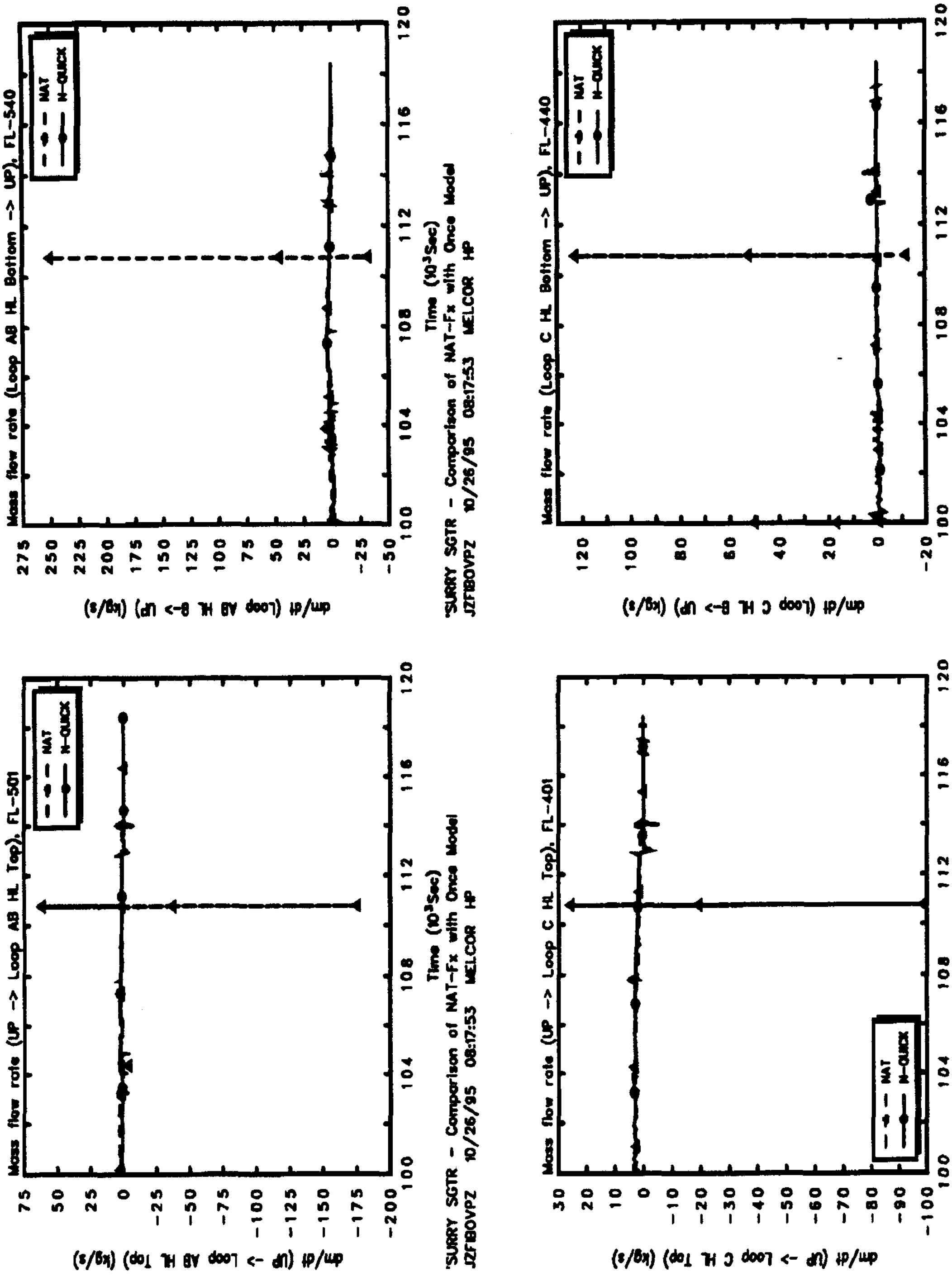

Fig. 2 Comparison of mass flow rates predicted by new model with those by previous models at the hot legs top and bottom