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Development of Piping Analysis Procedure of a PWR Surge Line for Stratified Flow

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Abstract

Piping Systems are usually designed for thermal expansion loads based on uniform temperatures at each cross section. However, in lines with low flow rates such as surge lines and spray lines, large transverse temperature gradients have been observed, resulting in two types of additional thermal stresses : (1) local thermal gradient stresses which are independent of routing and supports and (2) gross bending stresses due to induced pipe curvature which are routing and support system dependent. This paper presents a simplified method for analyzing a PWR surge line for stratified flow.

1. Introduction

The surge line in a PWR is typically a stainless steel pipe connecting the pressurizer and one hot leg pipe. Previous industry and NRC accepted design practice included dead weight, pressure, seismic, thermal expansion along the length of pipe and uniform circumferential thermal transients in the design bases. Recent observations at operating plants and subsequent U.S. NRC requirements[1,2,3] have identified a flow stratification in surge lines as a phenomenon that must be also considered in the design bases of surge line. A stratified flow is a condition in which hotter fluid flows over a colder region of the fluid. Although the mechanism initiating stratified flow is not fully understood, hot water flowing from the pressurizer through the surge line to the main loop flows over a layer of cooler water, resulting in the upper portion of the pipe being hotter than the lower portion.

Pipe loads resulting from stratified flow cause increased overall bending stresses and create local high stresses in the pipe cross section due to non-linear circumferential metal temperature distribution. Analysis requires definition of both the magnitude and distribution of the resulting top-to-bottom temperature differential and axial temperature distribution along the pipe. When these are known, pipe designs, routings and support arrangements can be evaluated. This paper presents a method for predicting the circumferential temperature distributions and the pipe top-to-bottom temperature differentials due to stratified flow condition. Also, a method for analyzing the gross bending stresses due to the stratified flow induc ed pipe curvature is presented.

2. Descriptions of Method

Piping analysis of a PWR surge line for stratified flow is divided into two areas of analytical evaluations. The first area is to perform heat transfer analysis for the surge line piping. The purpose of this evaluation is to obtain the outside pipe metal temperature distributions from the fluid conditions inside the surge line piping. Two dimensional finite element heat transfer analyses of the pipe cross section are performed to calculate the pipe wall temperature distributions for the design bases events. The second area of the evaluations is to perform structural analysis to determine piping stresses due to stratified flow induced curvature. The purpose of this analysis is to determine the stresses based on ASME SEC. III NB-3600. A special purpose piping analysis program, SUPERPIPE, is used to check the ASME code criteria.

3. Heat Transfer Analysis for Stratified Flow

The first step in the heat transfer analysis is to develop the thermal hydraulic model for stratified flow. A bounding analytical heat transfer model with various inside fluid conditions is developed in order to simulate the stratified flow condition. The stratified flow is defined by hot fluid(Pressurizer temperature) in the upper portion of the pipe and cold fluid(Hot leg temperature) in the lower half with sharp interface in between. During an outsurge from the pressurizer to the RCS(reactor coolant system), it is assumed that the upper(hotter) fluid is moving and the lower(colder) layer was stationary. Conversely, during an insurge from the RCS to the pressurizer, flow is assumed to occur only in the lower portion of the pipe. For the moving layer, the Reynolds number(Re) was calculated based on the expected flow rate. The Colburn equation[7] was then used to calculate the corresponding value of Nusselt number(Nu). For the stationary layer, it is assumed that the flow is laminar. The average heat transfer coefficients on the inside of the pipe were then calculated based on the relationship as shown in TABLE 1.

Table 1. Heat Transfer Coefficient(7)

Forced : Laminar	Forced : Turbulent
Re<2300	Re>2300
$Nu=3.6$	$Nu=0.023Re^{0.8}Pr^{0.33}$
$h_{avg}=N_u \cdot k/D_h$	$h_{avg}=N_u \cdot k/D_h$

where Pr : Prandtle Number
k : Thermal conductivity of the fluid
D_h : Hydraulic diameter based on flow area
h_{avg} : Average heat transfer coefficient

The boundary condition at the bottom of the pipe is assumed to be constant through the wall and equal to that of the hotleg as shown in Figure 1. The typical measured data[4,5] for the operating plant, as shown in Figure 2, corroborates this assumption. Figure 2 presents the typical temperature variations along the circumferential direction at the given pipe cross sections during a pressurizer outsurge. As indicated, the temperatures at the bottom of the pipe remain nearly constant and close to the hot leg temperature.

The second step in this evaluation is to calculate the circumferential temperature distributions at the pipe cross-section using the thermal hydraulic model. To determine the pipe wall temperature distribution

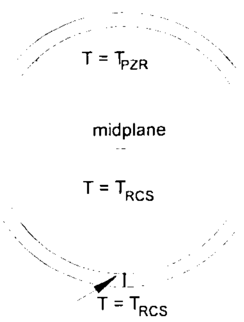

Fig. 1. Thermal hydraulic model for stratified flow analysis

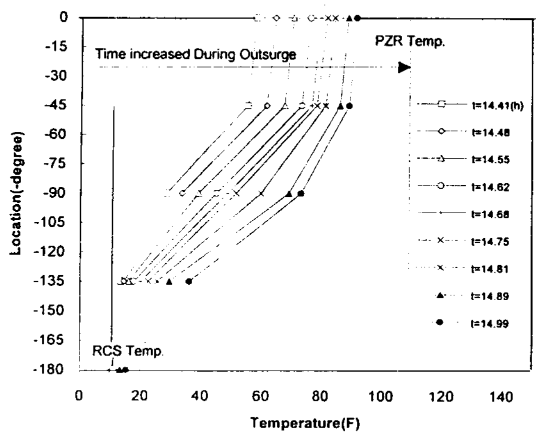

Fig. 2. Circumferential temperature distributions during an outsurge

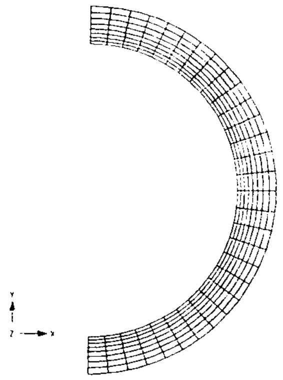

Fig. 3. Finite element model for heat transfer and structural analysis

for stratified flow, a 2-D finite element model of surge line cross-section is developed. This model is shown in Figure 3.

4. Structural Analysis for Stratified Flow

For the structure analysis of surge line for stratified flow, a transverse temperature gradient should be applied to the piping analysis model. Some general-purpose finite element programs permit direct input of a transverse temperature gradient in a beam or pipe element. However, this option is not usually available in special purpose piping analysis programs. Moreover, many of the general purpose piping programs do not permit the transverse gradient in curved pipe or elbow elements. Both of these problems can be overcome by application of equivalent support displacements, using the method of redundant structural analysis[6]. The basic steps are as follows : (1) calculate pipe curvature using separate finite element analysis, (2) remove enough supports to make the structure statically determinated, (3) calculate equivalent displacements at each support location by applying the calculated pipe curvatures, and (4) restore the displacements at each location to zero. The application of sets of equal and opposite displacements as support motions yields the bending stresses which would result from a stratified flow condition. Whereas the stresses are correctly calculated, the computed displacement must be corrected by subtracting the displacement corresponding to the initially deformed shape.

4.1 Calculation of Pipe Curvatures

For stratified flow loading, the pipe curvature is determined in order to reflect the bending moment effects of the top to bottom temperature differential. A two dimensional structural analysis is performed to calculate the pipe curvature. The temperature distribution calculated from the heat transfer analysis is used as an input to this structural analysis. Figure 3 shows a finite element model used for this analysis.

4.2 Calculation of Equivalent Displacements

For straight pipe anchored at one end as shown in Figure 4, the displacement and rotation angle at any point are calculated as follows:

$$\Delta y = -(1/2)Kx^2$$

$$\Delta\theta = Kx$$

where K : pipe curvature

These formulas also can be applied to other geometries as shown in Figure 5. This is a consequence of

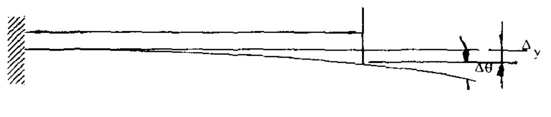

Fig. 4. Equivalent Displacement for Straight Piping

the fact that a structure is stress-free under a linear temperature gradient. The displacements at any point are therefore independent of the route taken by the pipe, since they are the same as would be calculated for a straight pipe segment running directly from the anchor to the point in question. Thus, with the pipe supported only as anchor A, the displacement at support B in Figure 5 can be calculated as follows :

$$\Delta y_B = -(x_B^2 + z_B^2)/2$$
$$\Delta\theta_x|_B = -Kz_B$$
$$\Delta\theta_B = K(x_B^2 + z_B^2)^{1/2}$$
$$\Delta\theta_z|_B = -Kx_B$$

To obtain the displacement to be applied at anchor D, the displacement and rotation at C is first calculated :

$$\Delta y_C = -K(x_C^2 + z_C^2)/2$$
$$\Delta\theta_z|_C - Kx_C$$
$$\Delta\theta_x|_C - Kz_C$$

Since the segment CD remains straight,

$$\Delta y_D = \Delta y_C$$

and

$$\Delta\theta_z|_D = \Delta\theta_z|_C$$
$$\Delta\theta_x|_D = \Delta\theta_x|_C$$

and

$$\Delta x_D = \Delta\theta_z|_C \times H$$
$$\Delta z_D = \Delta\theta_x|_C \times H$$

Since all support displacements must be restored to zero, the internal bending stresses due to the transverse temperature gradient are obtained by applying equal and opposite displacements $-\Delta y_B$, $-\Delta\theta_x|_B$ and $\Delta\theta_z|_B$ at support B and $-\Delta x_D$, $-\Delta y_D$, $-\Delta z_D$, $-\Delta\theta_x|_D$ and $-\Delta\theta_z|_D$ at anchor D. Any piping analysis program can perform this analysis and combine the results with those of the other load conditions.

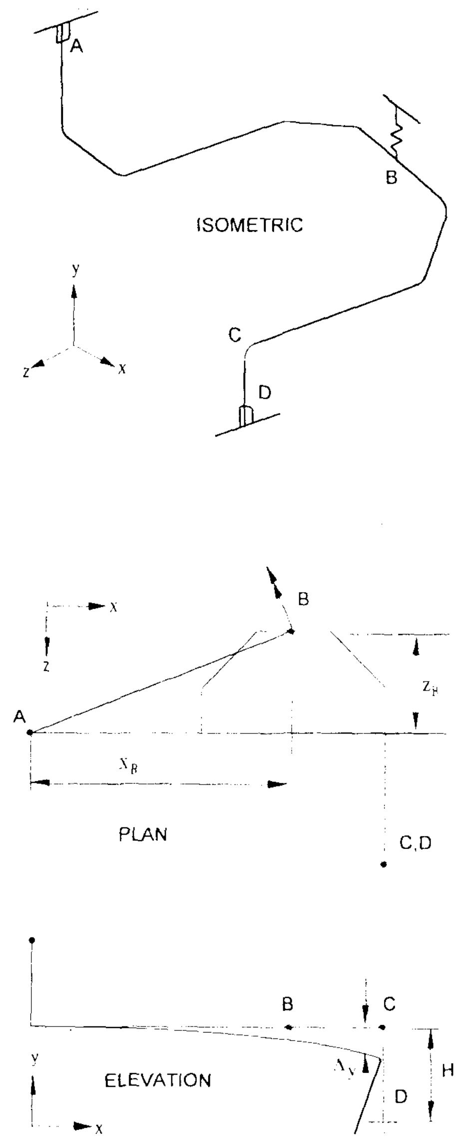

Fig. 5. Equivalent Displacement for Arbitrary Piping System

5. Application to the YGN 3 Surge line Stratification Test Evaluation

5.1 Circumferential Temperature Distributions

A heat transfer analysis was done to calculate the pipe wall temperature distributions for selected time points during YGN 3 heatup and cooldown, using the thermal hydraulic model developed in section 3. The time points selected were those containing the largest top-to-bottom temperature differentials during heatup and cooldown. In order to calculate the heat transfer film coefficients on the inside of the pipe, the Reynolds number(Re) was calculated based on a half the fluid in the piping having the measured flow rate and the other half of the fluid being stationary. The properties of each fluid were at their respective temperatures and were considered to be saturated water. Table 2 shows the fluid temperature and heat transfer coefficients at the top and bottom inside surface of the pipe at the selected time points. During the YGN 3 stratified flow test, some portions of the pipe including the measurement locations were not insulated. Thus the outside surface of the pipe exposed to air was assumed to be cooled by natural convection and radiation. The film coefficient at the outside surface was calculated as fllows ;

Heat transfer coefficient due to radiation (h_r)[7]

$$q_r = \varepsilon \cdot \sigma(T_2^2 + T_1^2)(T_2 + T_1)(T_2 - T_1)$$
$$h_r = \varepsilon \cdot \sigma(T_2^2 + T_1^2)(T_2 + T_1)$$

where q_r is heat transfer rate due to radiation,
σ is Stefan-Boltzmann constant (5.699×10^{-8} W/m^2 °K^4),
ε is emissivity assumed as 0.6[7] in this analysis, and
T_1, T_2 are temperature in °K.

Heat transfer coefficient due to natural convection (h_c)[7]

$$h_c = N_u \cdot k/D_h$$
$$N_u = 0.14(Gr \cdot Pr)^{1/3}$$

where $Gr = (g\beta D_h^3/v^3)(T_2 - T_1)$;Grashof number[7],
g is the gravity,
β is the volume coefficient of expansion, and
v is the kinematic viscosity.

Thus the combined heat transfer coefficient(h) is

$$h = h_c + h_r$$

Table 2. Thermal Hydraulic Data Used for the Analyses

	Heatup	Cooldown
$T_{PZR}^{(1)}$	440℃	440℃
$T_{RCS}^{(1)}$	120℃	146℃
$h_{top}^{(2)}$	590W/m^2℃	138W/m^2℃
$h_{bot}^{(2)}$	17W/m^2℃	17W/m^2℃
T_{air}	38℃	38℃

Note
(1) Data obtained from stratified flow test for YGN 3.
(2) Heat transfer coefficient at the upper portion of the fluid.
(3) Heat transfer coefficient at the lower portion of the fluid.

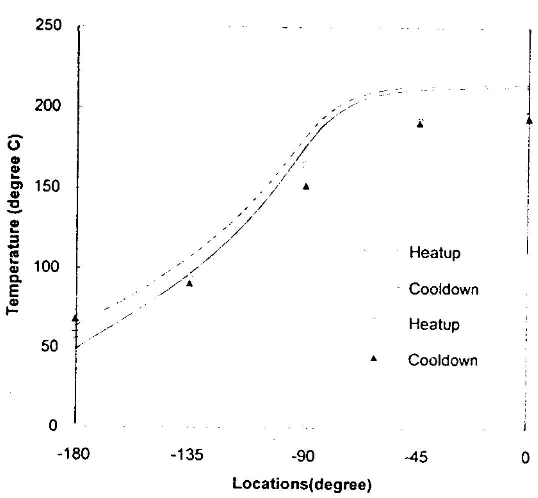

Fig. 6. Comparison of circumferential temperature distributions

Figure 6 shows the comparison of calculated circumferential temperature distributions along with the measured values during YGN 3 SST(Surge line Stratified flow Test) period[4,5]. The plot shows that the circumferential temperature distributions due to stratified flow can be conservatively predicted using this thermal hydraulic model.

5.2 Surge Line Displacements for Stratified Flow

The YGN 3 surge line displacements(Figure 7) were also calculated by modeling the surge line system on the SUPERPIPE computer program which is a conventional piping analysis computer program developed by VECTRA. The SUPERPIPE program, like a most piping analysis program, does not accept circumferential temperature variations but it can perform stratified flow analysis based on pipe curvatures converted to sets of equivalent support displacements. The time point which contains the largest pipe displacement was selected for this evaluation. First of all, the pipe curvature was calculated by applying the measured pipe temperatures to the CEMARC unit-length finite element model(Figure 3). The pipe curvature was then input into the SUPERPIPE model for bending effects. The variation of pipe curvature was assumed to be linear between thermocouple locations. This is based on the fact that there are no discontinuities in the piping system which would cause a major deviation from a linear variation.

The resulting displacements are listed in TABLE 3 along with the measured and calculated values using SUPERPIPE for comparison. TABLE 3 indicates that good agreement exists between measured and calculated values. The small descrepancies are due to the portions of the pipe at thermocouple locations that were uninsulated. A parametric study shows that with

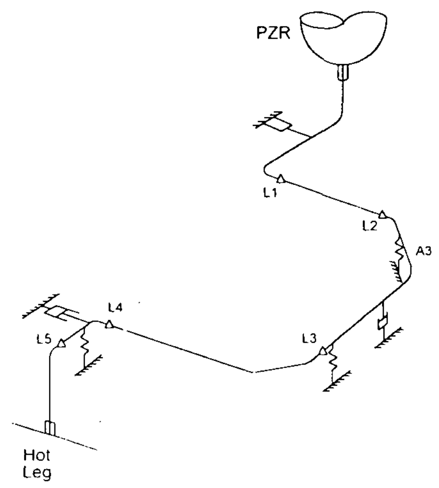

Fig. 7. YGN 3 & 4 Surge Line Geometry

Table 3. Vertical Displacements at each measurement loacations(unit : mm)

	L1	L2	L3	L4	L5
Measured	−3.048	−59.944	−94.996	21.082	5.080
Superpipe	−4.064	−51.054	−82.550	12.192	4.826

the same fluid conditions inside the surge line, an uninsulated pipe has temperature and curvatures that are approximately 14% and 15% lower, respectively, than an insulated pipe.

6. Conclusions

(1) The maximum pipe wall top to bottom temperature differentials and circumferential temperature distributions of the pipe due to stratified flow can be predicted with simple thermal hydraulic model presented in this paper.

(2) Using the method of redundant structural analysis presented in this paper, it is possible to perform stratified flow analysis by applying stratified flow induced pipe curvature to a piping analysis model.

(3) The method presented here can be used with the most piping analysis programs to consider stratified flow in the analysis of several arrangements during piping design.

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