Transient Response of Thermal Stress at a PWR Pressurizer Surge Line Pipe Subjected to Internally Thermal Stratification

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Abstract

This paper presents the numerical calculation results of the transient response of thermal stress at a pressurizer surge line pipe model of pressurized water reactor (PWR) subjected to internally thermal stratification. The transient temperature distributions in the piping system used as the requisite input data for the stress analysis are obtained by conducting three-dimensional numerical analysis of the unsteady conjugate heat transfer for the piping system with a finite wall thickness. A primary emphasis of the present study is placed on the investigation of the effects of surge flow direction on the determinations of the thermal stress distributions in the pipe wall. In the present numerical analysis, the thermally stratified flows (insurge and outsurge flows) in the pipeline are simulated using the standard $k-e$ turbulent model. The unsteady conjugate heat transfer analysis method is implemented in a finite volume thermal-hydraulic computer code based on a non-staggered grid arrangement, SIMPLEC algorithm and higher-order bounded convection scheme. The finite element code ANSYS is employed for the thermal stress analysis to calculate non-dimensional stress distributions at the piping wall as a function of time. Some numerical calculations are performed for a simplified PWR pressurizer surge line piping model with a shortened length, subjected to internally thermal stratification caused either by insurge or outsurge flow with a specified velocity, and the results are discussed in detail.

1. Introduction

In a piping system where hot and cold fluids coexist, the flow is stratified due to the difference in density (or temperature) between both fluids. Such thermal stratification causes the convective or conductive heat transfers between the stratified fluids and the pipe wall, in the fluid region, and in the pipe wall, which results in temperature gradients in the pipe wall. The steep temperature gradients can produces undesirable excessive thermal stress at the pipe in axial, circumferential, and radial directions, which may eventually threaten the integrity of piping system.

The piping systems of PWR nuclear power plant which are susceptible to the thermal stratification include pressurizer surge lines, emergency core cooling lines, residual heat removal lines, pressurizer spray lines, charging lines etc. Especially, the thermal stratification in the pressurizer surge line has been addressed as one of the significant safety and technical issues in most countries holding nuclear power plants since the USNRC issued Bulletins 88-08 [1] and 88-11[2] in 1988, requesting licensees to take proper actions for resolution of the issue. Thus, assessing the potential for piping damage due to the thermal stratification is one of the most important requisites to ensure the safety of operating nuclear power plants.

Several investigators [3-8] have made efforts to determine the temperature and stress distributions in the pipe wall by means of laboratory testing of a particular geometry or field measurement of temperatures or fully theoretical predictions. There are much difficulties and limitations in applying

the first two approaches for operating plants. Only a few literatures addressing the theoretical analyses are available. Yu et al. [7] obtained temperature and stress distributions for the steady-state heat transfer model of PWR pressurizer surge line. The model was simplified by using a commercial finite element analysis code based on the assumptions that the inside of the pipe wall is exposed to two distinct ambient fluids of which the temperatures are constant. An essential prerequisite for assessing the structural integrity of a piping system subjected to internally thermal stratification is to determine the transient temperature distributions in the pipe wall.

In this study, the transient temperature distributions in the pipe model subjected to internally thermal stratification are determined employing the computer program developed by Jo et al. [9] for the 3-dimensional unsteady turbulent conjugate heat transfer analysis of curved piping systems. Validation of the computer code was made by comparing the calculation results with available experimental data for a stratified laminar flow in a duct flow where the existence of wall thickness is neglected.

The stress analysis is performed using the commercial finite element code ANSYS [10]. The transient response of the stress distributions at the wall of piping system in which thermally stratified fluids flow is calculated from the transient temperature field obtained from the conjugate heat transfer analysis mentioned previously. Numerical calculations are performed for both cases of pressurizer surge flow causing thermal stratification called insurge or outsurge flows. Here, the insurge (outsurge) flow means the situation where the cold (hot) fluid coming up (down) from the bottom (top) inlet into the pipe line which is initially occupied with the hot (cold) fluid.

2. Problem

A typical schematic of PWR pressurizer surge line system and its simplified analysis model with shortened length are shown in Fig.1 and Fig.2, respectively.

Considering first the situation of insurge flow, hot fluid of specified temperature is flowing through the piping system so that the steady flow and thermal conditions are maintained initially, and then at a certain point of time cold water begins to flow up into the pipe bottom nozzle (the inlet for the case of insurge flow which is connected to the reactor coolant system) at a constant flow rate. In case of the outsurge flow, cold fluid is flowing through the pipe with maintaining a steady-state condition initially, and then at a certain time hot water begins to flow down into the pipe top nozzle (the inlet for the case of outsurge flow which is connected to the pressurizer).

In either situation, the cold fluid occupies the lower space of the pipe without mixing well with the hot fluid occupying the upper space due to the difference in density between the two fluids. This results in so-called thermally stratified flow in the pipe. Because the plant piping system is generally insulated to prevent heat loss, the adiabatic condition is specified at the outer wall surface of present pipe model.

Because the solution domain is symmetric thermally and geometrically, only half of the domain is solved. Thus along the symmetry plane, the symmetry boundary conditions are applied for all velocity components and temperature. On the solid inner wall, the wall function method is applied.

To obtain a suitable numerical mesh, it is assumed that the solution domain involves the pipe wall region and the fluid region of annulus between two concentric cylinders, where the outer cylinder is the pipe and the inner one is an infinitesimal such that the effect of its presence on the numerical calculations is negligible.

3. Numerical Solution Methods

In the present analysis, it is assumed that the thermally stratified fluids are Newtonian with constant properties and the Boussinesq approximation is valid. The $k - e$ turbulence model with wall function method is employed. The governing equations for conservation of mass, momentum, energy, and turbulence transport in a generalized coordinate system are the same as in the previous work [9].

The solution domain is divided into a finite number of hexahedral control volume cells. The discretization of the governing equations is performed following the finite volume approach. The

convection terms are approximated by a higher-order bounded scheme HLPA developed by Zhu [11] and the unsteady term is treated implicitly using the three-level second order scheme suggested by Ferziger and Peric [12]. The cell-centered, non-staggered grid arrangement is adopted in the present study. The wall function provided by Peric [13] is modified to the boundary condition at the inner wall surface of pipe in the present numerical analysis of unsteady conjugate heat transfer.

The momentum equations and energy equation are solved implicitly at the cell-centered locations. The resulting checkerboard pressure oscillation is prevented by the application of momentum interpolation method proposed by Rhie and Chow [14]. The original Rhie and Chow scheme is further modified in this study to obtain a converged solution for unsteady flows which is independent of the size of time step and relaxation factors.

The numerical method used here to treat the unsteady conjugate heat transfer is the extension of the Patankar's equivalent conductivity concept for the steady-state conjugate heat transfer analysis in the two-dimensional orthogonal grid system [15] to the unsteady flow analysis in the three-dimensional non-orthogonal grid situation, which makes the computer programming and computation easy. Details of the flow and heat transfer analysis described above can be found in the previous work [9].

The thermal stress in the surge line was evaluated using commercial finite element analysis (FEA) program, ANSYS [10]. The three-dimensional 8 node solid element (SOLID 45) in ANSYS was selected for the analysis. Totals of 39,168 nodes and 34,441 elements were modeled for the half of the surge line considering symmetry across the piping section.

The inlet and outlet nozzles of the surge line were assumed as terminal ends because they are connected with heavy components such as reactor coolant piping and pressurizer. The terminal ends are modeled as fixed points in the FEM calculation. The internal fluid pressure was not considered since this evaluation focuses on the thermal stress due to internally stratified flow.

4. Results and Discussion

The computer code [9] developed on the basis of the numerical method of flow and heat transfer analysis is used for the present calculations of transient temperature distributions in the pipe model subjected to internally thermal stratification. The code was validated in the previous work [9] by comparing the calculation results for the non-conjugate problem of curved duct with adiabatic thin wall, where the effect of wall thickness is neglected, with the measured data of Ushijima [16]. The result has shown that the prediction by the numerical approach applied for the present analysis agrees fairly well with the measurements by Ushijima.

First, to obtain the transient temperature distributions in the analysis model of PWR pressurizer surge line (see Fig. 2) subjected to internally thermal stratification with high Richardson number, a 3-dimensional unsteady turbulent conjugate heat transfer analysis has been analyzed. The calculations are performed for symmetric half of the solution domain. The 102 x 42 x 32 numerical grids are generated algebraically. The Reynolds number Re based on the hydraulic diameter of the pipe and the inlet velocity is 60,000, and the Richardson number $\text{Ri} = \Delta \boldsymbol{r} \, g \, d_i / (\boldsymbol{r}_{avg} \, u_{in}^2)$ is such a high value of 45 that the buoyancy force affects strongly the flow field.

In calculations, first, the steady state solution is obtained for the piping system involving the flowing fluid maintained either at high temperature of 232°C (for the situation of insurge flow) or low temperature of 80°C (for the situation of outsurge flow) and then the transient solutions for simulating the situation after the fluid with different temperature instantly begins to surge into the pipe maintained at the steady state condition are obtained using the steady state solution as initial condition. The inlet velocity of either surge flow is considered to be 0.05m/sec. Calculations are continued until 200 seconds using the time step size of 0.05 sec. The convergence of computation is declared at each time step when the maximum of the absolute sum of the residuals of momentum equations, pressure correction equation and energy equation is less than 10^{-3}. Other details of the computational parameters are provided in the Table 1.

Based on the present calculation results of transient temperature distributions in the wall of surge line model which were obtained from the above flow and heat transfer analysis, thermal stress analysis has been performed. The thermal stress in the surge line was evaluated using commercial finite

element method (FEM) program, ANSYS [10]. The three-dimensional 8 node solid element (SOLID 45) in ANSYS was selected for the analysis. Totals of 39,168 nodes and 34,441 elements were modeled for the half of the surge line considering symmetry across the piping section. The inlet and outlet nozzles of the surge line were assumed as terminal ends because they are connected with heavy components such as reactor coolant piping and pressurizer. The terminal ends are modeled as fixed points in the FEM calculation. The internal fluid pressure was not considered since this evaluation focuses on the thermal stress due to internally stratified flow.

As a measure of the thermal stress, the well-known von-Mises stress is used in this paper. The von-Mises stress $\boldsymbol{s}_{eff}$, is defined as

$$\boldsymbol{s}_{eff} = \sqrt{\frac{1}{2}\left[(\boldsymbol{s}_1 - \boldsymbol{s}_2)^2 + (\boldsymbol{s}_2 - \boldsymbol{s}_3)^2 + (\boldsymbol{s}_3 - \boldsymbol{s}_1)^2\right]}$$

where $\boldsymbol{s}_1$, $\boldsymbol{s}_2$ and $\boldsymbol{s}_3$ are the principal stresses. The calculated effective stresses were normalized by the yield stress $\boldsymbol{s}_y$.

Fig. 3 displays how the surge line pipe model is deformed when it is subjected to internally thermal stratification. The deformations at the elbow area are larger than those at both the horizontal piping area and the nozzle area because both inlet and outlet nozzles are assumed to be fixed points, which are, connected either the reactor coolant system or the pressurizer.

Fig. 4 shows the normalized effective stresses as a function of time for the case of insurge flow. The insurge flow case is that the surge line has initially the fluid of 232°C and at certain point of time the fluid of 80°C starts to surge in from the reactor coolant system through the bottom nozzle (inlet nozzle (p1) for this case of insurge flow) with the flow rate of 0.05m/sec. As shown in the figure, very high stresses are initially applied at both nozzles (p1 and p7) because of both the high initial fluid temperature of 232°C and the fixed boundary condition at the nozzles.

The figure also shows that the initial high stress at the outlet nozzle (p7) in the insurge case is slightly changed by the time of 100sec because the hot fluid only surges in near the elbow (p3) until 100sec, and that the stresses at both nozzles are relieved as the cold water of 80°C flows into the surge line pipe model so that the pipe model is to be cooldown.

In particular, the stress at the bottom nozzle (p1) rapidly decreases while that at the top nozzle (p7), which is maintained higher than at the bottom nozzle throughout the transient period of thermal stratification evolution, is smoothly decreases. The reason for the steep decrease is that the cold fluid rapidly relaxes the initial thermal expansion at the inlet nozzle. The stresses at the elbow (p2) and horizontal piping (p4) slowly increase and then decrease as the fluid of 80°C continuously surges in. However the stress levels at the elbow (p2) and horizontal piping (p4) are not so high compared to those at the nozzles. It means the nozzles are weak points for the integrity of the surge line piping.

The normalized effective stresses as a function of time for the case of outsurge flow is shown in Fig. 5. The outsurge flow case is that the surge line has initially the fluid of 80°C and at certain point of time the fluid of 232°C begins to surge out from the pressurizer through the top nozzle (inlet nozzle (p1) for this case of outsurge flow) with the flow rate of 0.05m/sec.

In this case, the initial stresses at both nozzles are low with the same level because the whole piping system is initially maintained at low temperature. The stresses at the top nozzle (p1) steeply increase in a moment when the hot water of 232°C surging out from the pressurizer flows into the surge pipe and then smoothly decrease, while the stresses at the bottom nozzle (outlet nozzle (p7) for this case of outsurge flow) slightly increase. Throughout the transient period when the flow stratification is maintained, the stress at the top nozzle (p1) is maintained higher than that at the bottom nozzle in the same way as the insurge flow case. Similar to the insurge flow case, the stresses at the elbow (p2) and horizontal piping (p4) slightly increase and then decrease as the fluid of 232°C continuously surges in.

From Figs. 4 and 5, it can be found out that the transient thermal stress at the top nozzle which functions either as the outlet nozzle for the insurge flow case or the inlet nozzle for the outsurge flow case is maintained at much higher level than at bottom nozzle and that the transient stresses at the top nozzle for the outsurge flow case are greater than those for the insurge flow case.

Fig. 6 displays the normalized effective stresses along the surge line from the inlet nozzle to the outlet nozzle for the insurge and outsurge flow cases at 100sec. The trends of transient evolution of

temperature fields and thermal stress distribution in the pipe for the insurge flow case are just opposite to that for the outsurge flow case but the development and duration times of thermal stratification for both cases of surge flows are nearly equal each other and also the stress levels of insurge flow case are similar to those of outsurge flow case except in the nozzle area. The reason for the reverse trend is that the temperature change directions in the insurge and outsurge cases are different from each other.

The findings discussed above may suggest that to evaluate the integrity of PWR pressurizer surge line system with a conservatism the transient temperature distributions in the piping system should be taken from the conjugate heat transfer analysis for the outsurge flow case rather than the outsurge flow case. In addition, the top nozzle support should be designed more strongly than the bottom nozzle support.

5. Conclusions

Detailed numerical analyses of unsteady conjugate heat transfer and thermal stress were performed for a PWR pressurizer surge line pipe model subjected to internally thermal stratification caused either by in-surge or out-surge flow.

Main emphasis of the study was placed on the investigation of the effects of surge flow direction on the determinations of the transient temperature and thermal stress distributions in the pipe wall.

The thermally stratified flows in the pipe were simulated using the standard $k - e$ turbulent model and a simple and convenient numerical method of treating the unsteady conjugate heat transfer was provided. The finite element method was employed for the thermal stress analysis.

Based on the discussions of calculation results, it is recommended that for the robust design as well as the reliable safety (integrity) evaluation of a PWR pressurizer surge line system the transient temperature distributions in the piping system should be taken from the 3-dimensional conjugate heat transfer analysis for the outsurge flow case rather than the outsurge flow case. In addition, the top nozzle support should be designed more strongly than the bottom nozzle support.

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Table 1. Computational parameters

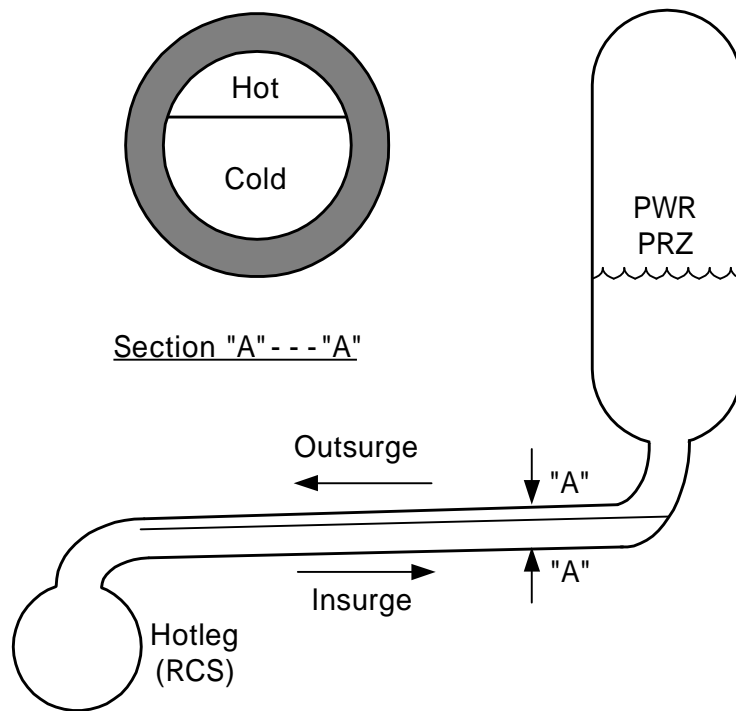| Parameters	Values
Material of pipe	SA-762-TP-316
Outer diameter of pipe, d_o	0.305 [m]
Inner radius of pipe, d_i	0.233 [m]
Conductivity of pipe, k_s	15.4 [W/m^{o}C]
Hot fluid temp., T_h	232 [^{o}C]
Cold fluid temp., T_c	80 [^{o}C]
Thermal diffusivity ratio, a_s/a_f	22.2
Thermal conductivity ratio, k_s/k_f	22.65
Re [$= \rho u_{in} d_i / \mu_f$]	6.0×104
Ri [$= \Delta\rho\, g\, d_i / (\rho_{avg}\, u_{in}^2)$]	45

Fig. 1 PWR pressurizer surge line piping system subjected to internally thermal stratification (PRZ = pressurizer, RCS= reactor coolant system).
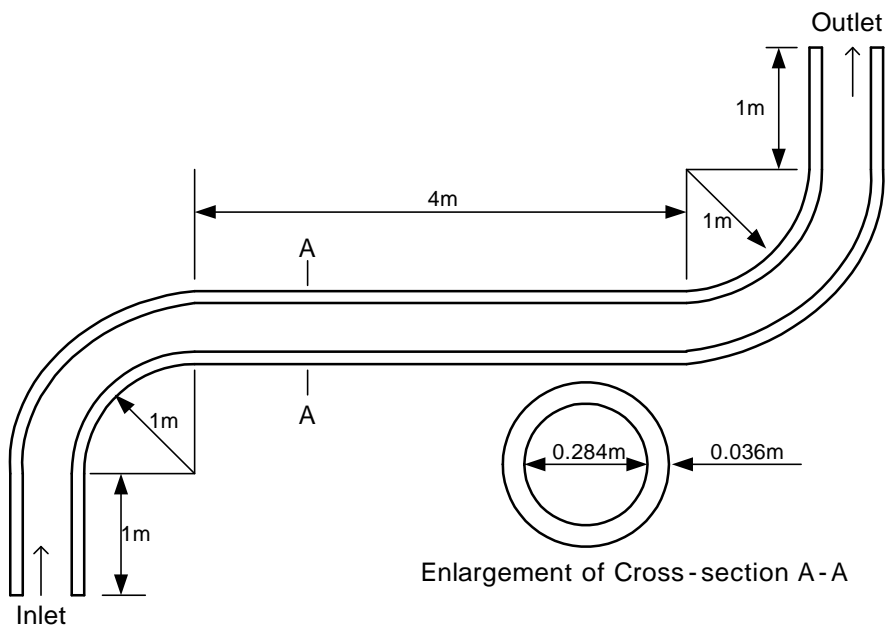

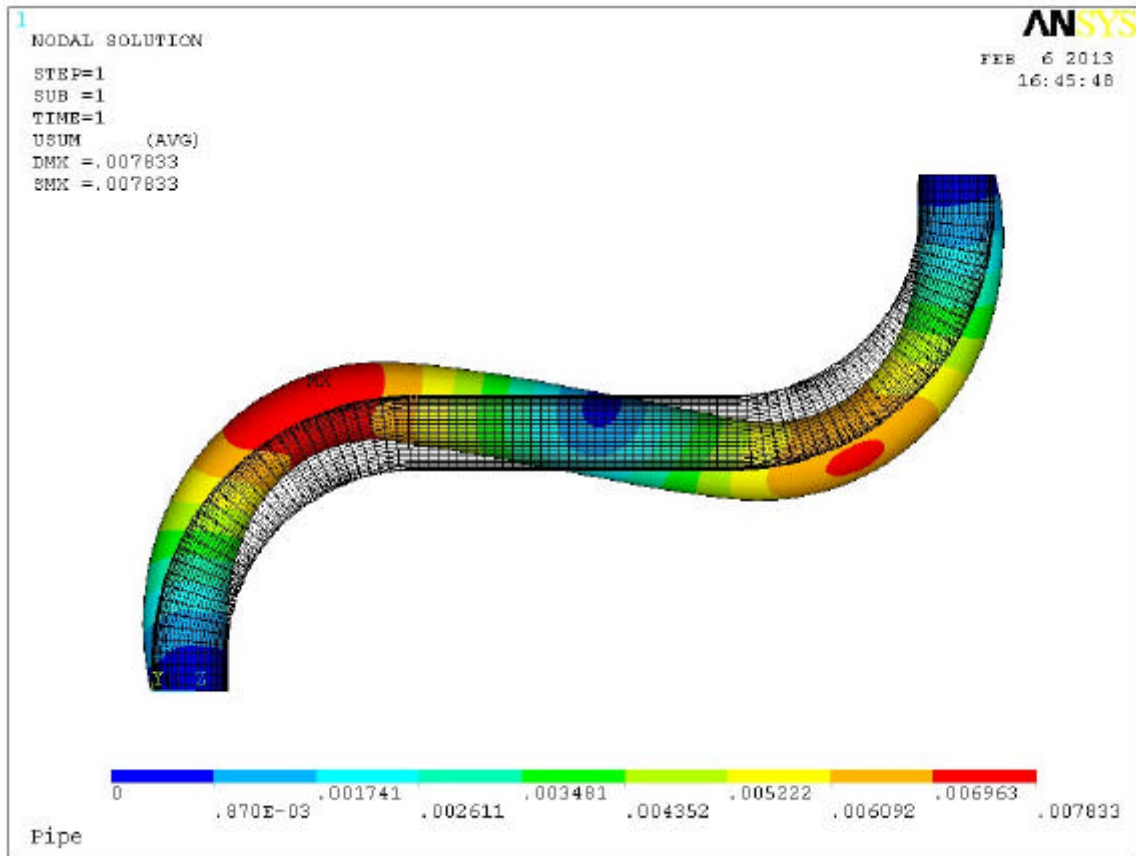Fig. 2 The simplified pressurizer surge line pipe model

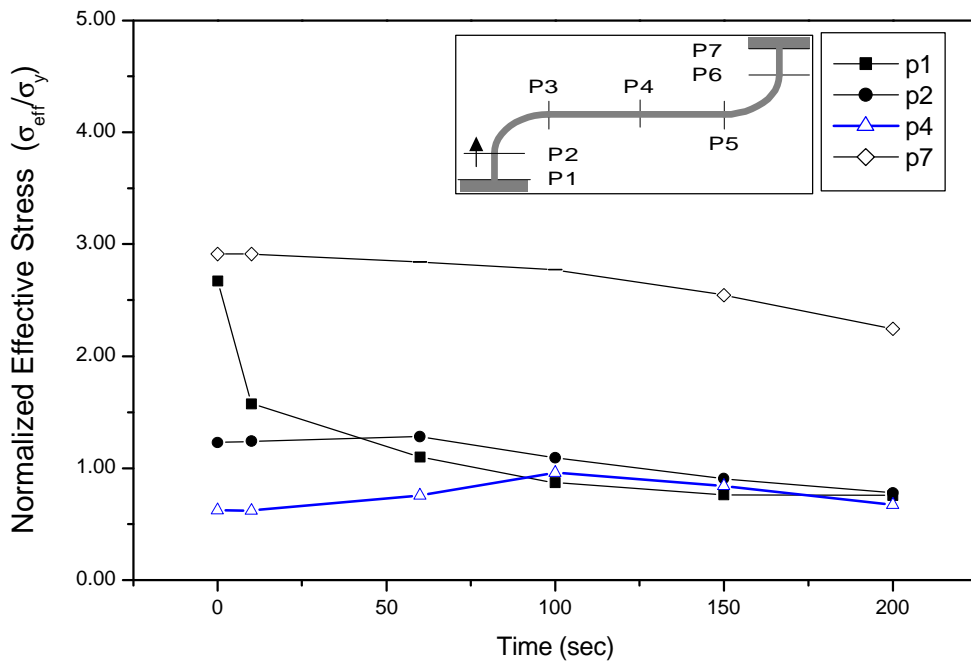Fig. 3　Deformed shape of the surge line model with non-deformed shape.

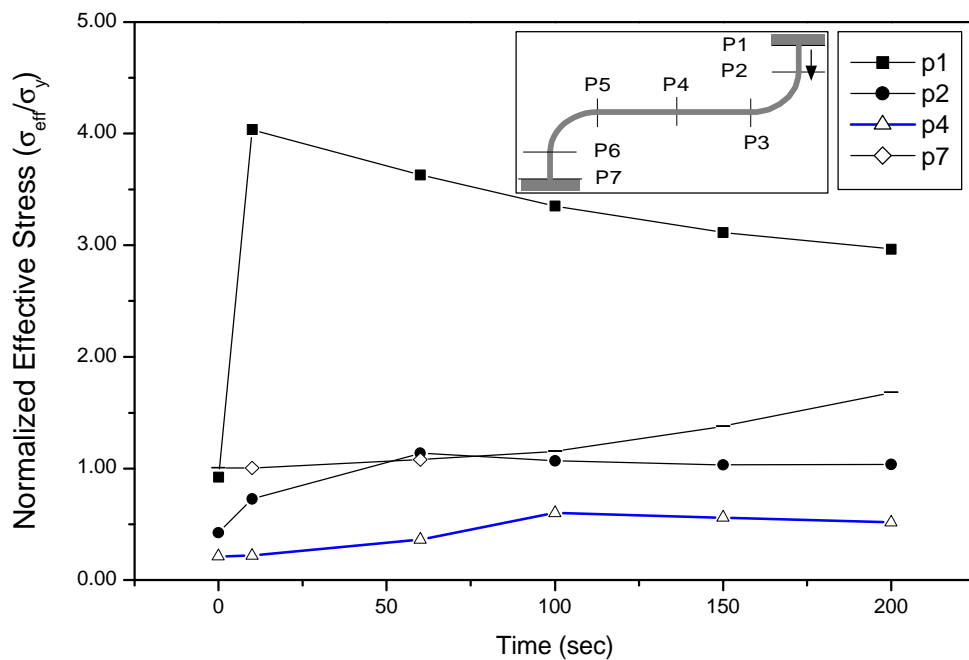Fig. 4 Normalized effective stresses as a function of time for the case of insurge flow.

Fig. 5 Normalized effective stresses as a function of time for the case of outsurge flow.
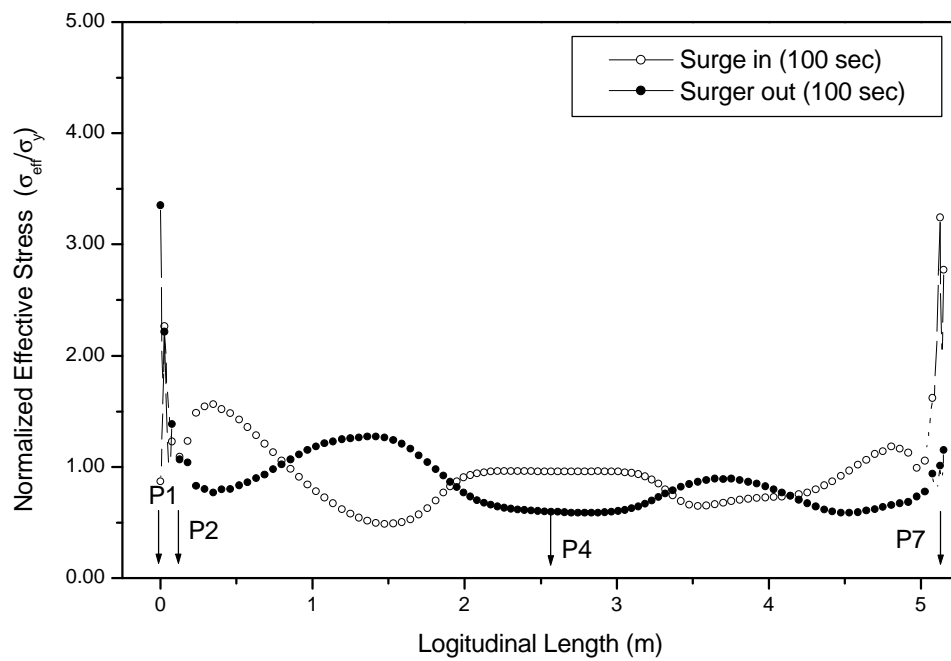
Fig. 6   Normalized effective stresses along the surge line model from the inlet nozzle to the outlet nozzle for the insurge and outsurge flow cases at 100sec.