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Three Dimensional Heat Transfer Analysis of a Thermally Stratified Pipe Flow

열성층 배관 유동에 대한 3차원 열전달 해석

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Abstract

This paper presents an effective numerical method for analyzing three-dimensional unsteady conjugate heat transfer problems of a curved pipe subjected to internally thermal stratification. In the present numerical analyses, the thermally stratified flows in the pipe are simulated using the standard $k-\varepsilon$ turbulent model and the unsteady conjugate heat transfer is treated numerically with a simple and convenient numerical technique. 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. Numerical calculations have been performed for the two cases of thermally stratified pipe flows where the surging directions are opposite each other i.e. in-surge and out-surge. The results show that the present numerical analysis method is effective to solve the unsteady flow and conjugate heat transfer in a curved pipe subjected to internally thermal stratification.

1. INTOODUCTION

The temperature difference in the fluid region due to the thermal stratification produces undesirable excessive thermal stress at the pipe in axial, circumferential, and radial directions, leading to thermal fatigue damage to the piping systems [1,2]. 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.

The main objective of this study is to develop an effective numerical method for determining the transient temperature distributions in the pipe subjected to internally thermal stratification. To achieve the objective, the stratified flow in the pipeline is simulated using the standard $\kappa-\varepsilon$ turbulent model and the unsteady conjugate heat transfer on a non-orthogonal coordinate system is treated by a simple and convenient numerical method. The numerical 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.

For investigating the applicability of present numerical method, a curved pipeline model is considered to being subject to internally thermal stratification caused either by insurge or outsurge flows with a specified velocity. 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.

Some numerical calculations are performed for both surge flows and the results are discussed in detail.

2. MATHEMATICAL FORMULATION

2.1 Governing Equations

Consider a general situation of fluid flowing in a curved piping system (see Fig.1). For simplicity, it is assumed that the thermally stratified fluids are Newtonian with constant properties and the Boussinesq approximation is valid. The $\kappa-\varepsilon$ 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 x^j are the same as in the previous works [3,4].

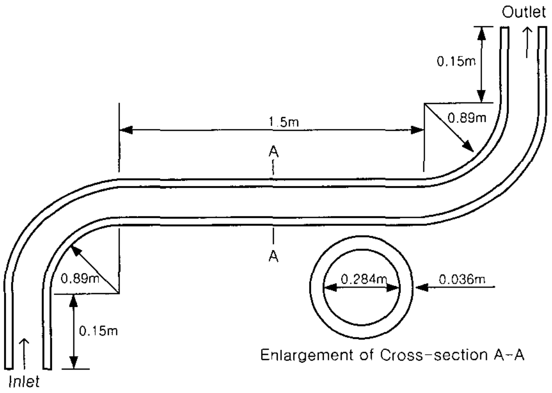

Fig. 1 The curved piping system model.

2.2 Initial and Boundary Conditions

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 inlet 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 inlet.

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.

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3. NUMERICAL METHODS [3,4]

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 (1991) and the unsteady term is treated implicitly using the three-level second order scheme suggested by Ferziger and Peric (1997). The cell-centered, non-staggered grid arrangement is adopted in the present study. The wall function provided by Peric (1985) 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 (19830. 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 [5] to the unsteady flow analysis in the three-dimensional non-orthogonal grid situation, which makes the computer programming and computation easy.

4. RESULTS AND DISCUSSION

The computer code developed on the basis of the numerical analysis method which is also applied to the present analysis has been validated in the previous works [3,4] 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 [6]. The result has shown that the prediction by the numerical approach applied for the present analysis agrees fairly well with the measurements by Ushijima .

As an illustration of the applications of the present numerical method to practical problems, calculations are performed for evolution of thermal stratification with high Richardson number in the simplified model of PWR pressurizer surge line (see Fig. 1). 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 based on the hydraulic diameter of the pipe and the inlet velocity is 60,000, and the Richardson number $Ri = \Delta\rho g d_i / (\rho_{avg} u_{in}^2)$ 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.

Fig. 2 shows the transient evolution of temperature fields at the symmetry plane for the insurge and outsurge pipe flows under consideration. And Fig. 3 displays the predicted isothermal lines at the cross sectional plane 'A-A' in Fig.1. These figures show the developments of the thermal stratification for both surge flows. The predicted temperature fields are normalized using the hot temperature and cold temperature, and the interval of the isothermal line is 0.1.

Fig. 2(a) shows that, during the transient period of evolution of thermally stratified insurge flow in the pipe, the cold fluid occupying the lower space of the pipe is warmed up with heat transferred from the interfacing hot fluid and the wall of which the initial temperature is the same as that of the hot fluid so that the initial heat capacity of wall is very large, while the hot fluid of the upper space is cooled down by transferring heat to its wetted upper part of wall being cooled down due to the heat conduction through the wall to the colder part of wall wetted by colder fluid in the upstream and lower space of the piping system.

Fig. 2(b) shows the transient evolution of thermally stratified outsurge flow of which the behavior is quite contrary to the insurge flow case shown in Fig. 2(a).

Figs. 3 shows in detail that the temperature gradients in the circumferential and radial directions for both cases of surge flows are not severe at the early stages of stratification, but they become steep gradually as the thermal stratifications evolves and reach their maximums, and then become easy finally as the thermal stratifications begin to vanish, as mentioned above. The temperature gradients in the radial direction at the lower portion of the pipe wall are steeper than those at the upper portion of the pipe wall throughout the duration of each stratified flow due to the heat transfer between the pipe wall and two stratified fluids with different temperatures flowing in the pipe.

It is seen from Figs. 2-3 that the trend of transient evolution of temperature fields in the pipe including its wall for the insurge flow case is 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. This is considered to be plausible physically because the stratified flow velocity field is only dependent on the specified inlet flow velocity of surging fluid and the gravity affects only the formation of stratified flow.

5. CONCLUSIONS

From the above discussions, it is considered that the present numerical analysis method is effective to solve the unsteady flow and conjugate heat transfer in a curved pipe subjected to internally thermal stratification. In addition, the computer code is considered to be valid for calculating the transient temperature distributions in the piping wall, which are needed as input data in the thermal stress analysis of the pipe.

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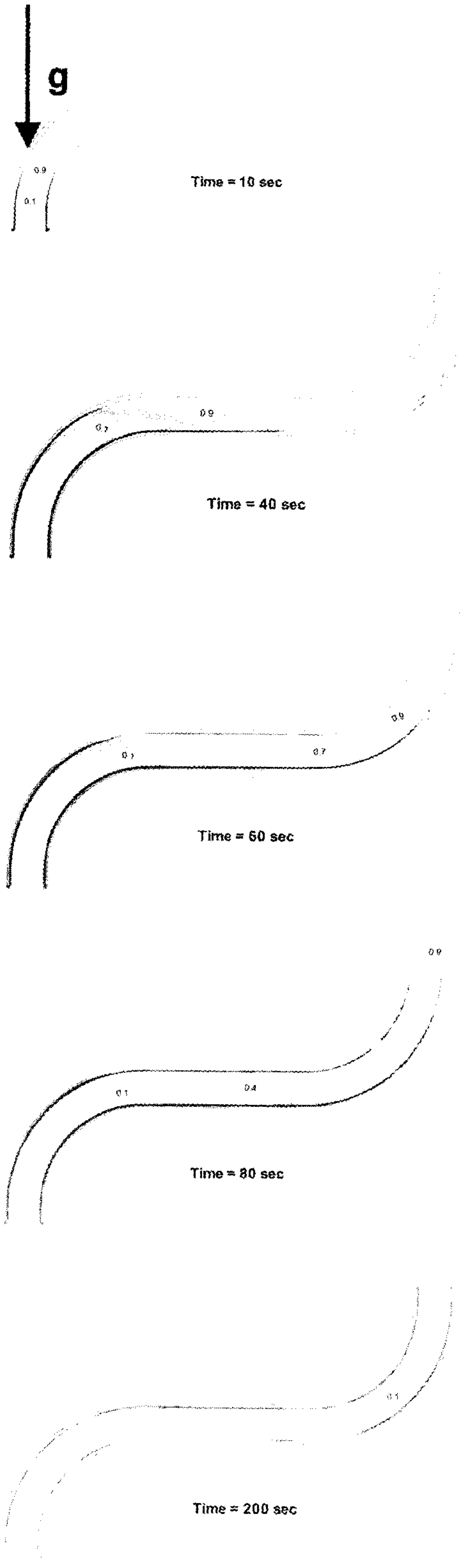

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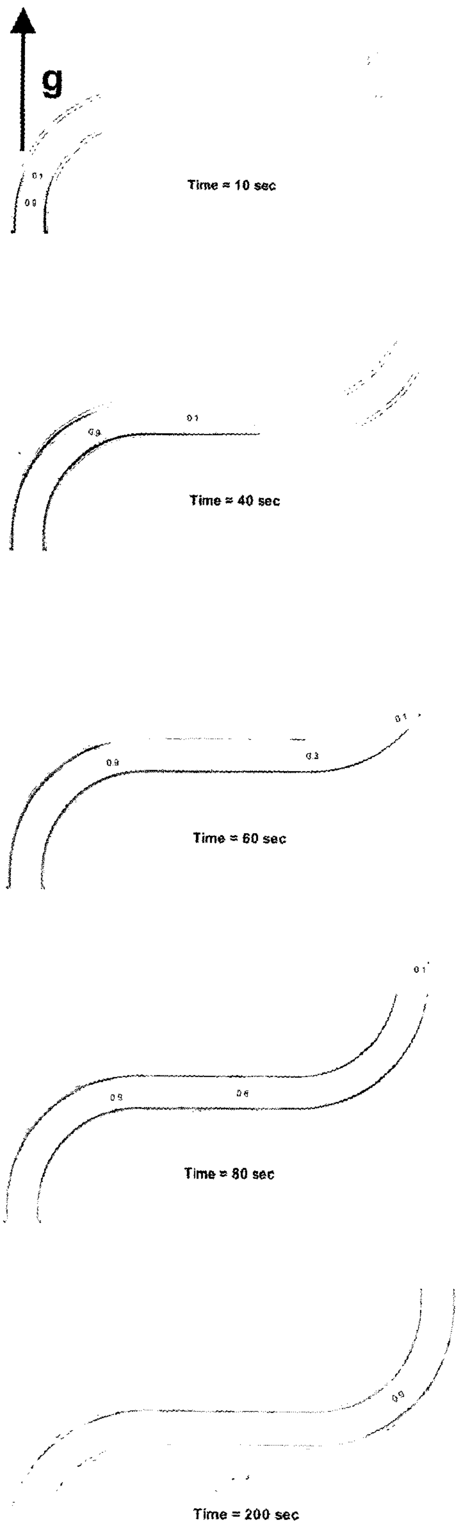

Fig. 2(b) Development of temperature field at the symmetry plane of the surge line model for the case of outsurge flow.

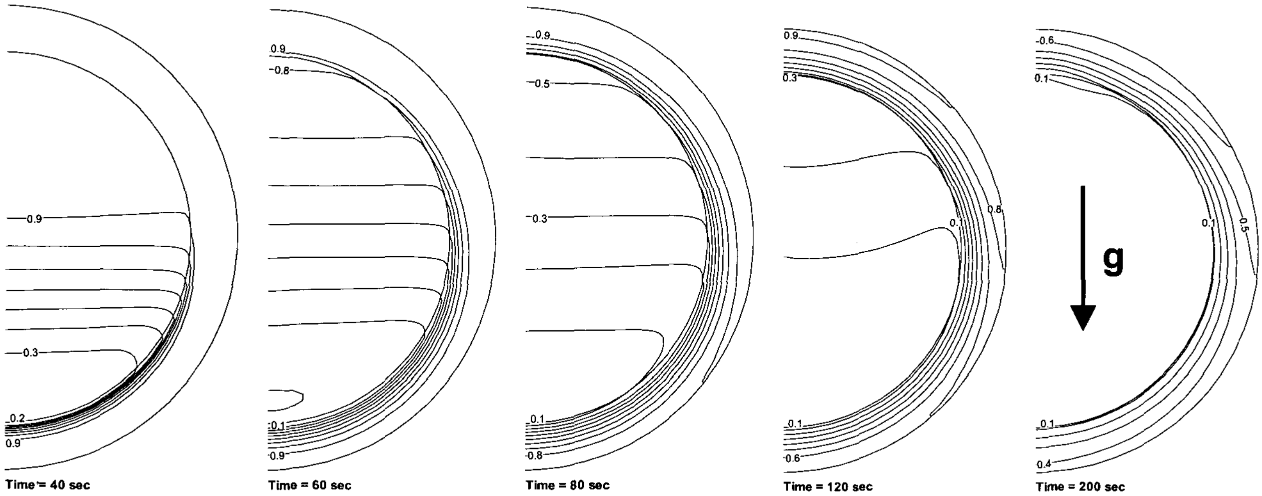

Fig. 3(a) Development of temperature field at the cross-sectional plane 'A-A' of the surge line model (see Fig.1) for the case of insurge flow.

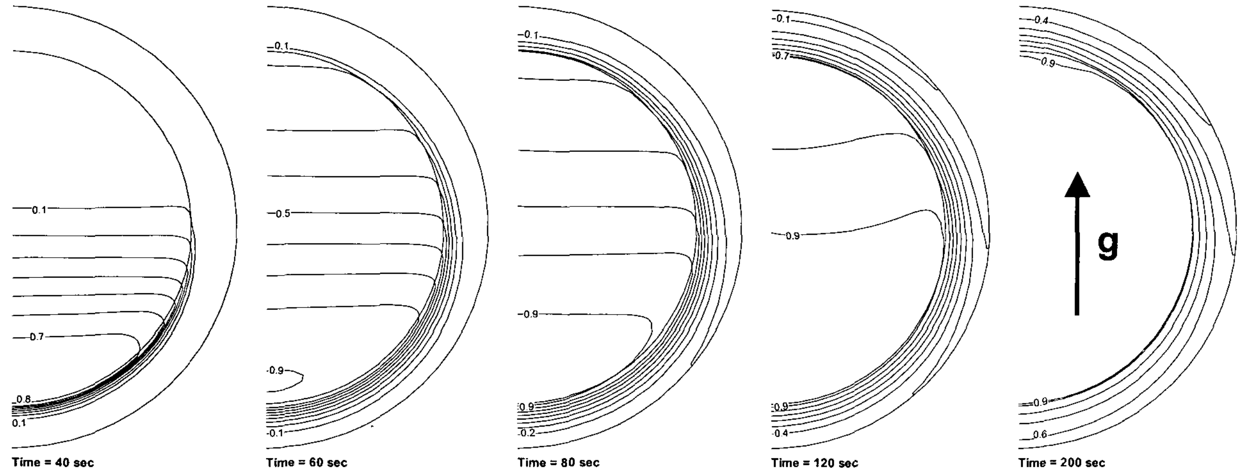

Fig. 3(b) Development of temperature field at the cross-sectional plane 'A-A' of the surge line model (see Fig.1) for the case of outsurge flow.