Proceedings of the Korean Nuclear Society Autumn Meeting
Taegu, Korea, October 1997

Investigations on the Optimum Design of Chemical Addition System for Nuclear Power Plants

Byong Hoon Chang
Junior College of Inchon

Chang Kyu Chung, Han Rim Choi, Eun Kee Kim, Tae Sun Ro
Korea Power Engineering Company, Inc.

Abstract

Mixing characteristics of the chemical additives in the chemical injection tank of the chemical and volume control system(CVCS) were investigated for the Yonggwang Nuclear units 5&6. Numerical calculations were performed with a low-Reynolds number turbulence model. Studies were also conducted for the injection tank with a disk located at 1/4H, 2/4H, and 3/4H from the inlet in order to see the effect in the enhancement of chemical mixing. Results show that the optimum arrangement is to locate a disk close to the inlet.

1. Introduction

The reactor coolant system of a pressurized water reactor nuclear power plant is susceptible to corrosion due to impurities such as dissolved oxygen, oxidizing species and chloride[1]. The corrosion products also increase the radiation level and thus chemical control of the coolant system is essential in order to minimize these effects[2]. The chemical control is performed by hydragen overpressure in the volume control tank and the chemical addition. At coolant temperatures above 150 °F, hydrogen is dissolved into coolant in the volume control tank to react with and remove the dissolved oxygen. At coolant temperatures below 150 °F, hydrazine is injected by the chemical addition system. For normal operation, the desired range of the pH of the coolant is maintained by controlling the lithium concentration in the reactor coolant system. Yonggwang 3&4 and Ulchin 3&4 have the chemical addition system connected downstream of the CVCS charging pump. This arrangement is advantageous in that the components upstream of the chemical addition system is free from contact by the high concentration chemical additives. But, the disadvantage of this arrangement is a need for a separate injection pump due to the high pressure downstream of the charging pump. Additional disadvantages are maintenance of the additional pump and a loss of chemical injection capability upon a failure of the pump. An alternative design is the chemical addition system connected upstream of the CVCS charging pump as adopted in Yonggwang 5&6. The advantages of this arrangement are that the need of a chemical injection pump and subsequently its maintenance are eliminated, and that the probability of the chemical injection failure is lowered.

However, since the chemical additives come in contact with the components of the CVCS including the charging pump, there is a limitation on the maximum concentration of lithium in order to protect the system from a possible chemical damage. In the present study, a numerical analysis has been undertaken in order to study the flow and chemical mixing characteristics of the proposed chemical addition tank to be connected upstream of the CVCS charging pump.

2. Analysis

In order to protect the components of the CVCS from corrosion, it is suggested that the maximum concentration of lithium be 600 ppm[3]. Based on this maximum concentration, the maximum injection flow rate of lithium allowed was calculated as 2 gpm in an initial study[3]. Previous studies[1,3,4] have performed numerical analysis for tank configurations of various height to diameter ratios, and the results showed that over 30% of the chemical additives remained in the tank of 11 gallons even after 2 hours upon injection. In order to enhance mixing and expedite the injection process of the chemical additives, a disk was placed at the various locations in the tank. Their calculations[1,3,4] showed that 30% of the chemical additives remained in the tank at about 8 minutes upon injection for a disk placed at 5/6H from the bottom. The role of the disk was to block the incoming fluid that has no chemical additives, and prevent the influx with zero chemical concentration from simply exiting the tank without adequate mixing with the surrounding fluids. For a disk at 5/6H, it took about 1/2 hour to completely discharge the chemical additives from the tank. They performed numerical studies for other disk locations of 2/4H and 1/6H from the bottom, and found that the disk located at 5/6H gave the best results. Calculations with three disks located at 1/6H, 2/4H, and 5/6H did not show significant improvement over a single disk located at 5/6H. Previous investigators[1,3,4] opted for a single disk located at 5/6H due to simplicity in manufacturing the injection tank.

For jet Reynolds number exceeding 1000, the shear layer between the jet and the ambient fluid is turbulent[5]. Jet is considered to be in transition regime for $1000<Re<3000$, and fully turbulent for Re greater than 3000[6]. In the present study, water is injected into the chemical addition tank through a pipe connected to the tank, and the flow is like a jet issuing from a nozzle into a stagnant fluid. The jet Reynolds number based on 2 gpm is 6350, and the flow is turbulent. However, previous investigators[1,3,4] have solved the problem assuming the flow is laminar. For a laminar jet in the range of $300<Re<1000$, it is reported that there is no noticeable diffusion of the jet into the surrounding fluid[6] due to small viscous forces compared to the inertial forces. We have solved the present problem as a laminar flow, and the results showed the same trend; there was little entrainment of ambient fluid and the jet exited through the outlet with very little mixing with the chemical additives, thus requiring a long time to empty the chemical additives of the tank.

In the present study, the flow field is calculated using a low-Reynolds number turbulence model. The widely tested Lam-Bremhorst low-Reynolds number $k-\varepsilon$ turbulence model[7] below has been selected since it has been proved suitable also for prediction of the transition[8].

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left\{\mu + \frac{\mu_k}{\sigma_k}\right\}\frac{\partial k}{\partial x_i}\right] - \rho\overline{u'_i u'_j}\frac{\partial u_i}{\partial x_j} - \rho\varepsilon \tag{1}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left\{\mu + \frac{\mu_t}{\sigma_\varepsilon}\right\}\frac{\partial \varepsilon}{\partial x_i}\right] - c_1 f_1 \rho\frac{\varepsilon}{k}\overline{u'_i u'_j}\frac{\partial u_i}{\partial x_j} - c_2 f_2 \rho\frac{\varepsilon^2}{k} \tag{2}$$

where

$$f_1 = 1 + (0.05/f_\mu)^3, \quad f_2 = 1 - \exp(-R_t^2)$$
$$f_\mu = \{1 - \exp(-0.0165\, R_y)\}^2, \quad R_y = k^{1/2} y/\nu, \quad R_t = k^2/(\varepsilon\nu) \tag{3}$$
$$\sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3, \quad c_1 = 1.44, \quad c_2 = 1.92$$

The turbulent Schmidt number in the effective diffusivity for the species equation was taken as 0.9. The discretized equations were solved using PHOENICS[9]. The SIMPLEST algorithm was used for the pressure-velocity coupling, and the integration in time was fully implicit, with the time step $\Delta\tau$ ranging from 2.3E-6 to 2.3E-5. For each time step, the solutions were regarded as converged when the absolute residuals of the equations summed over all cells in the computational domain divided by a reference value became less than 0.001 for the continuity equation and 0.01 for other variables.

3. Results

The flow and concentration field were initially solved for the chemical injection tank without any disk inside. The computed jet velocity profiles were compared with the self-similar jet profile that occurs for x/d>20. Although the computation domain extends only up to 21.3d in the axial direction, the results near the outlet and away from the tank wall gave good consistency with the experimental data[10]. The velocity profiles around the side wall could not be compared due to the reverse flow. Calculations showed that only about 10% of the lithium remained in the tank at 10 minutes. Laminar flow analysis was also performed, and it showed very little mixing of the jet with the ambient fluid, and over 85% of the lithium remained in the tank after 10 minutes. Figure 1 shows the streamline plots for laminar and turbulent flow at t=30 seconds. The ratio of the tank height to the tank radius is about 4.25, and the figures are presented somewhat compressed in the axial direction. The flow is symmetric about the center, and the results are shown only for half of the tank. The inlet radius is one tenth the tank radius. The inlet is located at the lower left-hand corner of the figures, and the outlet is at the lower right-hand corner. The results for laminar flow show that the injected fluid is projected out of the tank without much mixing with the ambient fluid. The streamline plots by previous investigators[1,3,4] showed the same results. Streamline plots for the turbulent flow in Fig. 1 show gradual spreading of the axisymmertric free jet.

The computations were also performed with a disk located at the height of 1/4H, 2/4H, and 3/4H from the bottom of the tank. The streamine plots for a disk located at 2/4H are shown in Fig. 2 for t=3 seconds and 60 seconds. The jet impinges at the disk, and a wall jet is formed along the disk in the radial direction. The second impingement occurs at the side wall and the flow separates into two recirculation bubbles. The transient plots show a gradual forming of a second recirculation bubble behind the disk(located in the center, but not shown in the plot). The steady-state streamline plots for the disk placed at 1/4H and 3/4H from the outlet are shown in Fig. 3. Figure 4 shows the concentration fields for t=30 seconds and 90 seconds. Flow with zero chemical concentration enters through the inlet at the lower left-hand corner, and a sharp gradient in concentration is produced there. Gradual diffusion and mixing about the center can be observed. Figure 5 shows the average concentration of lithium in the tank for various arrangements of a disk. The solid straight line in the figure indicates the lowest possible average concentration with time for the influx of 2 gpm, and the dashed line indicates the results obtained from laminar analysis. The average concentrations for all cases follow the solid line initially, since the fluid near the outlet is simply pushed out of the tank at the start of injection. The results show that mixing process improves as the disk gets closer to the inlet of the tank, and the configuration with a disk at 3/4H gives the best performance. The laminar flow analysis for a disk located at 3/4H gave average concentrations comparable with the turbulent flow calculations for a disk at 2/4H. Although the flow field from the laminar flow analysis is different from that for the turbulent flow analysis, low average concentration was obtainable due to the disk blocking the incoming jet, and a large recirculation region created behind the disk. The average concentration in Fig. 5 tapers off with time for all cases, and the effect of the position of the disk becomes smaller. However, the disk is to be designed with four support legs, and the actual top and bottom of the tank are supposed to be partly spherical in shape. Thus the actual mixing process is expected to be more efficient than the results shown by the present calculations.

4. Conclusion

Numerical analysis was performed to investigate the transient flow and mass transfer characteristics in the chemical injection tank of the CVCS. Calculations show that efficient mixing with the chemicals occurs as the turbulent free jet spreads in the tank. Significant improvement in mixing was obtained with a disk located closer to the inlet of the tank. Although, more efficient mixing is expected for an actual design with four support legs of the disk, it would be preferable to keep the operating condition in the turbulent regime.

Nomenclature

c	concentration	d	tank inlet and outlet diameter
D	tank diameter	H	tank height
k	turbulence kinetic energy	Re	Reynolds number, $\rho u_b d/\mu$
t	time	u_b	bulk velocity
x	axial coordinate	ε	turbulence dissipation rate
α	thermal diffusivity	τ	non-dimensional time, $t\alpha/(d/2)^2$

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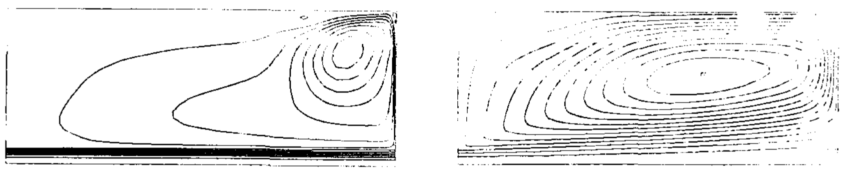
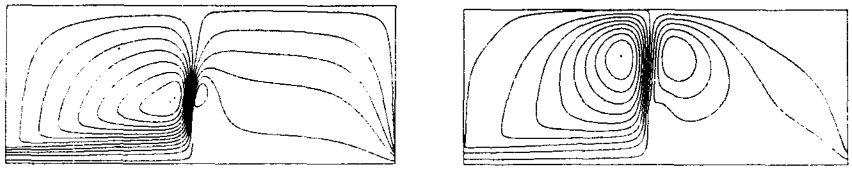


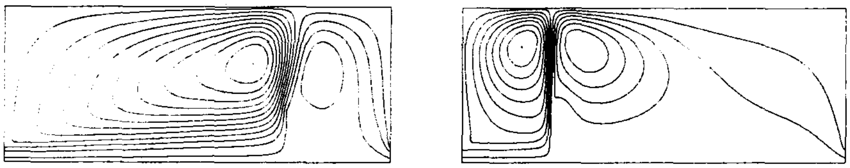
(a) (b)

Fig. 1 Streamline plots for (a) laminar flow, and (b) turbulent flow



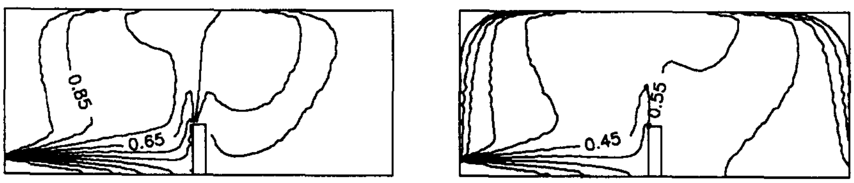
(a) (b)

Fig.2 Streamline plots for a disk located at 2/4H at (a) t=3s, and (b) t=60s.



(a) (b)

Fig.3 Streamline plots for a disk located at (a) 1/4H, and at (b) 3/4H.



(a) (b)

Fig.4 Concentration fields for a disk located at 2/4H at (a) t=30s, and (b) t=90s.

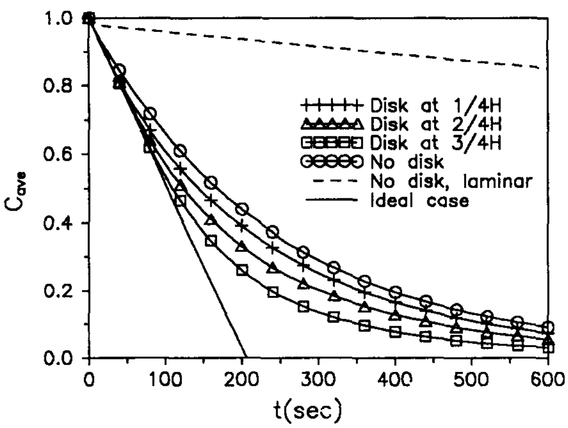


Fig.5 Average concentration of lithium vs. time.