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Transient Heat Transfer Analysis for Ion-Exchange Waste Removal Process

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INTRODUCTION

The small column ion exchange (SCIX) process treats low curie salt (LCS) waste before feeding it to the saltstone facility to be made into grout. Through this process, radioactive cesium from the salt solution is absorbed into the CST bed. A CST column loaded with radioactive cesium will generate significant heat from radiolytic decay. If engineering designs of the CST sorption column can not handle this thermal load, hot spots may develop locally within the column and degrade the performance of the ion-exchange process. The CST starts to degrade at about 80 to 85^oC, and the CST completely changes to another material above 120^oC. In addition, the process solution will boil around 130^oC. If the column boiled dry, the sorbent could plug the column and require replacement of the column module.

The objective of the present work is to compute temperature distributions across the column as a function of transit time after the initiation of accidents when there is loss of the salt solution flow in the CST column under abnormal conditions of the process operations. In this situation, the customer requested that the calculations should be conservative in that the model results would show the maximum centerline temperatures achievable by the CST design configurations.

The thermal analysis results will be used to evaluate the fluid temperature distributions and the process component temperatures within the ion exchange system. This information will also assist in the system design and maintenance.

DESCRIPTION OF THE ACTUAL WORK

For the SCIX process, the design process rate requires a column bed with dimensions of 15 ft long and 20 to 36 in diameter. A fully-loaded column may contain as much as 630 Ci/liter of Cs-137 [1]. This highly concentrated radioactive source will generate a significant amount of heat in the column, which corresponds to about 12 W/gallon of volumetric heat source. Typical loadings are expected to be less than 300 Ci/liter, which would generate about 6 W/gallon. Under normal operating conditions, process fluid flow through the column can provide adequate heat removal from the column through the conduction and convection coupled heat transfer mechanism. However, in the case of a loss of flow accident in the CST column, there are safety concerns about how fast the transient thermal response of the fully-loaded column is and how effectively the column is cooled down under the various design configurations.

For computational modeling purposes, a conservative approach is taken by assuming that the primary cooling mechanisms inside and outside of the column are conduction and natural convection, and axial heat removal from the column is negligible compared to that in the radial direction. A two-dimensional transient heat conduction model has been developed to assess the thermal performance of the CST column with loss of flow using the prototypic geometry.

The model considers four basic cases with no process flow as shown Fig. 1. All the cases consider heat transfer by conduction for the bed column filled with salt solution. Heat transfer analysis of the CST column for the basic design cases is performed for a given boundary condition by using a computational heat transfer approach on a two-dimensional domain.

Spherical CST particles are packed inside a stainless steel cylinder that is 28 in diameter with 5/16 inch thick wall as one of the reference conditions. Oak Ridge National Laboratory (ORNL) estimated the porosity of the CST packed bed is about 43.2 % [2]. The void volume fraction of the packed bed has a substantial impact on estimations of the thermal properties of a composite mixture. In the ORNL work, the bulk density of the CST column filled with salt solution was estimated to be about 1710 kg/m^3 considering that density of CST solid is 2,060 kg/m^3.

The material and thermal properties for the components of the CST packed column system are provided in Table 1. Using these thermal properties, a two-dimensional transient conduction model was performed to find transient thermal response of the CST fixed bed region in case of the loss of the CST process flow. For computational efficiency, effective thermal conductivity for the composite column region was used. Effective thermal conductivity of the CST bed region was estimated by the literature correlation [3]. That is, effective thermal conductivity of the bed ($k_{b,eff}$) was developed as function of the bed porosity ε in SI unit (W/mK) using the literature experimental data.

$$k_{b,eff} = k_f \left(\frac{k_p}{k_f} \right)^{A + B \log\left(\frac{k_p}{k_f}\right)} \tag{1}$$

where A = 0.280 – 0.757logε and B = -0.057.

In eq. (1), k_p and k_f are thermal conductivities of CST particle and fluid inside the bed column, respectively. Coefficient A is a function of the bed porosity. The thermal conductivity of the CST particle (k_p) is assumed to be constant for conservative estimation and computational efficiency. Effective material properties of the CST column filled with salt solution or air are computed in terms of the column porosity ε. Effective density and specific heat of the bed column are based on homogeneous assumption.

Based on the basic designs for the modeling calculations as shown in Fig. 1, a conservative approach was taken to estimate transient temperature profiles of a fully-loaded CST column with no process fluid flow. The present computations used the following main assumptions:

- Column is filled with a fixed bed of CST particles and salt solution.
- Column ambient temperature is constant (25 ^{o}C or 35 ^{o}C).
- Columns are assumed to be filled with one of two no-flow scenarios. One column consists of CST and salt solution (CST-salt solution), and the other is the column filled with CST and air (CST-air). Both of them have 25^{o}C initial temperatures for the purpose of transient system evaluations.
- Outside the column there is no forced convective airflow, so natural convection is the primary heat transfer mechanism from the exterior of the CST column wall. Radiative cooling contributions at the inner and outer wall surfaces of the column are conservatively assumed to be negligible.
- The heat source (^{137}Cs and ^{137m}Ba decay) is uniformly distributed throughout the entire bed of the CST column and produces 1.485 W/liter assuming that the column is loaded to 300 Ci/liter.

The overall energy balance should be checked to demonstrate the adequacy of the numerical accuracy. This was done by using eq. (2).

$$R = -\int_{A_W} q_w'' dA + q''' V_F \tag{2}$$

Volumetric heat source term, q''', in eq. (2) is given by the model input. For all the cases considered here, energy residual (R) is less than about 1 watt.

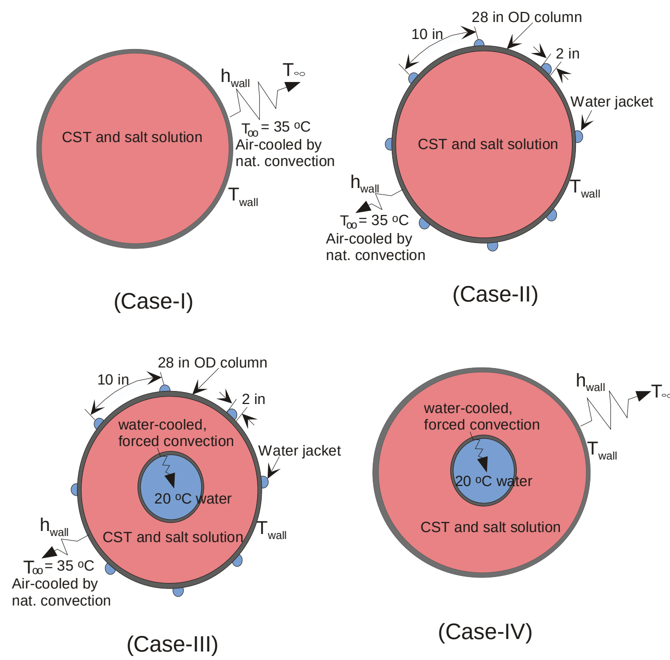

Figure 1. Basic designs considered for the present heat transfer analysis of the CST column

Table 1. Material and thermal properties for the CST column heat transfer calculations.

Material	Thermal conductivity (W/mK)	Density (kg/m3)	Specific heat (J/kgK)
CST-Salt Solution	0.2836#	1710.3**	2165.9**
Salt Solution [1]	0.68	1255.4	3630.0
Stainless steel [1]	17.30	7800.0	486.0

Note: # based on Eq. (1) at 25^{o}c temperature

** based on the condition that volume fraction of fluid or air in packed bed is 0.432 at 25^{o}c temperature

RESULTS

Transient two-dimensional heat conduction calculations with modeling assumptions have been performed to assess how fast a CST ion exchange column heats up on loss of flow under the potential operating conditions and design geometries. In the present analysis, convection and radiation transport processes inside the CST column were assumed to be negligible compared to conduction heat transfer under no process flow conditions. The CST-salt solution column was assumed to be cooled by natural convection or mixed convection. A computational heat transfer approach was taken. In addition, the results computed by the present model were verified by the theoretical results.

The Case-I and Case-II models investigated steady-state and transient temperature profiles of the CST-salt solution system due to natural convection cooling and mixed convection and quantified the CST temperatures inside the cylindrical packed column containing a decay heat source for the no process flow situation. The Case-III and Case-IV models quantified the transient temperature responses of the system heatup for various design conditions and different cooling mechanisms of the CST-salt column system since the modeling results of the Case-I and Case-II designs show that peak temperature of the CST-salt solution system reaches undesirable boiling condition in case of no process flow. The transient results for the column cooled by mixed convection showed that 130^{o}C maximum temperature of the column was reached about 10 days after the transient initiation of no flow conditions.

When emergency coolant systems are available during loss of flow accident, the transient results show that 100 ^{o}C maximum temperature of the 300 Ci/liter loaded column was reached about 56 hours after the initiation of no flow conditions, and the temperature trend is reversed about 12 hours after the activation of the emergency water cooling system. Sensitivity analysis for the CST column was made to find out how sensitive to each of these parameters is the coolability of the column and to quantify their impact on the system cooling capability. The parameters studied here are the efficient column geometry, heat load, and cooling mechanism of the CST column with no process flow situation.

From the modeling results, the main conclusions are made as follows:

- Under no process flow condition, the transient temperature response of the CST-salt column loaded with 300 Ci/liter decay heat is slow. It takes about 4 days for a 20-in column to reach boiling condition under the Case-I reference conditions.

- From the sensitivity study of the CST column parameters, it was found that water coolant system in the middle of the column is most effective in removing the column heat load under no flow conditions since an effective thermal boundary layer adjacent to the potential location of the peak temperature is formed by convective fluid motion.

- The analysis results indicated that the cooling mechanism at the column center has significant impact on maximum column temperature for the present configurations, compared to the cooling mechanism at the column boundary. Thus, the temperature difference between maximum and minimum temperatures of the column is reduced rapidly as cooling capability at the center of the column is enhanced.

REFERENCES

1. S. Y. Lee, “Heat Transfer Analysis for a Fixed CST Column”, Savannah River National Laboratory document, WSRC-TR-2003-00416 (2003).
2. B. B. Spencer, H. Wang, K. K. Anderson, “Thermal Conductivity of IONSIVIE-911TM Crystalline Silicotitanate and Savannah River Waste Simulant Solutions”, Oah Ridge National Laboratory, TN, ORNL/TM-2000/285 (2000)
3. R. Krupiczka, “Analysis of Thermal Conductivity in Granular Materials”, International Chemical Engineering, Vol. 7, No. 1, pp. 122-144 (1967).