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MODELING CONVECTIVE HEAT TRANSFER AROUND A WASTE CASK STORED IN THE YUCCA MOUNTAIN REPOSITORY

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ABSTRACT

This paper discusses the development of a thermal model for heat transfer in the potential repository at Yucca Mountain, Nevada, USA. The model is based on separating the calculation of the emplacement drift from the surrounding mountain rock. When ventilation of the drift is considered, the heat generated by the waste package is removed from the drift by the ventilating air and conduction through the drift wall. The heat transfer path through the rock is of less importance than that through the ventilating air, allowing zero-heat flux boundary conditions to be applied on the drift wall. The finite-volume method is used to accomplish the numerical simulation; k-ε closure is used to model turbulence. Influences of such parameters as velocity of the ventilating air, thermal loading, and radiation heat transfer on the drift wall temperature are analyzed. It appears that radiation does not play an important role when ventilation is used, and does not significantly increase the drift wall temperatures.

NOMENCLATURE

C_p specific heat at constant pressure
H
k turbulent kinetic energy (TKE)
p pressure
Re Reynolds number
t time
T static temperature
u velocity in X-direction
v velocity in Y-direction
u' fluctuating component of velocity
y^+ nondimensional distance to the wall
δ_{ij} Kronecker delta
ε TKE dissipation rate
κ heat conductivity
μ dynamic viscosity
ρ density
τ stress

Subscripts

in inlet parameters

INTRODUCTION

Located about one hundred miles northwest of Las Vegas in Nye County, Nevada, USA, Yucca Mountain is being considered as the USA's first long-term geologic repository for high-level radioactive waste. The volcanic rock of the mountain is capable of keeping the waste sufficiently isolated for thousands of years. The radioactive material will pose about the same or less risk of health effects to the public as that of unmined uranium ore. The water table at Yucca Mountain is deep, about three hundred meters below the level of the potential repository. The unique combination of rock characteristics and the deep water table lead many scientists to believe that the site is capable of isolating the spent nuclear fuel and high-level radioactive waste for thousands of years.

Radioactive waste emplaced in a geologic repository generates heat, increasing the temperature in the repository. The magnitude of this temperature increase depends upon the thermal loading of the repository and the geologic and engineered heat transfer characteristics of the repository. Several aspects of thermal loading, including density, age, burn-up and enrichment of the heat-producing nuclear waste have been under extensive investigation. These studies assumed simplified geologic heat transport characteristics such as pure heat conduction in the rock [1].

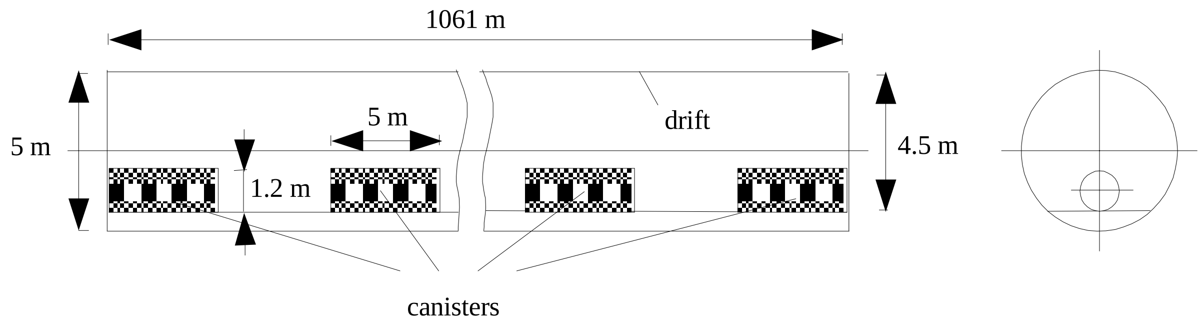

Figure 2. Waste packages in the drift

Moujaes and Bhargava [1] coupled the calculation of transient heat conduction in the rock with steady state analysis of radiation and convection heat transfer between the waste canister and the drift. The authors used the FIDAP software package for both the calculation of the repository drift and the calculation of the surrounding mountain rock. For the rock calculations part, they assumed that the heat flow from the canister is equal to the heat flow imposed on the wall of the drift. Ventilation inside the drift was ignored. The rock calculations were carried out for 1,000 years. The heat flux on the canister was considered decaying with time. The calculation of the rock was the first step of their coupling, using temperature values on the drift wall as boundary conditions for the drift calculations. They also found that without ventilation, radiation was a major mode of heat transfer between the canister and the drift.

Danko et al [2] coupled the temperature and humidity calculations in the rock using the VTOUGH (Vectorized Transport Of Unsaturated Groundwater and Heat) software package along with their own boundary element code. The drift temperature was calculated first with the temperature values on the drift wall serving as boundary conditions for the rock calculations in VTOUGH. Eight different cases with differing numbers of canisters and spacing between them, as well as different numbers of the emplacement drifts, were studied. The authors assumed that radiation was a major component of heat transfer between the canister and the drift, neglecting natural and forced convection (taking the air flow equal to zero). The authors found a case whereby 1,000 years after emplacement, the drift wall temperature would not exceed 100^{o}C - and therefore ventilation was not required. For all other seven cases considered ventilation was required to decrease the drift wall temperature.

Some experimental data for the drift temperatures at the Yucca Mountain are available from the work of Culbreth and Pattisam [3].

The focus of this paper is to introduce a thermal, two-dimensional model of the drift with ventilation. Modes of heat transfer between the waste package and the drift wall are shown on Figure 1. Influence of various factors, such as the air speed at the inlet and radiation, is analyzed.

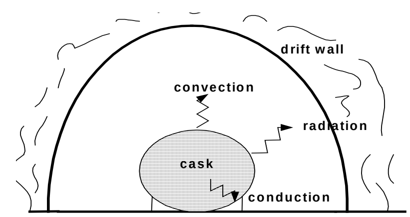

Figure 1. Modes of heat transfer associated with the cask and drift interior.

THERMAL MODEL FOR THE DRIFT

The dimensions of the drift were taken from the paper by Danko et al [2]. In their paper, the authors coupled the mountain rock calculations with the calculations of the drift through temperature boundary conditions on the drift wall. The emplacement area at the Yucca Mountain site was approximated by a rectangular domain of 1060 m by 2550 m. The emplacement drifts run along the shorter length of the area. The canisters, all equalized to be 5 m long by 1.2 m in diameter, were laid down on the floor of the drifts in cradles shown in Fig.2. The authors selected the most critical drift (selected from the eight cases) situated in the center of the emplacement panel for the analysis. Each waste package was represented by an equalized heat load, characteristic to an “older fuel first”, 26-year old fuel with an initial heat load of 7.284 kW at the time of the emplacement.

In this study, we insulated the temperature calculation in the drift from the calculation of the surrounding rock. We also simplified the three-dimensional problem to a simpler two-dimensional configuration. The ventilating air enters the drift from the left and exits from the right. The drift is approximated as a series of backward and forward facing steps. Several cases of varying velocities of the air were considered. Furthermore, only a small amount of heat reaches the wall of the repository via the air – thus the drift wall remains cool. Since the drift is insulated in this study, we only consider one drift assuming that the situation inside the

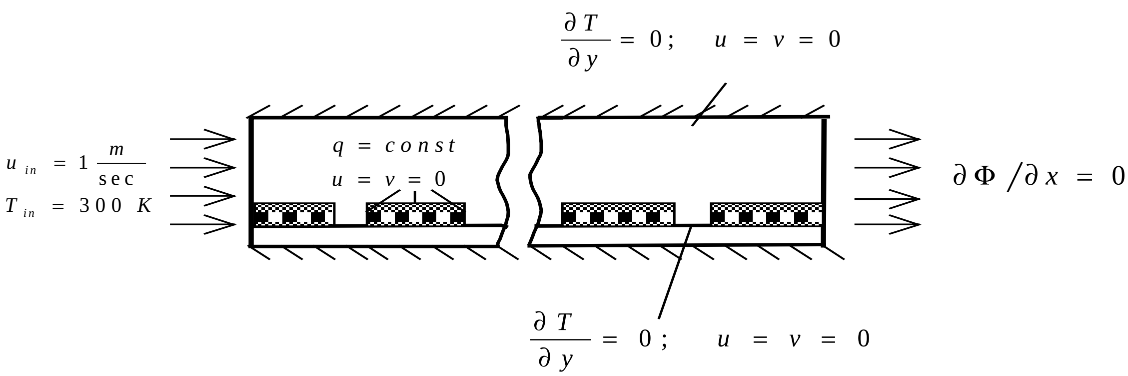

Figure 3. Computational domian with boundary conditions

other drifts is similar. Of the eight cases considered by Danko et al [2], we considered only three cases with the numbers of canisters equal to 21, 37 and 67. The insulation of the drift from the rock permits temperature calculations of the drift without coupling to calculations of the mountain rock. For the case without ventilation, this approach is incorrect since the mountain rock is the only pathway for transferring the heat generated by the waste packages. However, when ventilation is considered, the heat generated by the canisters is removed from the drift by the ventilating air. Heat conduction through the rock is considered as a path of large resistance. In this case, the approach of separating the drift from the rock by using non-zero heat flux boundary conditions on the drift wall seems justified. The cooling of canisters by the air can reduce the temperature on the canister surface significantly, depending on the air speed at the inlet, making the radiation transfer from the canister to the drift wall negligibly small.

In this study, the influence of radiation heat transfer on the drift wall temperature is included. The ventilating airflows in the drift are considered turbulent. The modeling is carried out using FLUENT, a well known commercial software package. FLUENT has a wide range of mathematical models for heat transport phenomena and the ability to model complex geometries, including turbulence modeling and radiation. In addition, it is one of only a very few Quality Assured codes accepted by the DOE for the Yucca Mountain work.

MATHEMATICAL MODEL AND NUMERICAL SIMULATION

The problem of interest is a two-dimensional incompressible turbulent convective flow with radiation. FLUENT has the ability to solve these types of problems with a variety of turbulence, radiation, and heat transfer models, including flows in complex geometries. The governing equations are the continuity, momentum and energy equations.

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial}{\partial x_j}\left(\mu\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right] - \frac{2}{3}\left(\mu\frac{\partial u_l}{\partial x_l}\right)\right) - \frac{\partial p}{\partial x_i} + \rho g_i + F_i + \frac{\partial}{\partial x_j}\left(\rho\overline{u'_i u'_j}\right) \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}(\kappa + \kappa_T)\frac{\partial T}{\partial x_i} - \frac{\partial}{\partial x_i}\sum_{j'} h_{j'} J_{j'} + \frac{Dp}{Dt}\tau_{ik}\frac{\partial u_i}{\partial x_k} + S_h \tag{3}$$

where F_i represents body forces, g_i - gravitational forces, κ_T is the turbulent conductivity due to turbulent transport, $J_{j'}$ is the diffusion flux of species j' and the source term S_h includes heat of chemical reaction, any interphase exchange of heat or any other volumetric heat sources defined by the user. D/Dt is the substantional derivative. Enthalpy h is defined as

$$h = C_p T \tag{4}$$

where C_p is specific heat at constant pressure.

Reynolds stresses are related to the mean flow via the Boussinesq hypothesis

$$\frac{\partial}{\partial x_j}\left(\rho\overline{u'_i u'_j}\right) = \rho\frac{2}{3}k\delta_{ij} - \mu_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \frac{2}{3}\mu_T\frac{\partial u_i}{\partial x_i}\delta_{ij} \tag{5}$$

The turbulent viscosity, μ_T, is computed at each point in the flow via solution of transport equations for turbulent kinetic energy, k, and rate of its dissipation ε.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho u_i k)=\frac{\partial}{\partial x_i}\frac{\mu_T}{\sigma_\varepsilon}\frac{\partial k}{\partial x_i}+G_k-\rho\varepsilon \tag{6}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho u_i\varepsilon)=\frac{\partial}{\partial x_i}\frac{\mu_T}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}+C_{1\varepsilon}\frac{\varepsilon}{k}G_k -C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{7}$$

where G_k is the generation of k and is given by

$$G_k=\mu_T\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right)\frac{\partial u_j}{\partial x_i} \tag{8}$$

The closure constants $\sigma_k,\sigma_\varepsilon,C_{1\varepsilon},C_{2\varepsilon},C_\mu$ are set to the standard values proposed by Launder and Spalding [4].

After the values of k and ε are calculated, turbulent viscosity is computed using an algebraic equation

$$\mu_T=\rho C_\mu\frac{k^2}{\varepsilon} \tag{9}$$

Since the standard k-ε model is not valid near the solid wall where turbulent Reynolds numbers are small, wall functions are applied for finding the wall shear stresses. The first near-wall node is located at the nondimensional distance from the wall $30 < y^+ < 100$.

The computational domain with boundary conditions is shown in Figure 3, where Φ stands for all parameters of the flow. The upper wall and a part of the lower wall located between the canisters is considered to be adiabatic. Along the whole upper and lower wall, the wall functions are applied to find the boundary conditions for the momentum and energy equations. At the inlet, a uniform velocity profile is assumed. The velocity at the inlet is assumed to be 1 m/sec for all calculations, although the influence of the inlet velocity will be studied. The parameters of the air at the inlet are taken as T = 300^{o}K, ρ = 1.225 kg/m^3, Cp = 1006.43 J/(kg*K), κ = 0.0242 W/(m*K); μ = 0.000017894 kg/(m*s). The values of k and ε at the inlet are taken equal to 0.01 m^2/s^2 and 0.01 m^2/s^3 respectively. At the outlet, gradients of all parameters are equal to zero. On the surface of a canister, the heat flux is set to 345.2 W/m^2 - though the influence of the heat flux value on the drift wall temperature will be analyzed. The heat generated by a canister should decay in time and within the first one thousand years should change greatly from its initial value. In this simulation, the heat flux on the canister was set to a constant, corresponding to a worst scenario where the heat generated by canisters would remain constant throughout the life of the waste storage.

FLUENT provides four radiation models. In our simulation, the Rosseland radiation model was applied [5]. This model is valid when the medium is optically thick. The advantage over other models is that it does not solve an extra transport equation for the incident radiation - and it is faster than other models while requiring less memory.

The SIMPLE method by Patankar and Spalding [6] was used to solve the governing equations. The mesh for all calculations was generated uniformly in both directions. Since the heat generated by the canisters was considered constant and the drift isolated from the rock, the process of heat transfer in the simulations was considered steady.

PRELIMINARY RESULTS

Figures 4-11 show results of the simulation. Figure 4 shows the drift wall temperature distribution along the drift for several thermal loadings assuming 67 canisters and the velocity of the ventilating air equal to 1 m/sec. As shown in Fig. 4, the highest value for the temperature at the end of the drift, 340^{o}K, is found for the highest value of the thermal loading considered, i.e. for 345.2 W/m^2. This is estimated from the consideration that each canister can be represented by a heat load at the time of emplacement equal to 7.284 kW, as considered in [2]. The value of the drift wall temperature at the end of the drift decreases almost linearly with the amount of thermal loading within each canister. The temperature of the drift wall at the beginning of the drift is assumed equal to the temperature of the ventilating air, 300^{o}K. According to Fig. 4, the highest temperature increase, 40^{o}K, is for the case with the thermal loading equal to 345.2 W/m^2, and the lowest one, 6^{o}K, for a thermal loading of 50 W/m^2.

Figure 5 shows the drift wall temperature distribution along the drift for several values of the velocity of the inlet air. The number of canisters is 67 and the thermal loading of each canister is 345.2 W/m^2. As seen in Fig. 5, the temperature increases to 208^{o}K, where the velocity of the ventilating air at the inlet is assumed to be 0.2 m/sec. For a velocity equal to 5 m/sec, the drift wall temperature does not change significantly along the drift – only about 8^{o}K. This simulation presents an optimal way for storing the waste.

Figure 6 shows the drift wall temperature distribution along the drift for several numbers of canisters. The thermal loading of each canister is 345.2 W/m^2, and the velocity of the air at the inlet is 1 m/sec. The temperature increase is 40^{o}K with 67 canisters, 22^{o}K with 37 canisters, and 12^{o}K for 21 canisters.

Figure 7 shows the drift wall temperature distribution along the drift with and without radiation heat transfer. The number of canisters is 67, the thermal loading of each canister is 345.2 W/m^2 and the velocity of the air at the inlet is 1 m/sec. From Fig. 7 we see that when radiation is considered, the temperature at all nodes of the drift wall increased by only several degrees. It is not surprising - when ventilation is used, the temperature on the canister surface is lower and does not radiate much heat. In such cases, radiation heat transfer from the canister to the drift wall is not important.

Figure 8 shows the distribution of the temperature on the surfaces of canisters 1, 34, and 67 along the canister's relative length. The thermal loading on each canister is 345.2 W/m^2 and the velocity of the air at the inlet is 1m/sec. The computational mesh along the surface consisted of 5 volumes (five nodes). In the finite-volume method the nodes for calculating parameters are located at the centroids. In Figure 8, the curves start at point 0.5 and finish at point 4.5, though the length of a canister is 5 m. As seen in Fig. 8, the temperature on each canister changes linearly with the X-coordinate (located from left to right). The temperature on all other canisters generally changes linearly with the canister number, but for convenience purposes we do not show it on Fig. 8. The highest temperature on the last canister, 67, is 352^{o}K. At such a low temperature the radiation is not significant, as shown in Fig. 7 where the effect of radiation was analyzed.

In Figures 9-11, velocity vector distributions at the beginning of the drift, the middle, and at the end are shown for 67 canisters, thermal loading of 345.2 W/m^2, and an inlet air velocity of 1 m/sec. The colors are inverted - the blue color corresponds to a high velocity and the red color to a low velocity.

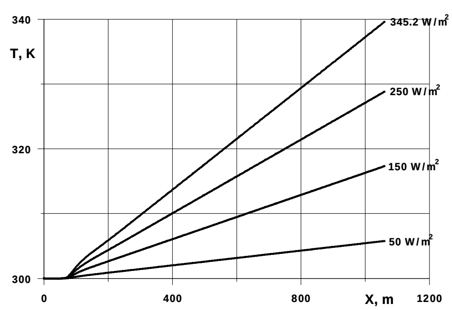

Figure 4. The drift wall temperature distribution along the drift for several thermal loadings (the number of canisters is 67, the velocity of the air at the inlet is 1 m/sec)

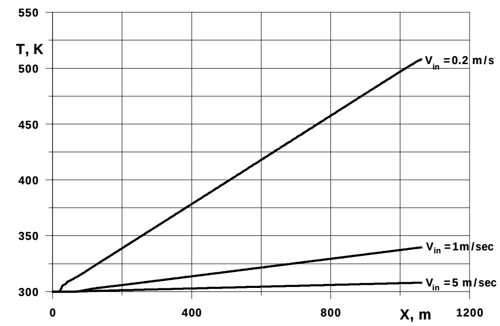

Figure 5. The drift wall temperature distribution along the drift for several values of the velocity of the air at the inlet (the number of canisters is 67, the thermal loading is 345.2 W/m^2)

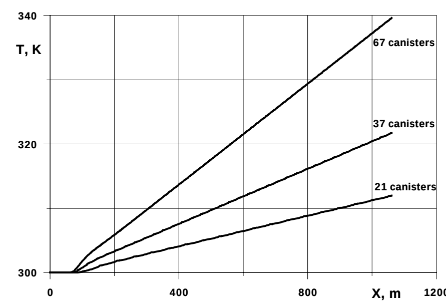

Figure 6. The drift wall temperature distribution along the drift for several numbers of canisters (the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

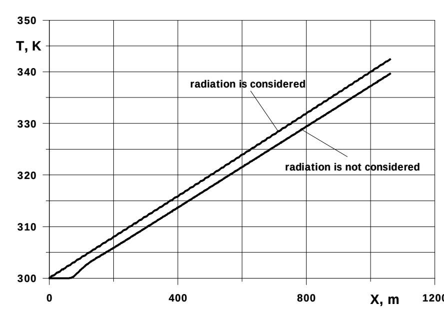

Figure 7. The drift wall temperature distribution along the drift when the radiation heat transfer is considered and not considered (the number of canisters is 67, the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

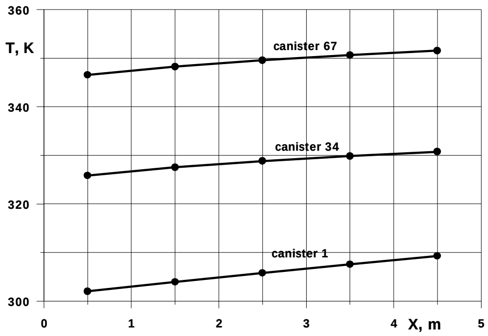

Figure 8. Distribution of the temperature on the surfaces of canisters 1, 34, 67 along the canister's relative length (the number of canisters is 67, the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

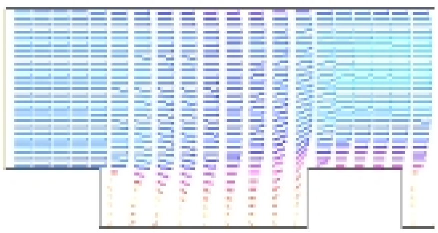

Figure 9. Velocity vectors at the beginning of the drift (the number of canisters is 67, the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

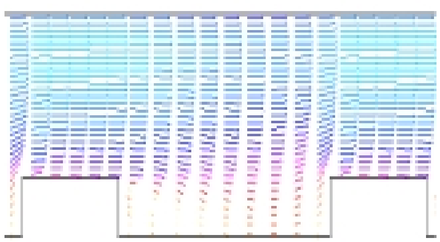

Figure 10. Velocity vectors in the middle of the drift (the number of canisters is 67, the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

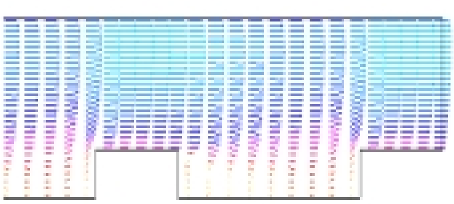

Figure 11. Velocity vectors at the end of the drift (the number of canisters is 67, the thermal loading is 345.2 W/m^2, the velocity of the air at the inlet is 1 m/sec)

CONCLUSIONS

A 2-D thermal-fluid model for convective heat transfer around a nuclear waste cask located within a drift (tunnel) at Yucca Mountain has been developed. The model separates the rock surfaces of the drift wall from the air surrounding the waste cask. Ventilation in the drift is a critical component of the model. FLUENT, a well-known commercial finite-volume code, was used to solve the turbulent flow and energy equations. Several factors, that include thermal loading of canisters, the number of canisters, the speed of ventilating air and radiation, were examined that influence the temperature distribution surrounding the canister. Radiation heat transfer from the canister to the drift wall was found to be an insignificant factor in the overall simulation.

ACKNOWLEDGMENTS

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