SEPARATE EFFECTS TESTS FOR GOTHIC CONDENSATION AND EVAPORATIVE HEAT TRANSFER MODELS

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ABSTRACT

The GOTHIC computer program, under development at EPRI/NAI, is a general purpose thermal hydraulics computer program for design, licensing, safety and operating analysis of nuclear containments and other confinement buildings. The code solves a nine equation model for three dimensional multiphase flow with separate mass, momentum and energy equations for vapor, liquid and drop phases. The vapor phase can be a gas mixture of steam and noncondensing gases. The phase balance equations are coupled by mechanistic and empirical models for interface mass, energy and momentum transfer that cover the entire flow regime from bubbly flow to film/drop flow. A variety of heat transfer correlations are available to model the fluid coupling to active and passive solid conductors.

This paper focuses on the application of GOTHIC to two separate effects tests; condensation heat transfer on a vertical flat plate with varying bulk velocity, steam concentration and temperature, and evaporative heat transfer from a hot pool to a dry (superheated) atmosphere. Comparisons with experimental data is included for both tests. Results show the validity of two condensation heat transfer correlations as incorporated into GOTHIC and the interfacial heat and mass transfer models for the range of the experimental test conditions. Comparisons are also made for lumped versus multidimensional modeling for buoyancy controlled flow with evaporative heat transfer.

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1. INTRODUCTION

GOTHIC (Generation of Thermal Hydraulic Information in Containments) is a general purpose thermal-hydraulics computer program for design, licensing, safety and operating analysis of nuclear containments and confinements, auxiliary buildings and related equipment. GOTHIC has been successfully used by several utilities to resolve key technical issues in the areas of equipment qualification, accident analysis in support of probabilistic risk assessment, high energy line break analysis, room heatup calculations, station blackout analysis, technical specification changes and other areas. The code has many of the modeling capabilities needed to analyze the thermal hydraulic response of the new passive containment designs as well as currently operating designs. Specifically, GOTHIC can model buoyancy dominated flow, condensation and evaporative heat transfer in the presence of noncondensing gases, stratification, hydrogen mixing, hydrogen burn and system controls. The code equation set and general assessment was previously described in [1] and [2]. This paper focuses on two separate effects test, the related GOTHIC models and comparison of GOTHIC results with the test data with some preliminary discussion of the general capabilities.

GOTHIC solves mass, momentum and energy balances for three separate phases; vapor, continuous liquid (pools, films, etc.) and dispersed liquid (drops). The vapor phase can be a mixture of steam and noncondensing gases and a separate mass balance is maintained for each component of the vapor mixture. Mass and energy balances are also maintained for an ice phase. The phase balance equations are coupled by mechanistic models and correlations for interface mass, energy and momentum transfer that cover the entire flow regime from bubbly flow to film/drop flow as well as single phase flows. The interface models allow for possibility of thermal nonequilibrium among the phases and unequal phase velocities.

A flexible noding structure allows the use of a variety of noding arrangements to accommodate the wide range of containment modeling needs. Containment compartments can be modeled using 1-, 2- or 3-dimensional rectangular grids. Many containment problems cover long periods of real time so that finely noded multidimensional models are impractical. For these problems a simpler lumped parameter analysis may be used. Lumped parameter volumes are connected by junctions that employ a one-dimensional model for flow between containment compartments. Combinations of lumped parameter and multi-dimensional analysis are also possible. Regions of special interest can be modeled in detail using multi-dimensional grids connected to lumped parameter volumes to model the remaining regions.

GOTHIC includes full treatment of the momentum transport terms in multidimensional models with an optional one parameter turbulence model for turbulent shear and mass and energy diffusion. GOTHIC includes models for heat transfer in solids with thermal connections to the fluid volumes. Wall heat transfer correlations are incorporated for a wide range of heat transfer situations, including condensation heat transfer in the presence of noncondensing gases. Special models for engineered safety equipment such as pumps, fans, valves, heat exchanges, coolers and vacuum breakers are included. Trip logic and control variables give the user almost unlimited capability to control the action of the safety equipment in response to changes in the containment atmosphere.

The GOTHIC code package includes a pre/post processor graphical interface. Because of the broad scope of GOTHIC, the code input is extensive and complex. The preprocessor is an indispensable tool for setting up models and eliminates nearly all user input errors. The postprocessor provides easy access to graphical output of the calculated results.

The code assessment program includes a broad spectrum of analytic tests and small and large scale experimental tests that include hydrogen dispersion, suppression pool performance, single and multicompartment water and steam blowdowns, and superheated steam blowdown. Multiple effects tests from HDR[3], LACE[4], Battelle Model Containment[5], Marviken[6], CVTR[7] and the HEDL ice condenser mockup[8] have been modeled with generally good to excellent agreement with the test data. In this paper, code comparisons are presented for two separate effects tests; condensation heat transfer tests on a vertical plate performed at the University of Wisconsin[9], and experiments on evaporative heat transfer from a hot pool carried out at Battelle Pacific Northwest Laboratory[10].

GOTHIC code enhancements are currently underway at EPRI/NAI, including tasks for a a more advanced turbulence model, a mechanistic hydrogen burn model and many user features to extended the capability. Released versions are currently available from EPRI and NAI. Enhanced versions will be released at the completion of the code assessment and prerelease testing by member utilities.

2. CONDENSATION HEAT TRANSFER

Condensation is an important phenomena in most containment analyses. GOTHIC includes models for condensation heat transfer on solid structures and at liquid vapor interfaces. The presence of noncondensing gases strongly influences the condensation and associated heat transfer rate. For solid structures, GOTHIC employs heat transfer correlations that account for the effects of condensing steam and the the noncondensing gases that build up in the boundary layer and reduce the rate of condensation. For vapor/liquid interface GOTHIC uses separate heat and mass transfer correlations to calculate the rate of condensation and the interfacial heat transfer as described in Section 3 below. The University of Wisconsin condensation tests provide a good benchmark for the heat transfer correlations used in GOTHIC to model condensation and heat transfer to solid structures.

The condensation options in GOTHIC include the empirical Uchida[11] correlation and the semi-empirical correlation developed by Gido and Koestel[12]. A third option in GOTHIC is to use the maximum of the values calculated from these correlations.

2.1 Uchida Correlation

The Uchida correlation is actually a fit to experimental data for saturated air/steam mixtures in a small scale (1 m^3) test facility. The correlation is a function only of the ratio of the steam mass to the noncondensing gas mass. The fit to data used in the GOTHIC code is

$$H_{Uchida} = 450.5 \left[\frac{\rho_{vs}}{\rho_{vg}} \right]^{0.8} \quad \frac{\mathrm{W}}{\mathrm{m}^2\mathrm{-K}} \tag{1}$$

where ρ_{vs} is the steam density and ρ_{vg} is the density of the noncondensing gas mixture.

There are no geometry or velocity parameters in the correlation. Despite these limitations, the correlation has been used extensively in containment analysis and is recommended for certain containment licensing applications in the United States.

2.2 Gido-Koestel Correlation

The more theoretically based correlation by Gido and Koestel (referred to in the following as G-K) is based on boundary layer theory with certain coefficients adjusted to give good agreement with experimental data including that obtained by Uchida. There are two parts to the G-K correlation, one for the free convection regime and one for the forced convection regime. The free convection correlation is

$$H_{GK}^{NC} = 5.25 \left[\left(\frac{u_f}{u_w} \right)^2 \frac{1}{Sc_t} \frac{u_w}{u_\delta} C^* \frac{(\rho_{vs} - \rho_{vs_i})}{\rho_l} \right]^{\frac{12}{7}} \frac{\rho_l h_{fg}}{T_{sat} - T_w} \left[\frac{\rho_l g^4 l^5}{\mu_l} \right]^{\frac{1}{7}} \tag{2}$$

and the forced convection correlation is

$$H_{GK}^{FC} = \frac{\left[\frac{u_f}{u_v} \right]^2 \frac{u_v}{Sc_t} C^* h_{fg} (\rho_{vs} - \rho_{vs_i})}{\left[1 - \frac{u_w}{u_v} \right] (T_{sat} - T_w)} \tag{3}$$

where $\frac{u_f}{u_w}$ is the ratio of the interface friction velocity to the wave crest velocity ($\approx 1/7.0$), Sc_t is the turbulent Schmidt number (ratio of momentum to mass diffusivity) ($\approx .5$),

$\frac{u_w}{u_\delta}$ is the ratio of wave crest velocity to the condensate interface velocity (≈ 1), C^* is a correction factor for high condensation rates, $\rho_{vs_i} = \rho_{vs}(P_{sat}(T_w), T_v)$ is the interface steam density, ρ_l is the liquid density, h_{fg} is the heat of vaporization, T_{sat} is the saturation temperature at the bulk steam pressure, T_w is the wall surface temperature, l is the height of the room, μ_l is the liquid viscosity, $\frac{u_f}{u_v}$ is the ratio of the interface friction velocity to the bulk gas velocity (≈ 0.05), u_v is the bulk vapor velocity estimated from the junction flows and the subvolume connection flows and $\frac{u_w}{u_v}$ is the ratio of the wave crest velocity to the bulk gas velocity (≈ 0.425).

The correction factor, C^*, accounts for effect of high condensation rates on the boundary layer profiles and is given by[13]

$$C^* = \frac{\log(1+\lambda^*)}{\lambda^*} \tag{4}$$

where λ^* is a function of the total pressure, the steam partial pressure and the saturation pressure at the wall temperature. It is given by

$$\lambda^* = \frac{P_{sat}(T_w) - P_{vs}}{P - P_{sat}(T_w)} \tag{5}$$

The maximum of the heat transfer coefficients calculated from these two G-K correlations is used for the G-K option. The forced convection correlation includes a bulk velocity term. An appropriate value is calculated in GOTHIC for both lumped and subdivided volumes. Both the free and force correlation include terms that give decreasing condensation rates as the noncondensing gas fraction increases.

2.3 Condensation Test Description

The University of Wisconsin condensation tests are for the flat plate geometry shown in Figure 1. The parameters varied in the experimental tests included the inlet temperature, steam partial pressure, flow rate and plate inclination angle from horizontal facing downward. The condensing surface of the aluminum plate was painted with Carbon Zinc II™ which is intended to promote the development of films on the surface. The back of the aluminum plate was cooled by oil circulating through coils. The heat transfer rates and coefficients were derived from the measured temperature rise and flow rate of the oil coolant and from the measured temperature profile near the condensing surface of the plate. Steady state results were obtained at selected values of the test parameters. Heat transfer coefficient were obtained at 7 locations along the length of the test section. Data from the 7 measurement locations were combined to obtain average heat transfer coefficients for the test section.

The GOTHIC model for the test is also shown in Figure 1. This simple model uses as single volume to model the test section. Although GOTHIC has the capability to model the test section in detail, the single volume model is consistent with the intended application of the heat transfer correlations where large computational cells (on the order of the test section or larger) are used to model the containment and bulk conditions are used to calculated the heat and mass transfer. The single volume model is also appropriate for comparison with the reported average heat transfer coefficient for the test section. One and two dimensional GOTHIC models were also used and provided average heat transfer coefficients that were very close to those obtained from the single volume model.

The prescribed air/steam mixture is injected into the bottom of the test model at the specified velocity and temperature. The mixture exits the top of the test model at atmospheric pressure. Rather than model the complexities of the coil cooled plate with the attendant uncertainties, the measured temperature at the plate condensing surface was used as a boundary condition for the test model. The condenser plate was modeled using a thin conductor with high conductivity and the temperature of the back face of the plate was set to the measured condensing surface temperature. This forces the condensing surface temperature in the model to match the measured value. The tests selected for comparison with GOTHIC are shown in Table 1. The test inlet conditions are representative of the entire range of experimental test inlet conditions. In all of the selected tests the plate is oriented vertically. This is consistent with the derivation of the G-K correlation for vertical surfaces. The experimenters observed a general increase in the heat transfer rates at smaller angles of inclination, although this effect was not consistent for all test conditions and in some cases the heat transfer coefficient decreased with increasing angle. The heat transfer coefficients at low angles were 0 to 30% higher than the values at 90 degrees. The effect of plate angle was greatest for the tests with low average heat transfer coefficient. At low angles of inclination thick dripping films formed on the condensing surface, increasing the effective surface roughness and the heat transfer rates. These effects are not included in the correlations used in GOTHIC.

TABLE 1. Selected Condensation Tests

Test No.	Velocity m/s	Steam Mole Fraction	Air Mass Ratio	Temperature C
92	1.0	0.312	0.78	70.1
48	1.0	0.464	0.65	79.7
71	1.0	0.681	0.43	89.6
83	1.0	0.836	0.24	95.1
49	2.0	0.299	0.79	69.8
50	2.0	0.464	0.65	79.8
63	3.0	0.312	0.78	69.8
66	3.0	0.464	0.65	79.8
99	3.0	1.000	0.00	99.2

2.4 Condensation Test Comparisons

The test conditions at each of the three velocities were simulated by varying the inlet conditions as a function of time. The transient was slow enough relative to the air/steam turn over rate in the test section that the calculated results could be considered quasi steady at any point in time and compared with the measured data. Results are shown for the Uchida and G-K condensation heat transfer options in Figures 2 through 4. The three vertically aligned symbols for each test represent the error band on the measured data. At the low velocity the Uchida correlation gives larger heat transfer rates than those measured while G-K correlation gives smaller heat transfer rates. Both correlations correctly predict the variation in the heat transfer rate with increasing steam concentration. At higher velocities the Uchida values are, of coarse, unchanged and tend to under estimate the heat transfer rates as the velocity increases. The sharp cutoff in the Uchida heat transfer coefficient at about 1500 W/m^2-K is due to an upper limit placed on the calculated valued in the GOTHIC code. The upper limit is applied to maintain consistency with past licensing applications. The velocity dependence of the G-K correlation is evident in the comparisons at the higher velocities and provides good agreement with the data.

3. EVAPORATIVE HEAT TRANSFER

Evaporation is an important heat transfer mechanism in many containment accident and operating scenarios. It contributes to cooling of superheated atmospheres and hot pools and sprays. Evaporation is important in determining the steam generation as hot water falls into relatively dryer air in the lower containment. It also plays a major role in the long term cooling in advanced passive containment designs.

The evaporative heat transfer model in GOTHIC is part of the interfacial heat transfer logic. This model calculates the mass and energy transfer at the phase interface by performing mass and energy balances for the interface. The model is described below in terms of evaporation but the model applies as well to condensation at the interface.

The heat transferred to the interface from the vapor and liquid phases is

$$Q_v = H_v A_i (T_v - T_i) \tag{6}$$

and

$$Q_l = H_l A_i (T_l - T_i) \tag{7}$$

where Q is the heat transfer rate, H is the heat transfer coefficient, A is the interface area, T is the fluid bulk temperature and T_i is the interface temperature. Excess heat at the interface is used to convert water to steam. Assuming that no heat can be stored at the interface, an energy balance gives

$$\Gamma = \frac{Q_v + Q_l}{\delta h} \tag{8}$$

where Γ is the rate of evaporation and δh is the heat of vaporization. In GOTHIC it is assumed that δh is $h_v - h_l$ where h_v is the enthalpy of the bulk steam and h_l is the enthalpy of the bulk liquid. This implies that the excess heat at the interface must heat the evaporating liquid up to the saturation temperature, cause the phase change and heat the steam up to the bulk steam temperature.

The mass transfer rate is given by

$$\Gamma = H_m A_i \frac{x_i - x_b}{1 - x_i} \tag{9}$$

where H_m is the mass transfer coefficient, x_i is the steam concentration at the interface and x_b is the steam concentration in the bulk. It is assumed that saturation conditions exist at the interface. This implies

$$x_i = \frac{P_{sat}(T_i)}{P} \tag{10}$$

where $P_{sat}(T_i)$ is the saturation pressure at the interface temperature and P is the total pressure. Given the bulk conditions (T_v, T_l, x_b and P) and the heat and mass transfer coefficients (H_v, H_l and H_m), the above set of five equations can be solved iteratively for the unknown interface temperature and steam concentration, liquid and vapor side heat transfer rates and the mass transfer rate.

For the pool geometry and low vapor velocities of the test, GOTHIC uses a turbulent natural convection heat transfer coefficient on the vapor and liquid sides of the interface. The mass transfer correlation is obtained using a heat/mass transfer analogy and the heat transfer coefficient on the vapor side of the interface.

3.1 Evaporation Test Description

Recent tests at Pacific Northwest Laboratories provide a limited data set for verifying evaporative heat transfer models in GOTHIC. The experimental facilities was designed, in part, to measure the cooling of a grout mixture intended for long term storage of hazardous waste. As part of the preliminary check out of the grout mold, some tests for evaporative heat transfer from a heated pool were performed and these data are useful for benchmarking the evaporative heat transfer model in GOTHIC.

The experimental facility is shown in Figure 5. The mold is a rectangular chamber with forced ventilation. Ambient air is forced into the mold at the top near one side and is vented at the top on the opposite side. In the evaporative heat transfer tests, water was added to the bottom of the mold to a depth of about 15 cm. An immersion heater in the pool was turned on until the water temperature reached 48-50 $^\circ$C. The heater was then turned off and the ventilation fan started. During test phase, the water temperature and inlet outlet air humidity and temperature measured. The inlet air temperature and relative humidity varied during each test and ranged between 17 to 27 $^\circ$C and between 18 to

32%, respectively. The test was terminated when the pool temperature decreased to about 30 °C. Four tests were run at varying ventilation flow rates: 2.8, 6.1, 11.3 and 17.0 liter/s. The corresponding turn over rates for the free volume in the mold were 35.6, 16.4, 8.9 and 5.9 minutes, respectively.

Two GOTHIC models were developed for the test mold. The first model was a single volume model and was used to simulate all four of the tests. The second model was a 2-D subdivided model (5 high by 5 wide) used to model the test with the lowest air flow. The initial amount of water in the pool and heat loss from the pool to the grout mold were not well characterized in the test so it was not possible to model the pool cooling directly. Instead, the measured pool temperature was used to force the model pool temperature over the transient so that valid comparison could be made for the air heating and pool evaporation rates. This was accomplished by putting a large conductor in the pool with a large heat transfer coefficient and the back side at the measured pool temperature.

3.2 Evaporative Heat Transfer Test Comparisons

Figures 6 and 7 show the GOTHIC calculated and measured outlet temperature and humidity for the three lowest ventilation cases. GOTHIC agrees very well with the data for both temperature and humidity for the two high flow cases. For the low flow case GOTHIC over estimates the outlet temperature and under estimates the evaporation rate. The fourth case was also run but not included in the graphs. Comparison between the GOTHIC results and the measured data for the fourth case are qualitatively similar to those for the 8.9 minute turn over case.

Although the predictions with this simple single volume model were reasonable, some further work was done to investigate the differences between the data and code calculated results at the low flow rate. The single volume model is applicable as long as there is good mixing within the volume. At the low ventilation rates more variation in the atmosphere conditions are expected. The 2-D model was constructed to more accurately predict the temperature and steam concentration distribution within the volume. The size of the computational cells is still large compared to the boundary layers so that the heat transfer coefficients were still applicable in the cells with the liquid/vapor interface.

The velocity vector map in Figure 8 shows the GOTHIC predicted flow pattern that quickly develops and persists throughout the test. Cold air enters the upper left side of the mold, drops down and moves along the water surface, collecting steam and heating up. It rises on the opposite side of the mold where some of it is forced out through the vent and some is recirculated in the interior of the mold. Using the local fluid properties near the water surface results in more evaporation and cooler exit temperatures. Figure 9 compares the calculated and measured exit conditions for the single volume and subdivided volume case. The results from the subdivided model agree very closely with the measured data.

4. CONCLUSIONS

For the limited range of data of the University of Wisconsin condensation tests both the Uchida and Gido-Koestel correlations reasonably match the test data. The Gido-Koestel correlation does somewhat better overall because it includes the effect of the bulk velocity on the condensation rate. At higher velocities the difference between the two correlations would be much more pronounced. Because of the mechanistic foundation of the G-K correlation, it should be able to predict heat transfer rates over a fairly wide range of conditions. The difference in the measured and calculated heat transfer coefficients could easily be within the range of results for different surface finishes as indicated by the experimenters. Further separate effects testing covering a wider range of pressures and velocities is needed to fully assess the correlations as implemented in GOTHIC.

The interfacial heat transfer logic and correlations in GOTHIC predict the evaporative heat transfer in the PNL grout mold tests very well. While the model is mechanistic, proper care must be taken to select heat transfer coefficients (and the related mass transfer coefficients) that are appropriate for the geometry and flow regime. The data set is limited and further comparisons at other conditions are needed to fully assess the validity of the models. The importance of local variations in fluid properties within a compartment under low flow conditions was noted. The subdivided GOTHIC model was able to accurately predict the evaporative heat at the lowest ventilation rate. The differences between the single and subdivided model results are expected to grow as the ventilation rate is further decreased.

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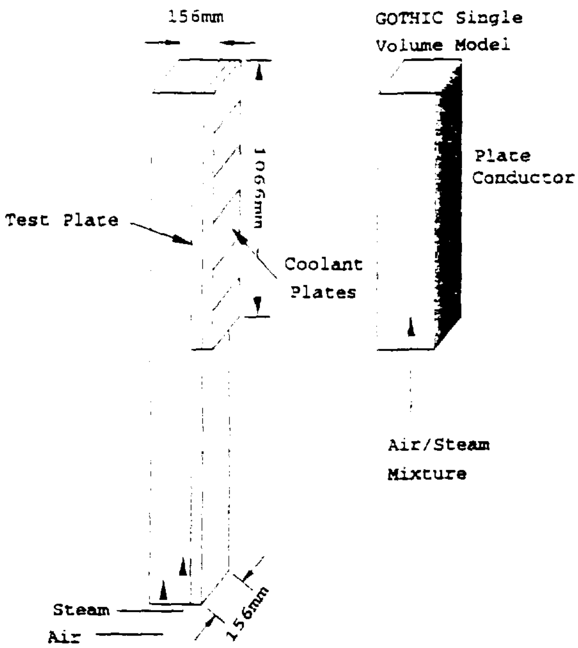

Figure 1. Test Section and GOTHIC Model for Condensation Tests.

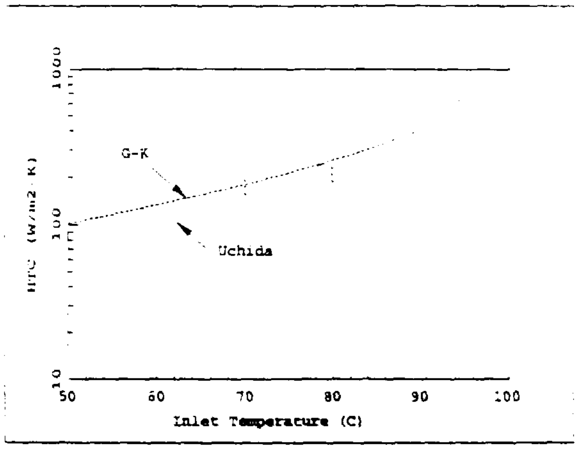

Figure 3. Condensation Heat Transfer Coefficients at 2 m/s.

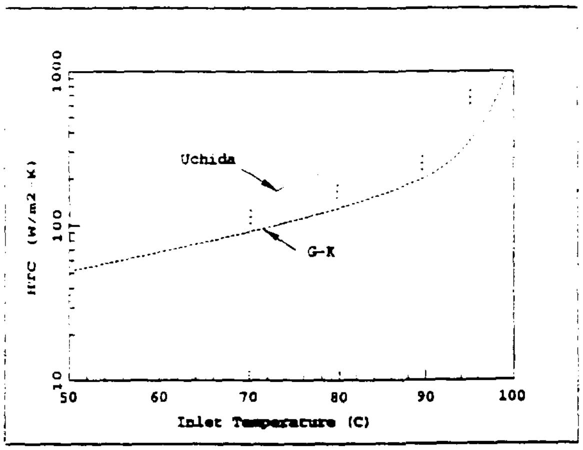

Figure 2. Condensation Heat Transfer Coefficients at 1 m/s.

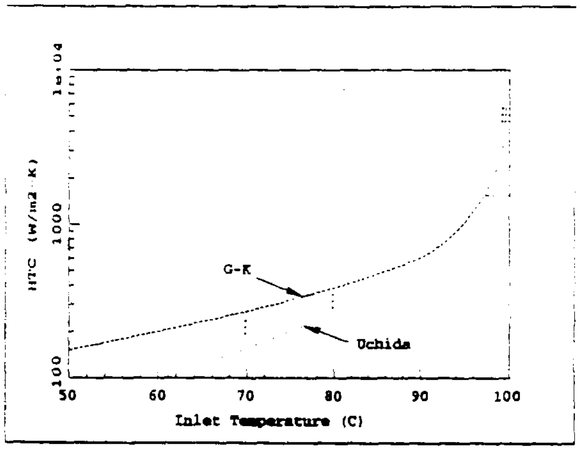

Figure 4. Condensation Heat Transfer Coefficients at 3 m/s.

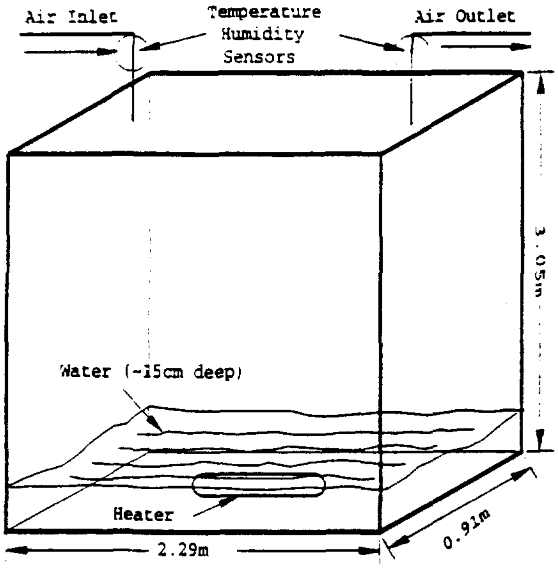

Figure 5. Test Geometry for Evaporative Heat Transfer Tests.

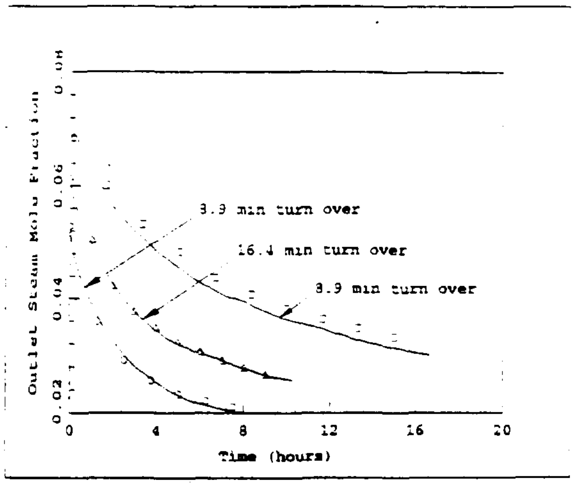

Figure 7. Grout Mold Outlet Steam Mole Fraction.

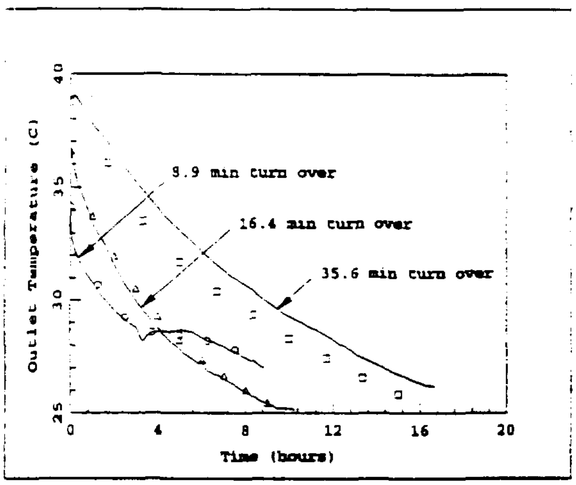

Figure 6. Grout Mold Outlet Temperatures.

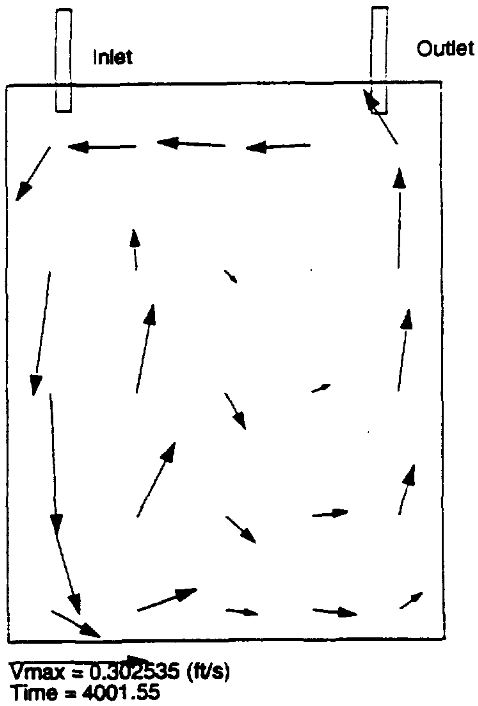

Figure 8. Calculated Vapor Velocities in the Grout Mold.

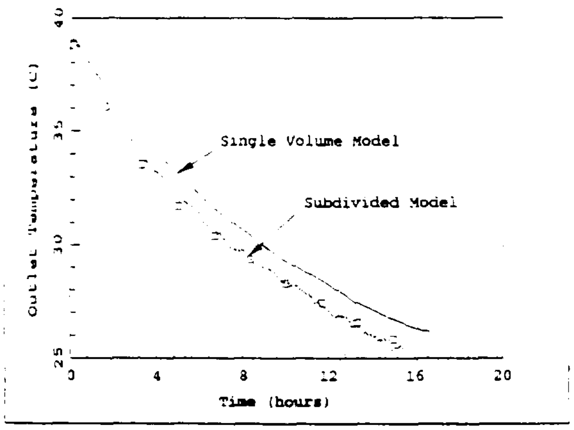

Figure 9. Lumped Versus Subdivided Results for Outlet Temperature.

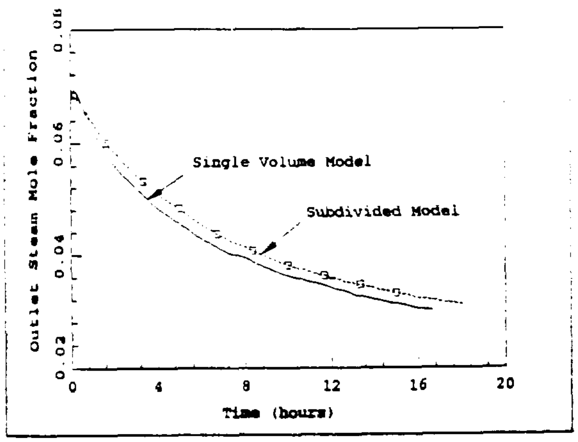

Figure 10. Lumped Versus Subdivided Results for Outlet Steam Mole Fraction.