Yucca Mountain Ventilation Studies:
Past, Present, and Future

Public Comments by:

George Danko, Ph.D.
Professor
University of Nevada, Reno
Mackay School of Mines

Submitted to NWTRB

University of Nevada, Reno

May 1, 2002

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PAST: VENTILATION STUDIES BETWEEN1990 – 1999

Cooling Enhancement Studies, University of Nevada, Reno (UNR)

Objectives: (1) to demonstrate that ventilation can significantly reduce maximum temperatures for a variety of evolving design scenarios, (2) to show that long-term, pre-closure, buoyancy-driven (natural) ventilation is feasible, and (3) to demonstrate the advantages of post-closure, closed-loop, natural ventilation.
Achievements: the NUFT-based hydrothermal-ventilation code, MULTIFLUX was developed
Cooperations: LLNL, TRW, NWTRB

Thermal Loading System Studies, TRW, with UNR involvement

Objectives: (1) show temperature and humidity reduction, (2) to increase storage capacity for the same maximum temperatures, and (3) to study the feasibility of blast cooling for re-entry of the emplacement drift.

Advanced Conceptual Design, TRW, with UNR involvement

Objective: to support Performance Assessment (PA) studies for conceptual design alternatives with ventilation simulations (using MULTIFLUX with NUFT).
Main achievement: ventilated repository concept was found acceptable, based on PA studies.

PRESENT: AMR REV01 VENTILATION STUDIES, 2000-2002

Objectives: (1) to simulate ventilation effects with the Subsurface Design group at M&O, and from 2001, the EBS Modeling group working on the AMR Rev01 report, (2) to use MULTIFLUX V1.1 (with NUFT) for benchmarking comparisons with ANSYS, and (3) to qualify the model and the software of MULTIFLUX.
Main achievements: (1) proved the expected heat removal capabilities of ventilation, (2) proved that for a simplified model configuration used in AMR Rev01, MULTIFLUX agreed with the ANSYS-based ventilation model almost perfectly, (3) verified the simplified model configurations used in the studies.
Clarification: The ANSYS-based ventilation model used by BSC includes spreadsheet hand-calculations for the determination of air temperature increase along the drift between consecutive drift segments. The ANSYS software is used to simulate the two-dimensional, radial heat flow in the dry rock generated by radiation and convection from a line heater segment. Therefore, the name "ANSYS-based Spreadsheet Ventilation Simulation," ABVS, will be used for clarity.

FUTURE: QUESTIONS AND RECOMMENDATIONS, 2002

1. **How does ABVS compare with MULTIFLUX if the heat load is point-like with large gaps between waste packages?**

The ABVS model can be used only with line heat load, assuming that the waste packages are uniform heat sources and are laid in a row with no gap between them. This simplification may not be acceptable in future design considerations with variable waste package heat load, and large emplacement gaps between the packages for achieving a low-temperature repository.

Variable heat load due to variable heat dissipation of the different types of waste packages significantly affects drift wall and waste package temperatures along the emplacement drift. This effect was studied with MULTIFLUX V2.0 (Danko, Shah, and Bahrami, 2002), using the AMR Rev01 input data except for the local heat load, that was not line-averaged, over the eight different waste packages. The drift wall temperature variation for a 600 m emplacement section from MULTIFLUX is shown in Figure 1 for 10 m^3/s airflow.

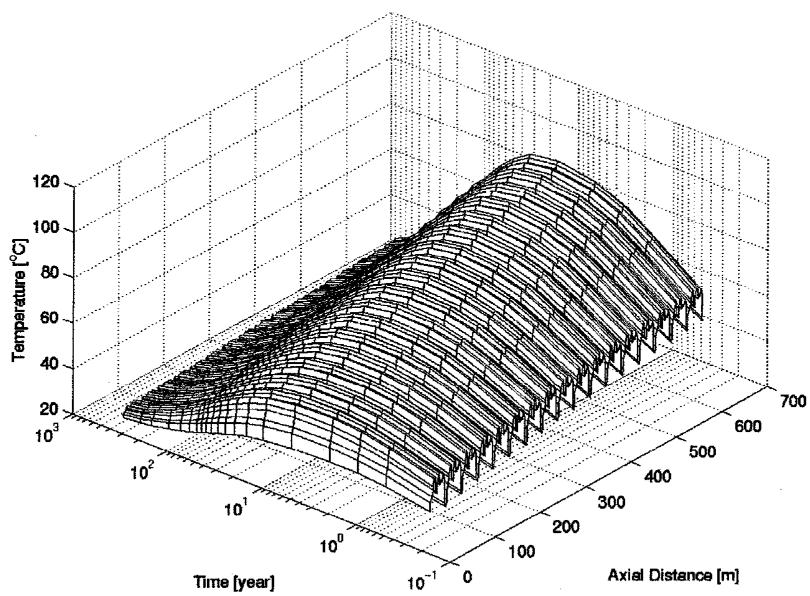

Figure 1. Drift wall temperature variation along a 600 m emplacement section during 300 years of ventilation with 10 m^3/s airflow, according to MULTIFLUX.

As depicted, the three-dimensional image of the drift wall temperature is rugged, even for this end-to-end waste package arrangement. More significant temperature variation is found along the line of waste packages shown in Fig. 2.

The ABVS model gives smooth wall temperature change due to its limitation to line-averaging of the variable heat load. Figure 3 is a comparison between the MULTIFLUX and the ABVS models for the last eight waste packages over the last 35.5 m section of a 600 m-long emplacement drift. As depicted, the averaged, line-load model under-estimates the maximum drift wall temperature by about 10% when compared to the variable heat load model. This already significant difference is expected to further increase for point-load emplacement cases where the gaps between the waste packages are large. Point load cases were not addressed in the

AMR Rev 01 study. However, MULTIFLUX was used in point load ventilation studies without any difficulty to support alternative repository options in 1998-1999. The temperature variations between the cold and hot spots on the drift wall reached 20% for a ventilated case using 10 m^3/s airflow (MULTIFLUX Draft Control Point 2 Document, 1999)

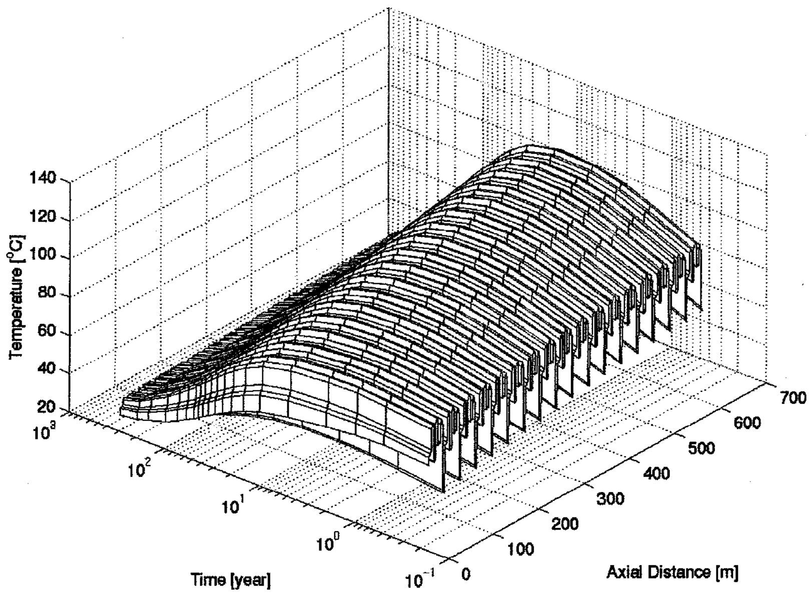

Figure 2. Temperature variation along the line of waste packages for a 600 m emplacement section during 300 years of ventilation with 10 m^3/s airflow, according to MULTIFLUX.

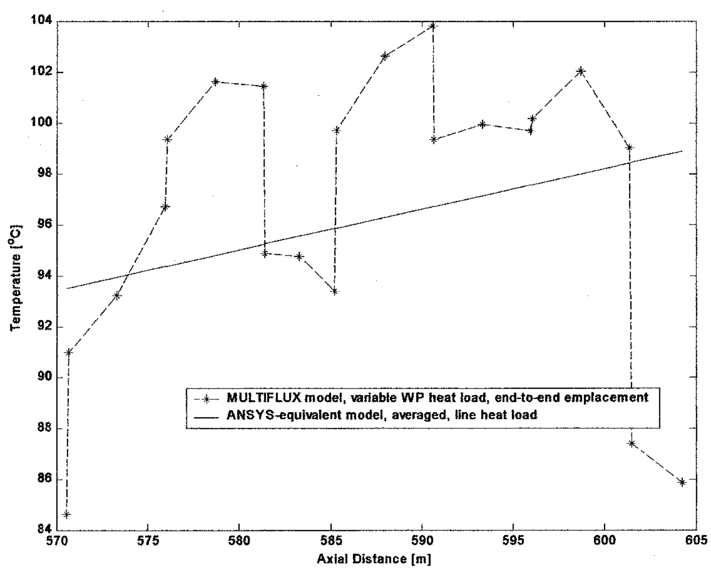

Figure 3. Comparison of drift wall temperatures between the MULTIFLUX and the ANSYS-equivalent ventilation model results along the last 35.5 m drift section (with eighth waste packages), at year 5 after emplacement.

2. How does ABVS compare with MULTIFLUX if rock drying with invert effect is included?

Another conclusion of the MULTIFLUX benchmarking calculations against ABVS last year was that MULTIFLUX was found to give more realistic calculation results than ABVS when the effect of rock drying, enhanced by the invert, was included. Originally, ABVS was considered to be "conservative" against a hydrothermal model since dry heat conduction is known to be less effective than conduction plus evaporation plus convective moisture/vapor transport. This assumption was found wrong during the MULTIFLUX vs. ABVS comparisons. If realistic, moist rock and invert properties are applied in the NUFT input deck used by MULTIFLUX, the waste package, rock, and air temperature results are generally higher than those from ABVS due to rock drying caused by ventilation and the resultant decrease in the rock conductivity in the surrounding drift wall. It is impossible to incorporate this effect correctly in the ABVS ventilation model. Because of the conflicting effects, it is impossible to determine whether or not a simplified ABVS ventilation model under- or over-estimates temperatures for a given design. It is recommended to include, instead of ignore, the rock drying effects upon conductivity, and document sensitivities to these differences in future AMR revisions.

3. How does pre-closure rock dryout affect post-closure temperature rise and subsequent maximum temperatures?

Rock drying caused by ventilation during pre-closure, and the resultant decrease in the rock conductivity in the surrounding drift wall, has a major effect upon the second temperature increasing cycle during post-closure. The ventilation study-part of the AMR Rev01 report focuses only on the first temperature cycle, a short occurrence of a few decades. The second, post-closure temperature cycle is a more critical period for repository performance because of its longer duration of several hundred years. In addition, during this second temperature cycle, there will be no possibility to correct the thermal process.

It is important to recognize that the post-closure temperature cycle can only be simulated using the initial conditions provided by the first cycle. This need has not been adequately addressed in the present ventilation studies. Initial temperature and saturation profiles for post-closure calculation can only be generated using MULTIFLUX with NUFT. An ABVS ventilation calculation cannot provide initial conditions for saturation distributions. The ventilation study-part of the AMR Rev01 report does not address this deficiency. A ventilation study, published in 1998, shows a characteristic relationship between the pre-closure and post-closure temperature cycles regarding maximums and duration, shown in Figure 4. As depicted, the second temperature cycle is more critical than the first one during the pre-closure period of 75 years in this exercise.

It is recommended to critically evaluate the effects of the pre-closure ventilation cycle upon the second, post-closure temperature cycle.

It is also recommended that a single, coherent, hydrothermal-ventilation model be used over the entire 1000 years period that will most likely cover both temperature cycles.

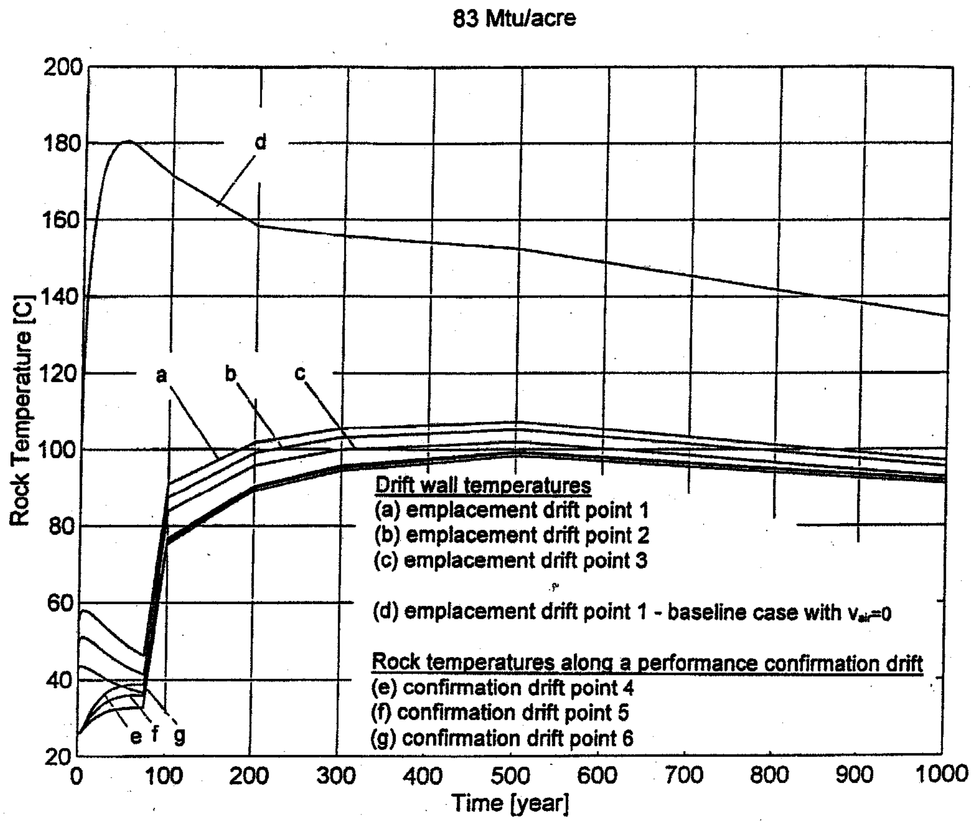

Figure 4. Example of pre-closure (0-75 years) and post-closure (75-1000 years) temperature cycles. (from reference [6]).

4. How will ventilation software and models be refined and qualified?

Based on the foregoing, the timely completion of the software qualification of MULTIFLUX is recommended. Additional tests and comparisons are recommended with the ABVS model against MULTIFLUX, especially considering wide-spaced waste package arrangements in low temperature design applications. Verifications are recommended to complement the line-load comparison cases in the recent AMR Rev01 report, which do not include point-type applications, the most likely scenarios in future Yucca Mountain design. Additional comparisons are also needed between MULTIFLUX and the Ventilation Test Facility measurement results obtained at DOE's Atlas facility. The application of more realistic heat- and moisture-transfer model elements is recommended in future ventilation analyses, such as a computational fluid dynamics (CFD) model, used in a recent, complementary ventilation study (Danko et. al, 2002).

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5. MULTIFLUX Draft Control Point 2 Document, Appendix 11 to SN-M&O-UNR-024-V3, Scientific Notebook, 1999.
6. Danko, G.,(1998). "Merits of Ventilation for the Proposed Repository at Yucca Mountain," Proceedings, 8th Int. High-Level Radioactive Waste Management Conference, Las Vegas, NV, pp. 758-761.

APPENDICES:

Appendix 1 – Reference [2]
Appendix 1 – Reference [3]

APPENDIX 1

VENTILATION ANALYSIS OF A COLD CONCEPTUAL REPOSITORY USING MULTIFLUX WITH NUFT

G. Danko, D. Bahrami, and A. Adu-Acheampong
Mackay School of Mines
University of Nevada, Reno
Reno, NV 89557
(775) 784 4284

Introduction

The purpose of the calculations is to support site characterization regarding expected temperature and humidity variations at Yucca Mountain (YM) with respect to a hypothetical, conceptual high-level nuclear waste repository with ventilation. Specifically, hydrothermal-ventilation analyses are made using MULTIFLUX 1.0[1] with embedded NUFT 3.0 for the calculation of complete temperature and relative humidity variations for three hundred years along the length of a selected drift at the center of the conceptual repository.

The input parameters for the calculation are specified by the YM Subsurface Facility Design Department to be identical to those used in another, ANSYS-based ventilation model that employs a dry, conduction-only rock model for YM. Since the heat and water movements caused by ventilation affect the YM barriers and are inputs to the EBS Water Distribution and Removal Process model, the application of a more realistic, hydrothermal-ventilation model is justified. A summary of the basic input parameters used in the present study is as follows:

Rock input data:	NUFT3.0 input deck specified in the Multiscale Thermohydrologic Model[2] (MSTHM). The spatial rock domain is represented by 17 NUFT chimneys, shown in Figure 1.
Drift dimensions:	600 m long, 5.5 m in diameter, according to MSTHM.
Ventilating air:	10 m^3/s at 25°C intake temperature with 30% relative humidity
Waste packages:	Eight Waste Packages (WP) in a repeating drift segment of 35.5 m according to MSTHM. The arrangement is shown in Figure 2.
Average load:	56 MTU/acre

The MULTIFLUX ventilation model

MULTIFLUX is a coupled hydrothermal - ventilation numerical simulation program package designed to calculate time-dependent heat, moisture, and ventilation air fluxes in and/or around a subsurface opening. MULTIFLUX comprises three independent, stand-alone model elements which are solved simultaneously based on a new coupling method, called Numerical Transport Code Functionalization, (NTCF) developed at the University of Nevada, Reno.

The first stand-alone model-element is the functionalized rockmass model (NTCF-NUFT). This model-element is based on the application of Non-isothermal Unsaturated-Saturated Flow and Transport (NUFT), a hydrologic, hydrothermal and a scalar pollutant transport code developed at Lawrence Livermore National Laboratory (LLNL). The NTCF part of MULTIFLUX evaluate responses calculated by NUFT to changes in the temperature and partial pressure of vapor at the drift wall, and organizes the responses into transfer matrices.

The second stand-alone model-element is the drift (or airway) model that includes the nuclear waste packages, using Computational Fluid Dynamics (CFD) heat and mass transport solvers. MULTIFLUX is supplied with two simplified CFD components, one for heat and one for moisture, based on network models specifically developed for nuclear waste repository ventilation calculations.

The third stand-alone model-element is the coupler between the NTCF-NUFT and the two CFDs. The coupler balances the transport processes within the drift to those in the rock mass.

RESULTS AND DISCUSSION

The drift wall surface temperature, the relative humidity, as well as the waste package surface temperature along the drift and with respect to time are shown in Figures 3, 4 and 5. As shown in Figure 3, the drift wall temperature remains below-boiling during the entire period of ventilation. The arithmetic average of the varying drift wall temperature over the last 35.5 m segment is 89.4 °C in year 5, which is in a very good agreement with the value of 89 °C from the ANSYS model applied to the same heat load conditions[3]. The relative humidity, shown in Figure 4, decreases with length but increases with time and remains well below the value of the intake air of 30%. The waste package temperature variation with drift length and time shown in Figure 5, is similar to that of the drift wall but runs proportionally higher with a maximum difference of less than 20°C.

In order to assess the long-term effect of ventilation, the heat removed by ventilation is compared to the total heat generation by the waste. Various ratios are calculated to characterize the efficiency of the cooling effect of ventilation. A summary of these ratios are given in Tables 1 a and b.

Table 1.a. Heat Table

Time	a	b	c	d	e	f	g
[year]	[W]	[%]	[%]	[%]	1e15xJ	1e15xJ	[%]
0.2	5.74E+05	65.80	0.38	0.12	0.003	0.003	1.77
0.5	6.27E+05	72.84	1.21	0.38	0.010	0.009	2.22
1	6.48E+05	76.77	2.50	0.79	0.020	0.018	2.78
2	6.58E+05	80.28	5.12	1.62	0.041	0.037	3.11
5	6.49E+05	83.60	12.86	4.07	0.102	0.093	2.84
10	6.07E+05	85.59	24.93	7.90	0.198	0.180	2.41
15	5.58E+05	86.91	36.02	11.41	0.286	0.261	2.19
20	5.14E+05	87.77	46.23	14.65	0.367	0.336	2.06
25	4.74E+05	88.49	55.67	17.64	0.442	0.406	1.98
30	4.39E+05	89.11	64.39	20.41	0.511	0.471	1.92
35	4.07E+05	89.65	72.49	22.97	0.575	0.531	1.88
40	3.79E+05	90.20	80.02	25.36	0.635	0.587	1.86
45	3.53E+05	90.67	87.05	27.59	0.691	0.640	1.84
50	3.30E+05	91.13	93.61	29.67	0.743	0.690	1.84
60	3.00E+05	91.59	105.55	33.45	0.838	0.780	1.84
75	2.60E+05	92.47	121.03	38.36	0.960	0.899	1.86
100	2.13E+05	93.40	142.19	45.06	1.128	1.061	1.93
150	1.63E+05	94.83	174.63	55.34	1.386	1.312	2.12
200	1.26E+05	95.87	199.69	63.28	1.585	1.507	2.31
300	1.03E+05	96.51	240.48	76.21	1.908	1.826	2.65

a. Instantaneous heat flux removed by air: $q_a(t)$.
b. Heat flux removed by ventilation, $q_a(t)$, divided by the heat dissipation of all the waste packages, $q_w(t)$, at corresponding times: $q_a(t)/q_w(t)$.
c. The cumulative heat, $Q_a(t)$, (integrated $q_a(t)$ from zero to time t) removed by ventilation divided by the waste packages heat dissipation, $Q_w(50)$ (integrated for first 50 years): $Q_a(t)/Q_w(50)$.
d. The cumulative heat, $Q_a(t)$, removed by ventilation divided by the waste packages heat dissipation, $Q_w(inf)$ (integrated from time zero to time infinite): $Q_a(t)/Q_w(inf)$.
e. Cumulative heat, $Q_a(t)$, removed by ventilation (sensible+latent) in 10^{15} Joules.
f. Cumulative heat, $Q_{approx}(t)$, removed by ventilation (sensible+latent), using approximate formula, $Q_v.c_p.\rho.DT$ with dry c_p, (heat capacity of air) only, in 10^{15} Joules. Comparison of columns e and f gives a quick and approximate check on MULTIFLUX balancing (the balance is perfect within 10^{-12} when the specific heat, c_p, correctly includes the moisture content).
g. Latent heat component, $Q_{al}(t)$, of the cumulative heat, $Q_a(t)$, in percent: $Q_{al}(t)/Q_a(t)*100$.

Table 1.b. Moisture Table

Time	a	b	c
[year]	[kg/sec]	[kg]	[kg]
0.2	4.34E-03	2.28E+04	2.28E+04
1	6.54E-03	9.16E+04	9.16E+04
1	9.23E-03	2.37E+05	2.37E+05
2	9.72E-03	5.44E+05	5.44E+05
5	7.40E-03	1.24E+06	1.24E+06
10	5.06E-03	2.04E+06	2.04E+06
15	4.03E-03	2.68E+06	2.68E+06
20	3.48E-03	3.23E+06	3.23E+06
25	3.14E-03	3.72E+06	3.72E+06
30	2.90E-03	4.18E+06	4.18E+06
35	2.73E-03	4.61E+06	4.61E+06
40	2.58E-03	5.02E+06	5.02E+06
45	2.46E-03	5.41E+06	5.41E+06
50	2.38E-03	5.78E+06	5.78E+06
60	2.30E-03	6.51E+06	6.51E+06
75	2.19E-03	7.55E+06	7.55E+06
100	2.08E-03	9.19E+06	9.19E+06
150	1.96E-03	1.23E+07	1.23E+07
200	1.90E-03	1.53E+07	1.53E+07
300	1.83E-03	2.11E+07	2.11E+07

a. Moisture flux, $q_m(t)$, removed by ventilation (calculated from the rock side).
b. Cumulative (integrated $q_m(t)$ over time zero to t) moisture, $Q_m(t)$ removed by ventilation (calculated from the rock side).
c. Cumulative moisture removed by air, calculated by MULTIFLUX from the air side.

CONCLUSIONS

As shown in Table 1.a, column b, the portion of the instantaneous waste heat flux removed by ventilation is greater than 70% from year 0.5. Therefore, the performance goal of 70% waste heat flux removal by ventilation can be met using any length of ventilation time above half a year. Column c of Table 1.a shows that if the performance goal is to remove at least 70% of the integrated waste heat over a 50-year time period, then only a period of 35 years of ventilation is needed. For a 50 year ventilation, the ANSYS model[3] predicts 68 % total heat removal ratio by ventilation, while MULTIFLUX gives a much higher, 93.61% ratio.
The under-estimation in the heat removal but agreement in the drift wall temperatures together imply that in the ANSYS ventilation model, the portion of heat flow (by either or both convection and radiation) from the WPs to the drift wall is somewhat lower than that in the MULTIFLUX model. Therefore, the differences in the results may be attributed to the differences in the heat transport within the drift, and not in the surrounding rock. This argument is further supported by examining the moisture and related latent heat removal that are present in the MULTIFLUX and absent in the ANSYS model. As shown in Table 1.a, column g, the latent heat component calculated from the moisture evaporated (given in Table 1.b, column a) remains lower than 3% of the total heat removed by ventilation. Thus, the heat removal by evaporation is not seen to be a significant component; and other reasons may be needed to explain the discrepancy between ANSYS and MULTIFLUX results.

The ventilation tests at the DOE's ATLAS facility may provide a significant proving ground for the ventilation models regarding the most important heat and moisture transport model elements used in the codes.

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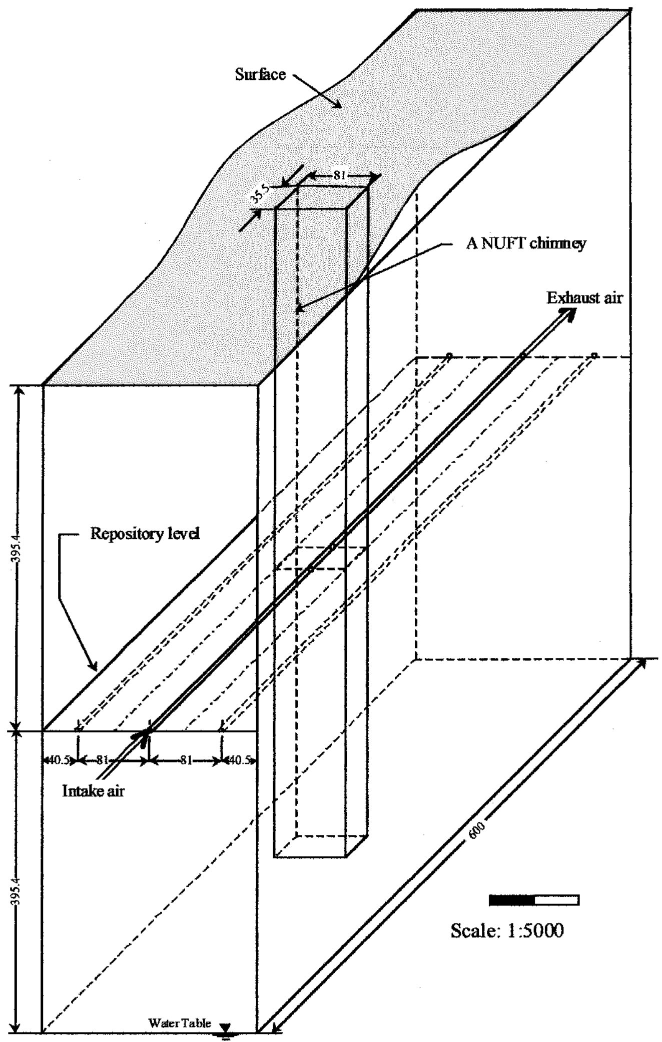


Figure 1. The rock domain with a central and two neighboring drifts, and one NUFT chimney (out of 17) along the central drift.

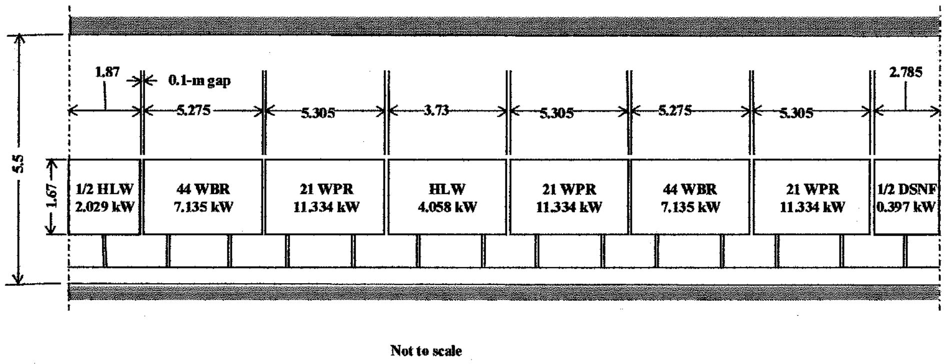


Figure 2. Eight Waste Packages in a repeating drift segment of 35.5 m.

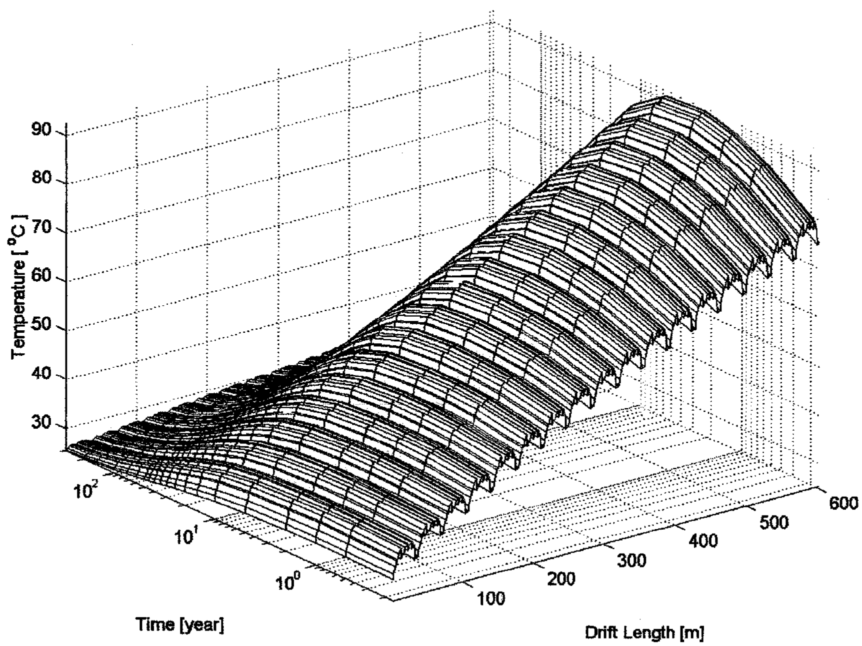


Figure 3. Drift wall surface temperature distribution.

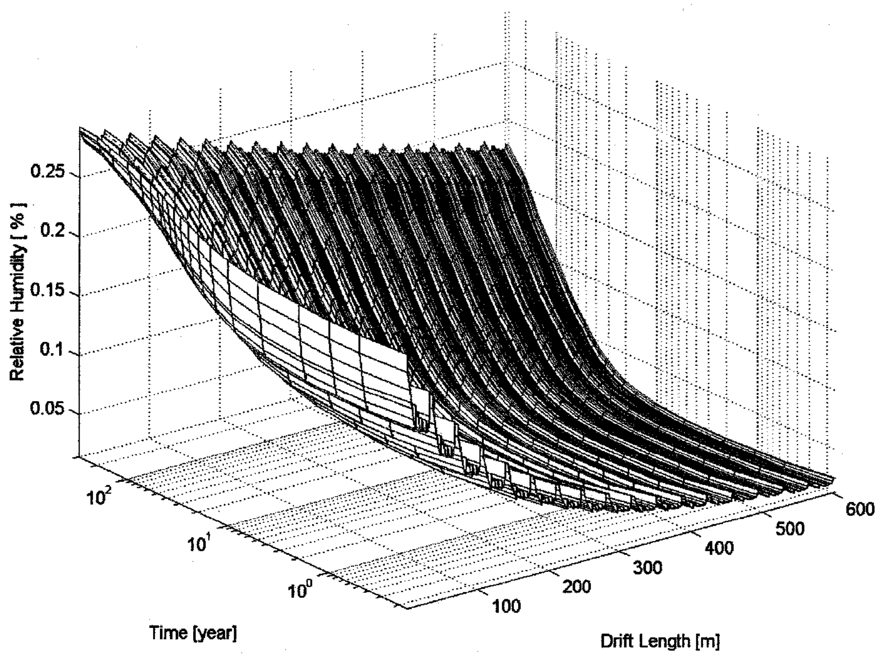


Figure 4. Drift wall surface relative humidity distribution.

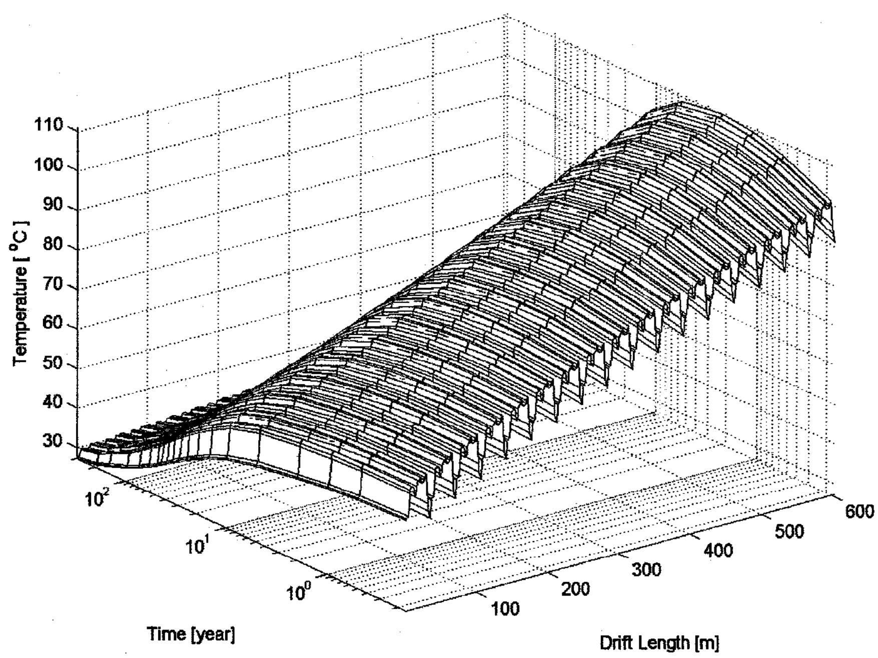


Figure 5. Waste Packages temperature distribution.

APPENDIX 2

THE APPLICATION OF CFD TO VENTILATION CALCULATIONS AT YUCCA MOUNTAIN

G. Danko, and D. Bahrami, Mackay School of Mines
University of Nevada, Reno
Reno, NV 89557, (775) 784 4284

ABSTRACT

This paper presents the results of the application of CFD to ventilation calculations at Yucca Mountain using MULTIFLUX. Seven cases were selected to study the effect of the heat transport coefficient on the drift wall temperature distribution. It was concluded that variable heat transport coefficients such as those given by the differential–parameter CFD used in MULTIFLUX are considered the most appropriate approach of all cases presented. This CFD model agrees well with FLUENT results and produces the lowest temperature results, which is favorable to ventilation performance.

INTRODUCTION

Hydrothermal-ventilation analyses are being conducted using MULTIFLUX 1.1 with embedded NUFT Version 3.0s [1] to predict temperature and relative humidity variations for three hundred years along the length of a selected drift at the center of the conceptual repository at Yucca Mountain (YM).

The heat and water movements caused by ventilation affect the YM barriers and are inputs to the Engineered Barrier System (EBS) Process Model.

MULTIFLUX is a coupled hydrothermal - ventilation numerical simulation software package designed to calculate time-dependent heat, moisture, and ventilation air fluxes in and/or around a subsurface opening. The drift (or airway) model-element includes the heat and mass transport between the nuclear waste packages, ventilating air, and the drift wall, using Computational Fluid Dynamics (CFD) heat and mass transport solvers. MULTIFLUX includes two CFD components, one for heat and one for moisture transport calculation. Significant sensitivity of the drift wall and waste package surface temperatures to the heat transport coefficients was found in a previous paper [2]. The aim of this paper is to study the relationship between the heat transport coefficient distribution on the emplacement drift and waste packages surfaces, and the temperature variations along the surfaces in the airflow direction.

THE MULTIFLUX VENTILATION MODEL

The method of the present analysis is to conduct ventilation calculations with a differential parameter (eddy diffusivity) CFD model in MULTIFLUX to simulate computational heat transport coefficient distribution on the waste package and wall surfaces. In addition, FLUENT [3] is used for comparison. Four computational cases (Cases I-IV) are selected to compare heat transport coefficient distributions for ventilation calculations. The coefficients are dependent on the temperature variation of the surfaces in the thermally developing turbulent flow. For the comparison three additional cases (cases V through VII) are used with simplified heat transport models. The summary of the basic input parameters used in the study is as follows:

Rock input data:	NUFT Version 3.0 input deck specified in the Multiscale Thermohydrologic Model [4] (MSTHM).
Drift dimensions:	600 m long, 5.5 m in diameter, according to MSTHM.
Ventilating air:	10 m^3/s at 25°C intake temperature with 30% relative humidity.
Waste packages:	Eight WPs in a repeating drift segment of 35.5 m according to MSTHM; 17 sections.
Areal mass load:	56 MTU/acre.

Computational Heat Transport Model Comparison

The input parameters result in turbulent flow in the drift with Re = 112,940. Other relevant input properties are as follows:

Specific heat of fluid at constant pressure	$c_p = 1006.44$	(J/kg·K)
Prandtl Number	Pr = 0.71	
Density	$\rho = 1.1665$	(kg/m^3)
Thermal Conductivity	$k = 0.026487$	(W/m·K)
Kinematic Viscosity	$\nu = 1.87\times10^{-5}$	(kg/m·s)
Pressure	$p = 88720$	(Pa)
Fluid Mean Axial Velocity	$u_m = 0.463652$	(m/s)

Physical Parameters:

Inner Radius	$r_i = 0.835$	(m)
Outer Radius	$r_o = 2.75$	(m)
Number of radial divisions between the WP & DW	60, non-equally spaced	

Length of a drift section:

Case I and II	150	(m)
Case III	35.5	(m)
Case IV	17×35.5= 603.5	(m)

Number of Sections:

Case I, II, III	1
Case IV-VII	17 (603.5 m total length)

Method and Domain for Case I and Case II:

These two cases are used to compare results from (i) MULTIFLUX differential CFD, (ii) FLUENT, and (iii) experiments. The boundary conditions for these cases are (i) inside wall is kept at constant temperature, outside wall is unheated, and (ii) outside wall is kept at constant temperature, inside wall is unheated.

a) MULTIFLUX calculations

Fig. 1 shows a drift section for the MULTIFLUX Differential Parameter CFD calculations. The drift section is 150m long and has 50 segments of 3m each. There are 60 unequally spaced segments along the radius. The flow is assumed to be fully developed hydraulically when entering the drift section. The eddy diffusivity and the velocity profiles are given in the dimensionless equations by Kays and Leung [5]. These eddy diffusivity and velocity profiles are input parameters in the energy equation for heat transport calculation in turbulent flow. The energy equation, a second-order partial differential equation, is solved by MULTIFLUX to calculate the heat transport coefficient (*h*) for constant wall-temperature boundary condition.

b) FLUENT calculations

The goal of the FLUENT calculation is to provide values for comparisons in studying convective heat transfer characteristics in turbulent flow in a concentric annular drift. FLUENT 5.5 was used in the study. The computational domain for FLUENT is shown in Fig.1.b

Temperature and heat flow distributions were calculated in a drift with a length of 300 meters of which an unheated leading section of 150 meters was used to allow velocity profile development under isothermal condition. A step change in temperature was applied over the heated section. A mesh grid was defined with 0.5 meter axial and 0.095 meter radial sizes.

Case III: A Comparison Case

This case is used to compare MULTIFLUX with FLUENT when both walls are heated using variable temperatures over the surfaces in the flow direction.

a) MULTIFLUX calculations

There is only one drift section included in this case, shown in Fig. 1.c. The length of the section is 35.545m. There are 21 segments along the axis that are variable in length, corresponding to half WP lengths and to the small gaps between the WPs. There are 60 segments of variable length along the radius. The discretization of the length along the axial direction and the radial direction is shown in Tables I and II, respectively.

b) FLUENT calculations

The total length used was 185.5m, shown in Fig. 1.d. The first 150 meters were used as developing region for the airflow. The next 35.5m section was divided in 21 axial segments identical to those used in MULTIFLUX.

Table I. Discretization of the Length along the Axial Direction

Division	Length	Division	Length
1	1.865	11	0.1
2	0.1	12	2.6525
3	2.6375	13	2.6525
4	2.6375	14	0.1
5	0.1	15	2.6375
6	2.6525	16	2.6375
7	2.6525	17	0.1
8	0.1	18	2.6525
9	1.865	19	2.6525
10	1.865	20	0.1
		21	2.785

CALCULATION RESULTS

Case I, Verification

This case had two conditions:

a. Inside wall is kept at 50°C, outside wall unheated.
b. Outside wall is kept at 50°C, inside wall unheated.

Three different heat transport models were used under these conditions:

- Experimental heat transport coefficient correlations for circular annulus
- MULTIFLUX Differential Parameter CFD sub-model
- FLUENT

The results are shown in Fig. 2 a and b.

Case II, Comparison, Constant Temperature

In this case both the inner and the outer walls were kept at a constant temperature of 50°C. There are no experimental data available for this case. The computational results are shown in Fig. 2 c.

Case III, Comparison, Varying Temperature
In this case, both walls are heated and maintained at axially-varying temperatures which were determined from a preliminary MULTIFLUX calculation assuming an axially constant value of heat transport coefficient of 1.37 W/(m²K) for the inner and outer walls. The result of heat flux density values compares well with the FLUENT results. The results, however, are not shown here for the sake of brevity.
The run time for variable temperature for first section at the fifth time period using the MULTIFLUX Differential Parameter CFD was 14 seconds, with a 1.7 GHz Pentium IV processor. FLUENT was run on a SGI workstation and took about 2 minutes to complete the calculation.

Table II. Discretization of the Distance along the Radial Direction

Division	Length	Division	Length
1	0.835	31	0.149293
2	5.03×10^{-07}	32	0.167838
3	3.81×10^{-06}	33	0.145884
4	1.56×10^{-05}	34	0.126157
5	4.53×10^{-05}	35	0.108504
6	0.000106	36	0.092772
7	0.000215	37	0.078817
8	0.000393	38	0.066499
9	0.000664	39	0.055686
10	0.001058	40	0.04625
11	0.001604	41	0.038067
12	0.002341	42	0.031023
13	0.003307	43	0.025005
14	0.004546	44	0.019909
15	0.006104	45	0.015636
16	0.008034	46	0.012091
17	0.010389	47	0.009187
18	0.013228	48	0.006842
19	0.016614	49	0.004977
20	0.020612	50	0.003523
21	0.025293	51	0.002415
22	0.03073	52	0.001592
23	0.037	53	0.001
24	0.044184	54	0.000592
25	0.052368	55	0.000324
26	0.06164	56	0.00016
27	0.072093	57	6.82×10^{-05}
28	0.083822	58	2.35×10^{-05}
29	0.096929	59	5.73×10^{-06}
30	0.111516	60	7.58×10^{-07}

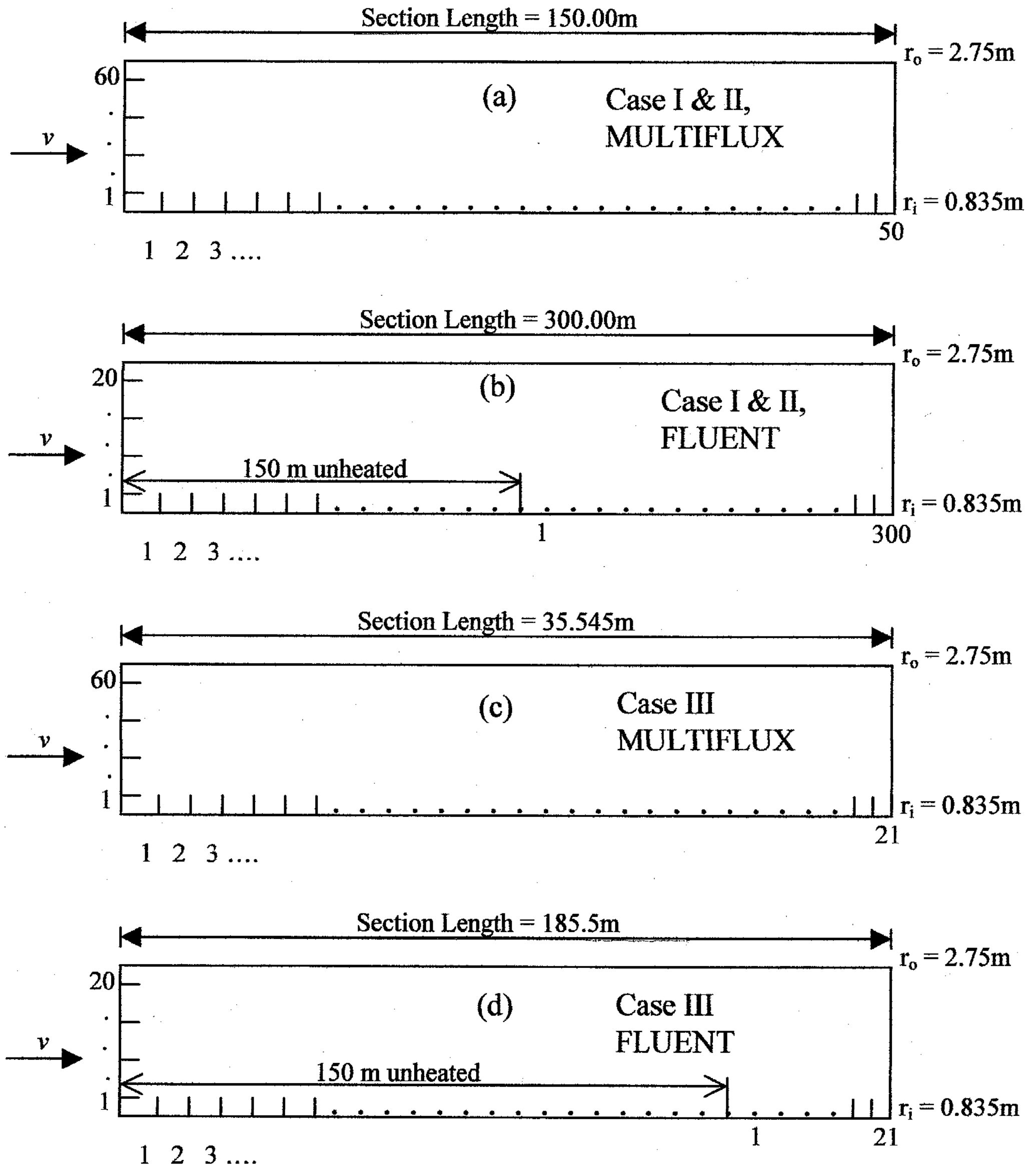


Fig. 1 Drift Sections used in cases I-III in MULTIFLUX

Application of MULTIFLUX V1.0 differential parameter CFD to ventilation calculation

Four additional cases were prepared to study the effect of the variable heat transfer coefficient on the drift wall temperature. The calculation domain includes a full drift length of 603.5 m. Results are presented as a function of both time and position for cases IV-VII. A non-uniform waste package heat load was used in the MULTIFLUX calculations.

Case IV: In this case, variable heat transfer coefficients, calculated by the differential parameter CFD are used. The heat transport coefficient variations are iteratively calculated, over time and space for a full drift as a function of inner and outer wall temperatures. The corresponding temperature distributions and heat transport coefficients of time and position are given in Fig. 3.

Case V: In this case, constant heat transfer coefficients (inner wall hi=1.84, outer wall ho=1.33), obtained from averaging the variable coefficients of Case IV, are applied to ventilation calculation.

Case VI: In this case empirical constant heat transfer coefficients (inner wall hi=1.59, outer wall ho=1.15) are used in the ventilation calculation. These coefficients are obtained from an empirical heat transfer model specifically developed for turbulent flow in a circular annulus with walls kept at a constant temperature, according to Kays and Leung [5].

Case VII: In this case, an AMR- equivalent heat transfer coefficient of Dittus and Boetler [6] of 1.37, based on airflow in equivalent circular duct, is applied to ventilation calculation.

Figure 4 shows the graphical presentation of the results for the 1st and 17th sections for the fifth time interval by comparing cases IV through VII.

CONCLUSIONS

Four models are compared to study the effect of heat transport coefficient variability on the drift wall temperature distribution. Case VI may be considered as a reference model since it is experimental-empirical and specifically obtained for a circular annulus. This model gives the highest temperatures for the duct wall. However, the correlation conditions (i.e., the assumption of thermally developed flow with constant wall temperatures) are not applied in these cases.

Case VII uses the Dittus-Boelter experimental-empirical model, and it results in similar temperatures to those of Case VI. However, the correlation conditions are violated not only by the variable-temperature boundary but also by the geometry which is not a simple circular duct but an annulus.

Case IV uses the MULTIFLUX differential parameter CFD results, based on an experimental-empirical eddy-diffusivity model specifically determined for circular annular duct flow. The CFD model agrees with experimental results published for heat transfer in annular duct flow (Case I). Therefore, variable heat transport coefficients such as those of Case IV are considered the most appropriate approach of all cases presented. This CFD model produces the lowest temperature results, which is favorable to ventilation performance.

Case V is closer to Case IV than the other cases. It is based on using the average of the Case IV variable heat transport coefficients, rather than constant values obtained by other means. However, the difference between the variable coefficient and constant coefficient results is still significant. This observation quantifies the value of using variable, instead of averaged, heat transport coefficients in ventilation calculations.

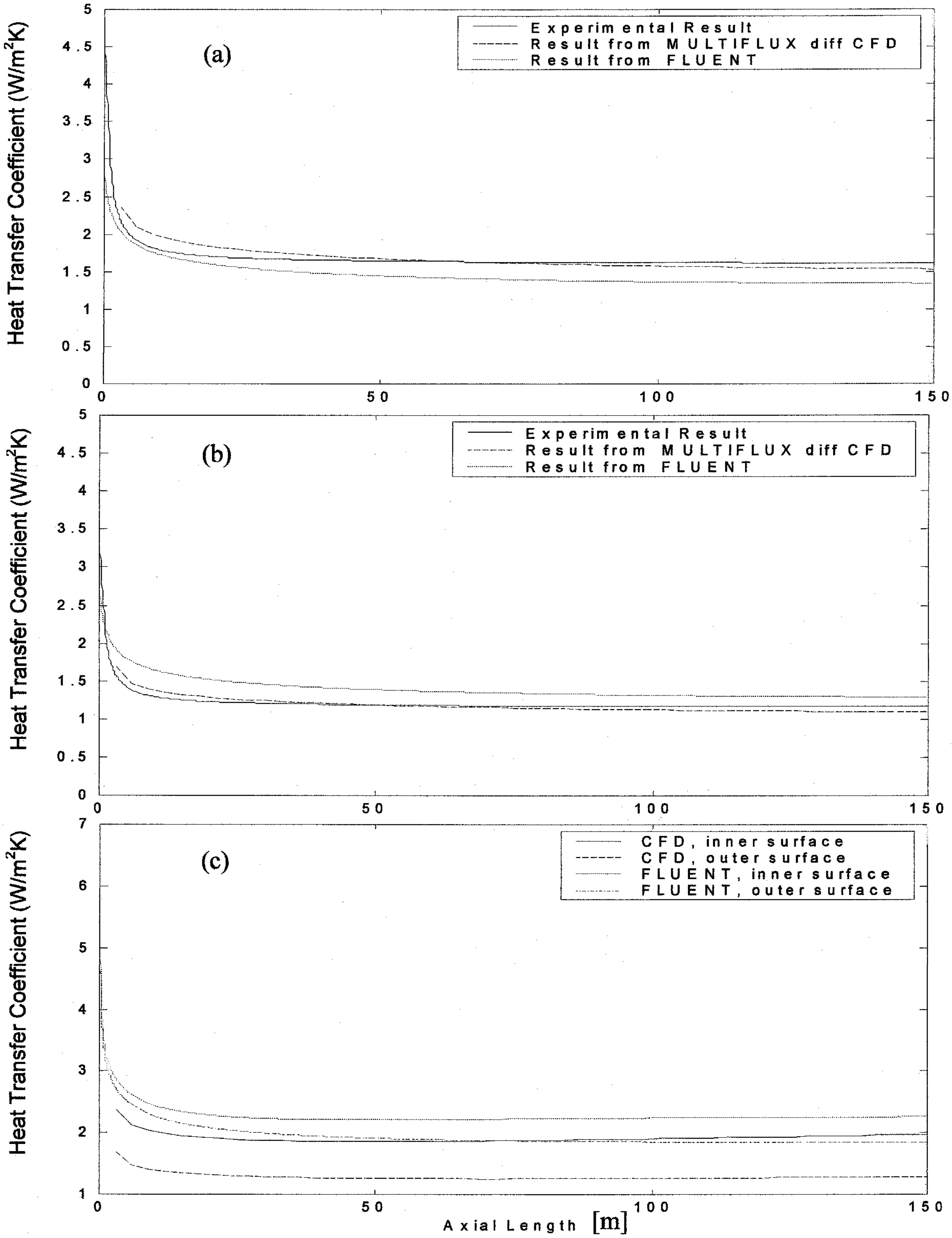


Fig. 2 Comparison of Heat Transport Coefficient variations (a) Heated inner surface and unheated outer wall (b) Unheated inner surface and heated outer wall (c) Heated inner and outer wall

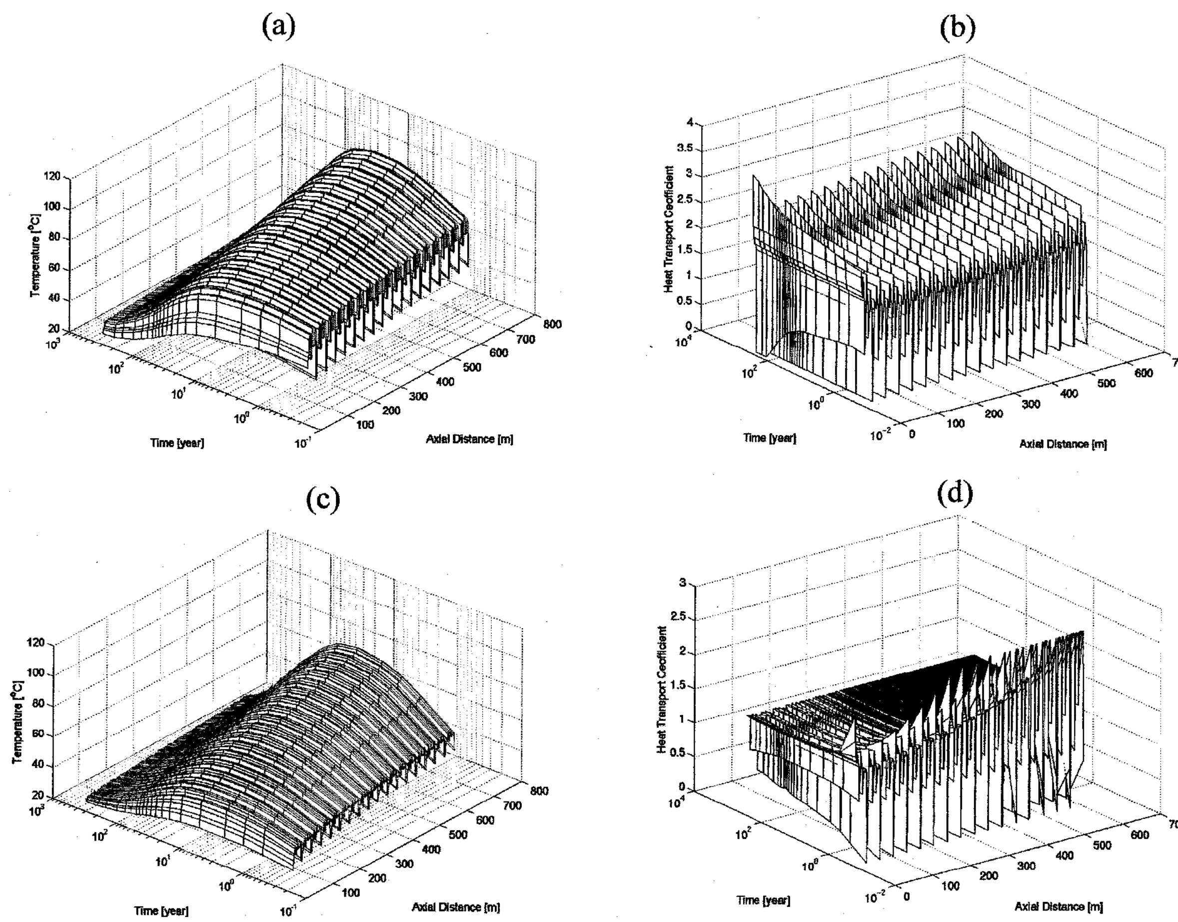
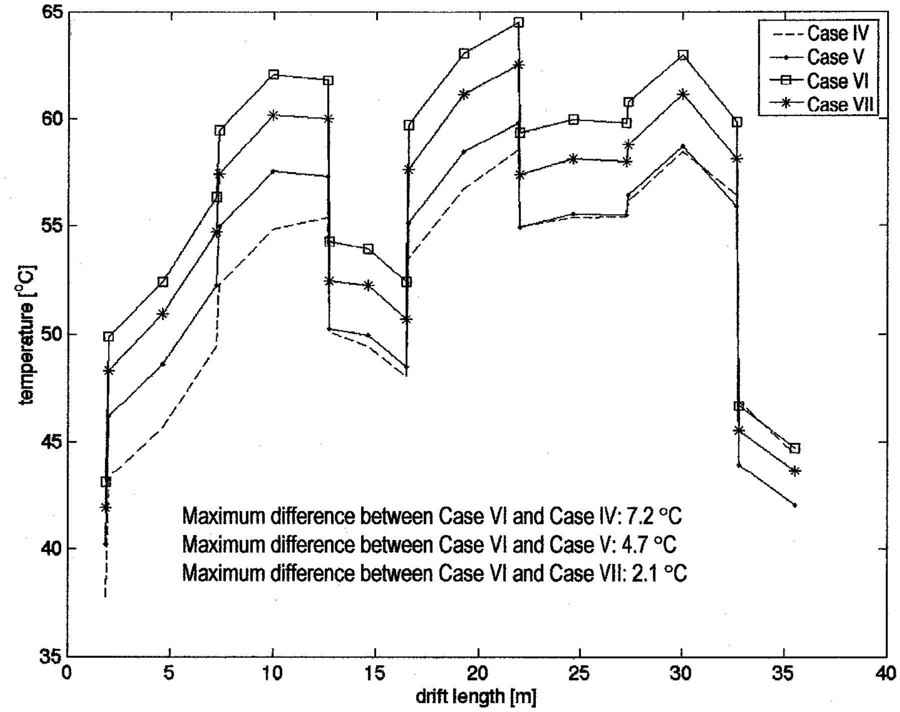


Fig. 3 Corresponding temperature and heat transport coefficient distributions, (a) temperature distribution at the inner wall, (b) , heat transport coefficient on the inner wall, (c) temperature distribution at the outer wall and (d) heat transport coefficient on the outer wall.

(a)



(b)

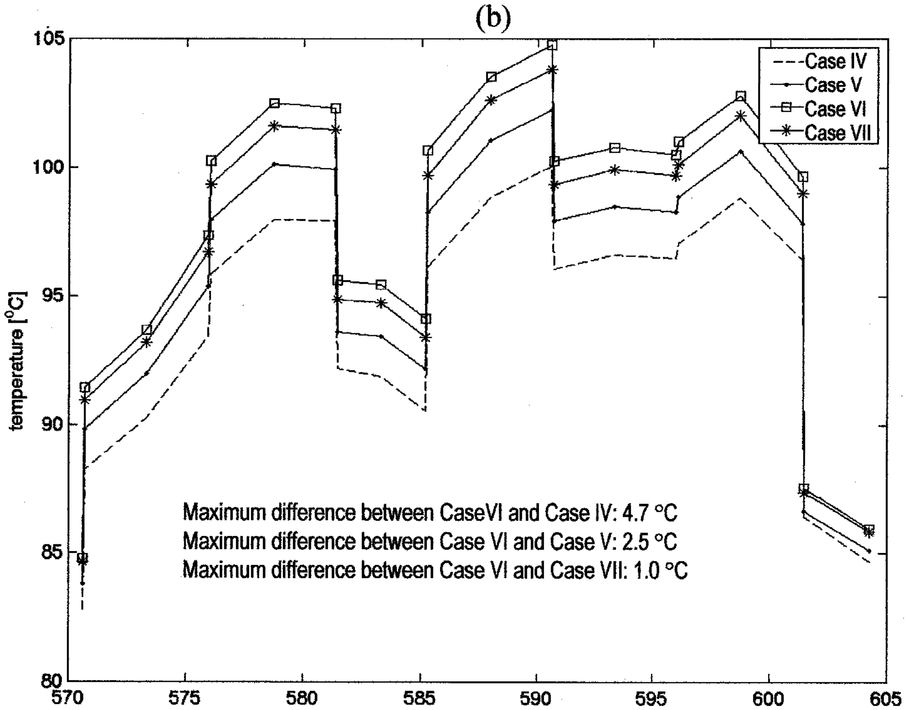


Fig 4 Comparison between the cases IV- VII: (a), first drift section; (b), 17th drift section

ACKNOWLEDGMENTS

The support of the work by DOE Cooperative Agreement Number DE-FC08-98NV12081 (Task 20) is acknowledged. The technical and editorial comments of Dr. James A. Blink, LLNL, are gratefully appreciated.

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