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Application of MULTIFLUX for air, heat and moisture flow simulations

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ABSTRACT: MULTIFLUX, a new thermal, hydrologic, and airflow model and software is being developed to solve the flow of heat, moisture, and air in and around an underground opening. MULTIFLUX couples two distinct domains that are solved separately first and re-coupled as an iterative task: (1) the rockmass, and (2) the airway. The airway is solved with a lumped-parameter Computational Fluid Dynamic (CFD) module which is an embedded part of the MULTIFLUX code. The CFD model includes convection, conduction, and radiation for heat, as well as convection and diffusion for moisture transport in an air-filled opening. The CFD model also solves for the airflow field. The surrounding rockmass model may be from any analytical solution, or from a complex thermal-hydrologic numerical model such as NUFT or TOUGH2. The rockmass model is interfaced to MULTIFLUX using a novel technique called Numerical Transport Code Functionalization (NTCF). The method provides fast convergence on a personal computer platform. The paper reports the results of MULTIFLUX simulations for a mine drift, comparing calculations with a known mine climate software, CLIMSIM, and with measured data. Through this validation example, the performance of MULTIFLUX is demonstrated. The results show excellent agreement due to the use of realistic modeling assumptions and boundary conditions.

1 Introduction

The coupled solution of air, heat, and moisture flows in and around a mine opening has been the subject of renewed interest. The goals for new simulation and design support are to increase safety and predictability, and to reduce energy consumption for ventilation and air cooling. Apart from using an advanced, general-purpose simulation software, such as ANSYS [1], or a computational fluid dynamics code (CFD), such as FLUENT [2], only a few specific software and model versions are available for mining applications, such as CLIMSIM [3], MIVENA [4], and VUMA [5]. There is a widening gap between the capabilities of the general-purpose CFD models and those of the specific software developed for mining ventilation and climatization design support. Even VUMA with its new support modules and user-friendly interfaces applies the solution foundations of the past and lacks the capacity of modern CFD solvers. A new approach has been taken to bridge the gap with the development of MULTIFLUX [6].

The MULTIFLUX (MF) software is developed for supporting coupled, time-dependent thermal-hydrologic and ventilation calculations in a subsurface opening, such as a mine work face or an emplacement drift in a high-level nuclear waste repository [6]. The design allows for analyzing large, complex systems, which typically involve a mountain-scale rockmass surrounding an air-filled opening with small, equipment-scale details. A typical mining task is the analysis of the working climate in a mine production face with sub-meter-scale heat and moisture sources on excavation and loading machines, and dissipation into the mined cavity of several hundred meters in size that is surrounded by the host rockmass. A typical exothermic nuclear waste storage environment task is the analysis of temperature, humidity, and liquid water distribution in the emplacement cavity in a waste container scale, coupled to the mountain-scale rockmass of hundreds or thousands of meters.

Appendix 1 is a user activity diagram for MF in a complete application [6]. The current software version of MF supports only a part of a complete task, indicated in Appendix 1 and repeated as the current, main data and logic flow chart in Appendix 2. MF is composed of three main software modules needed to calculate distributions of temperature, T, partial vapor pressure related to relative humidity, P, heat flow, q_h, and moisture flow, q_m, in an airway, constructed in a geologic rock formation. The three modules are: (1) the CFD airway module in the form of a lumped-parameter Computational Fluid Dynamic (CFD) solvers for heat, moisture, and airflow; (2) the NTCF thermal-hydrologic simulation processor module in the form of a Numerical Transport Code Functionalization (NTCF) solver [7,8] that pre- and post-processes the computational results of a Porous-Media Hydrothermal Code (PMHC) to model the time-dependent heat and moisture flow in the rockmass around the drift; and (3) the DISAC (Direct Iteration and Successive Approximation Coupler) module that balances the results of the CFD and NTCF modules by iteration and successive approximation on the interfacing drift wall during each time division. The DISAC module performs an Inside Balance Iteration (IBI) between the heat and mass transport results of the NTCF and CFD modules. As shown in Appendices 1 and 2, the PMHC model calculations in the current MF version are performed off-line, as an outside simulation to obtain data. Nevertheless, a surrogate, NTCF model imports the essential and relevant information into MF about the thermal-hydrologic responses of the PMHC.

An open software structure is employed in the current version of MF in which the NTCF and CFD modules can be independently and meaningfully used. The DISAC coupler may be considered a main program module to perform a balancing iteration between results from the NTCF and CFD modules. The NTCF module [7,8] is composed of two parts: (1) the NTCF model identification part, a one-time used, preparatory function; and (2) the NTCF Matrix Equation application part, a multiple-time used function repeatedly called by DISAC during iteration. For one IBI process, the NTCF model is kept constant: the model coefficients in the user-selected linear or non-linear operator equations are used unchanged. The NTCF model acts as a surrogate model of the PMHC when it describes the time-dependent heat and moisture fluxes at any drift wall segment as a function of wall temperature, T, and partial vapor pressure, P, during the IBI cycles. In the current version, it is the user's responsibility (outside of MF) to check how well the NTCF model retains its accuracy at the end of the IBI. The software is designed to provide a sufficiently accurate NTCF model for a working regime within which temperature and partial vapor pressure may vary during an IBI iteration. However, in highly nonlinear cases, if the differences are too high between start-up values for T and P (called the central values for temperature T_c and partial vapor pressure P_c, the ones used in the PMHC runs for generating data for model identification) and the values found at the end of the IBI process, the accuracy of the NTCF model may not be acceptable. An outside balance evaluation should be performed in which the user compares the output T and P from IBI with T_c and P_c used for the current NTCF model identification. If the comparison shows a large difference (e.g., more than 5%) difference in any of the values of the multi-component vectors, the NTCF model should be replaced with a new one, starting the Outside Balance Iteration (OBI) process from the beginning with the new $T_c = T$ and $P_c = P$ vectors as input variables. It must be noted that in conventional mine climate models, such as CLIMSIM and VUMA, linear rockmass models are used assuming only heat conduction in the rockmass. In this case, the NTCF model is linear, and there is no need for an OBI process since the model itself does not change with changing temperature.

The NTCF and DISAC modules are vectorized, capable of performing simulations for more than one time divisions consecutively and automatically. The time-dependency of the processes are modeled. The CFD module in the current version assumes the in-drift processes to be quasi-steady-state. Vectorization allows for performing one, automatic IBI with a number of time divisions, effectively packaging the OBI calculations for a conveniently long simulation time period and minimizing the need for user interaction, shown in Appendix 1. It is possible to run OBI calculations from the same MATLAB [11] environment automatically under the control of a user-written MATLAB macro without the need for any modification of the current version of MF; however, such a macro usage is not discussed in the current software documentation.

A PMHC can be TOUGH2 [9], NUFT [10], or any other code relevant to modeling coupled thermal-hydrologic processes. If only heat transport is of interest, the PMHC may be a conduction-only model, such as ANSYS [1]. If comparison with analytical results is of interest, for example in a qualification-validation exercise, the PMHC may be emulated with the numerical result of an analytical expression. The time-honored Gibbson function, the basic analytical solution applied e.g., in CLIMSIM and VUMA, can also be used, replacing a PMHC when the surrounding rockmass is homogeneous, isotropic, infinite, and lacks fracture flows.

2 Brief Description of the Solution Technique Used in MF

Two distinctly different model domains are dealt with in heat, moisture/vapor and air transport calculations: (1) the rockmass, and (2) the air space. The two domains require two different modeling solutions: (1) a PMHC is needed for the rockmass, and (2) a CFD is required for the air space. Both domains may be modeled with readily available software. The basic problem with using different models for rockmass and the air space is the need to couple the two distinct model-elements, that is, to make them cooperate with each other for a common solution on the rock-air interface.

MF uses an innovative, system theory-based solution method for coupling in-rock and in-drift processes. The philosophy of the coupling is to separate the two problems, analyze each of them numerically, describe the general behavior of each problem mathematically with surrogate models fitted to data, and re-couple the general, mathematical, surrogate models for the solution of the composite problem.

A typical, user-selected NTCF operator equation is a second-order, nonlinear matrix equation. The surrogate model of the in-drift domain is a lumped-parameter CFD with three coupled, CFD sub-models, one for heat, one for moisture/vapor and one for air flow. The lumped-parameter CFD model is surrogate to a fully-discretized-parameter CFD model, or an experimental model, or a suit of experimental models: its transport coefficients and other parameters are imported from these models.

The transport equations used in the CFD for heat, moisture, and air transport follow the general formulation in the literature. A transport network method is used in which the transport connections are represented by connection resistances or admittances (the reciprocal of resistances). The transport fluxes are driven by potential differences: temperature difference, ΔT , for heat flux, qh;

vapor mass fraction difference, $\Delta\omega = (\rho_v /\rho)$, for vapor mass flux, *qm*; and total pressure difference, ΔPb, for air-vapor mixture mass flux, *qa*. The vapor mass fraction, ω, is a monotonous, nonlinear function of the partial vapor pressure, *P*, and the conversion between them is unique according to the following equation:

$$\omega = \frac{P \cdot \Re a / \Re v}{Pb - (1 - \Re a / \Re v) \cdot P} \tag{1.1}$$

In Eq. (1.1), $\Re a$, and $\Re v$ are the specific gas constants for air and vapor.

While ω and *P* are convertible, the differences, $\Delta\omega$ and ΔP are not, therefore, ΔP cannot be used as a driving force of *qm*. For this reason, ω will be used everywhere in the CFD and DISAC modules together with *P*, which is still needed when calculating saturated vapor pressure P_s. *P* will be kept in the NTCF modules for the boundary condition definition, where *Pb* is also given and the conversion for ω is unique.

The NTCF surrogate model is an input-output representation of the PMHC results in operator equations. The following equations express the heat and moisture transport components in general form, explicit in the boundary fluxes:

$$qh = F_1(T, P, ...) \tag{1.2}$$

$$qm = F_2(T, P, wf, ...) \quad \text{with } wf = f_1(T, P, ...) \tag{1.3}$$

The F_1 and F_2 time-invariant, dynamic operators are determined matching the PMHC results that are obtained for a set of pre-determined input vectors of *T* and *P* on the boundary. The elements of the T and P vectors are values at the instants along pre-selected time divisions. The typical number of PMHC runs for generating a sufficient set of results is three. The NTCF model-building process is part of MF. The F_1 and F_2 operators are dependent on many input parameters and variables, such as barometric pressure, liquid water condensate recharge, *qc*, rockmass properties, and boundary conditions on surfaces other than that of the drift wall. These other input parameters are not shown in Eqs. (1.2) and (1.3). The *wf* expression in Eq. (1.3) plays a passive role as it is kept unchanged during an IBI iteration cycle. The f_1 function is not functionalized but left for correction during the OBI iterations. During an IBI cycle, F_1 and F_2 are independent of the *T* and *P*, time-dependent functions.

The heat and moisture CFD model-elements provide the other two equations that are needed for a unique solution for *T*, *P*, *qh* and *qm*:

$$qh = F_3(T, P(\omega), qa, ...) \tag{1.4}$$

$$qm = F_4(T, P(\omega), qa, ...) \tag{1.5}$$

In Eqs. (1.4) and (1.5) the partial vapor pressure, *P*, is shown as a function of vapor mass fraction, ω, calculated from the unique inverse solution of Eq. (1.1) in the useful regime of *P,* which will be discussed later in the document. Instead of identifying the time-invariant, general F_3 and F_4 operators with the NTCF method (which is indeed a possible solution), they are generated as explicit solutions from the transport network equations (hence the "direct" in the name of DISAC, indicating direct calculations with the lumped-parameter CFD model-elements). The F_3 and F_4 operators are not kept constant during IBI cycles, but rather re-calculated due to temperature and humidity dependencies. There are additional input parameters and variables in Eqs. (1.4) and (1.5), other than *T* and *P*, which are implicitly included in the F_3 and F_4 operators, such as heat or moisture sources or sinks, barometric pressure distribution, air velocity distribution, condensation at any node, and transport properties in the laminar or turbulent boundary layers.

The air flow field during both powered or buoyancy-driven natural ventilation primarily affects the transport of heat and moisture. The philosophy of modeling convective transport is to provide the user with choices for either (1) using the velocity field in some lumped-parameter CFD sub-models for heat and moisture convection, or (2) employing convective-dispersive transport coefficients without the need for the velocity field in other sub-models; or use a combination of (1) and (2). Specifically, the $v \cdot grad(T)$ and $v \cdot grad(\omega)$ terms in the heat and moisture transport equations explicitly require the knowledge of the velocity field. The CFD module includes sub-models from which the user may select a suitable element. The design of the lumped-parameter CFD model provides model-elements that can be used to capture the relevant transport processes. The velocity field may be exported from another, outside CFD calculation. MF supports pressure- or buoyancy-driven duct flow models of air-vapor mixture; this model-element can be used to simulate air flow in the air space:

$$qa = F_5(T, P, Pb, qh, qm, \ldots) \tag{1.6}$$

The solution from Eq. (1.6) may be used to generate the velocity field included in the F_4 and F_5 operators. User-defined corrections may be used, if deemed necessary and/or practical in the MF model against a more detailed, outside CFD calculation. The lumped-parameter CFD model is designed to be powerful on its own, but still kept in surrogate in nature, by allowing for adjustments against other models.

Solution to the set of Eqs. (1.4)-(1.6) is provided within the CFD module, embedded as successive approximations in the iterations for the solution of Eqs.(1.2) and (1.3) performed by the DISAC coupler. The main data and logic flow chart for the solution is shown in Appendix 1. Time variation is modeled by discretization with time in the direct CFD solution. In most applications, the task involves an air space surrounded by a large rockmass, with much higher heat and moisture storage capacity than that of the air space. For this reason, the main focus in the CFD model is to solve for heat and moisture fluxes in a steady-state air flow. When a non-steady state CFD model is desired, capacitance terms are added to the model. The air flow field, however, is always assumed to be in steady equilibrium state either prescribed, or modeled and linked to slowly changing heat and moisture transport processes. Since the rockmass NTCF model is already non-steady state and the coupled solution applies time discretization, the addition of capacitance elements in the CFD require no modification in the coupling solution structure. For this reason, all variables are considered sampled values at a given time instant with all relevant dynamic effects included.

The constitutive equations used in the CFD for heat, moisture, and air transport follows the general formulation in the literature [12]. A transport network method is used in which the transport connections are represented by connection resistances or admittances (the reciprocal of resistances). The transport fluxes are driven by potential differences: heat flux, *qh*, by temperature difference, ΔT; moisture flux, *qm,* by vapor mass fraction difference, $\Delta\omega$; and air-vapor mixture mass flux, *qa,* by total pressure difference, ΔPb. The special case of ΔPb-driven superheated steam is integrated in the moisture transport network. The constitutive equations are as follows, written using either resistances (*Rh*, *Rm*, *Ra*) or admittances (*irh*, *irm*, *ira*):

$$qh = \frac{\Delta T}{Rh} = irh \cdot \Delta T \tag{1.7}$$

$$qm = \frac{\Delta \omega}{Rm} = irm \cdot \Delta \omega \tag{1.8}$$

$$qa = \frac{\Delta Pb}{Ra} = ira \cdot \Delta Pb \tag{1.9}$$

Networks are formed by connecting resistances (or admittances) between network nodes which represent finite volumes or finite surface areas in the model domain. The constitutive equations are represented by the branches of the network, while the conservations of the flow of heat, moisture and air are represented by the connection of the branches at its nodes. A network model may be considered a state-space model in which the space is two-dimensional with potential and current being two state variables. In the model space, the spatial, 3-D variations define a set of state variables, taken at the network nodes. Time variations make all state variables time-dependent. The fundamental advantage of a network model as a special type of state-space model is that the conservation of current is built into it during model formulation. Another advantage is that the second-order systems for heat, mass and momentum transport can be described with a set of first-order equations. In comparison, a computational model that uses only the potential as one state variable must include the conservation laws in separate equations. In addition, all governing equations are in second-order, partial differential equation form.

Three networks are used: one for heat, one for moisture, and one for air flow. Five different types of connections are used in MF: (1) ordinary, passive connections; (2) active, controlled di-pole connections; (3) active, controlled tri-pole connections; (4) series connections with booster potential; and (5) switched connections. Capacitive connections to generator points kept at the initial potential may be used to model dynamics, i.e., storage of heat or moisture. These connections fall into the ordinary, passive connection category. The networks are solved, using matrix-vector formulation, based on nodal balance formulation, discussed later in the document. The nodal balances for active, controlled di-pole and tri-pole connections are built into special network solvers, an original formulation used first in MF. The solution for these controlled elements is automatic and requires no calculation overload. The swiched connections represent diodes (or rectifiers) and require the application of logical decisions using the nodal connection evaluation.

3 Application Example to Mine Climate Simulation

Detailed description of the solution methods used in MF is given in the User's Manual of the MULTIFLUX software [6], with sample problems as tutorials. Sample problem 2 is recited here to illustrate the use of MF in an application example, that has also been solved with CLIMSIM [3].

The purpose this sample problem is to compare temperature and relative humidity results in a mine drift obtained from (1) MF, (2) CLIMSIM, and (3) from field measurements.

Field studies were performed at the Home stake Gold Mine in South Dakota for CLIMSIM verification [3]. One of the published studies was carried out between March and July, 1984 on the 2350 m level below ground. Air flows, barometric pressure, and wet and dry bulb temperatures were measured at two measurement stations along the horizontal drift, about 247 m apart. Figure 1 shows a simplified view of the measurement drift. Measurement data were published [3] and were used to verify the CLIMSIM mine climate software. These measurement data as well as the CLIMSIM simulations results are also used here to compare with the MF results.

During the measurement period, the airflow varied from 2.98 to 7.38m^3/s. An uncovered drainage channel in the floor carried cold water from a heat exchanger during the first nine weeks of measurement. The effect of water cooling effect in terms of heat removal was calculated based on the water flow rate in the channel, and the temperature change of the drainage water between the two stations using the heat capcity formula of the water as follows:

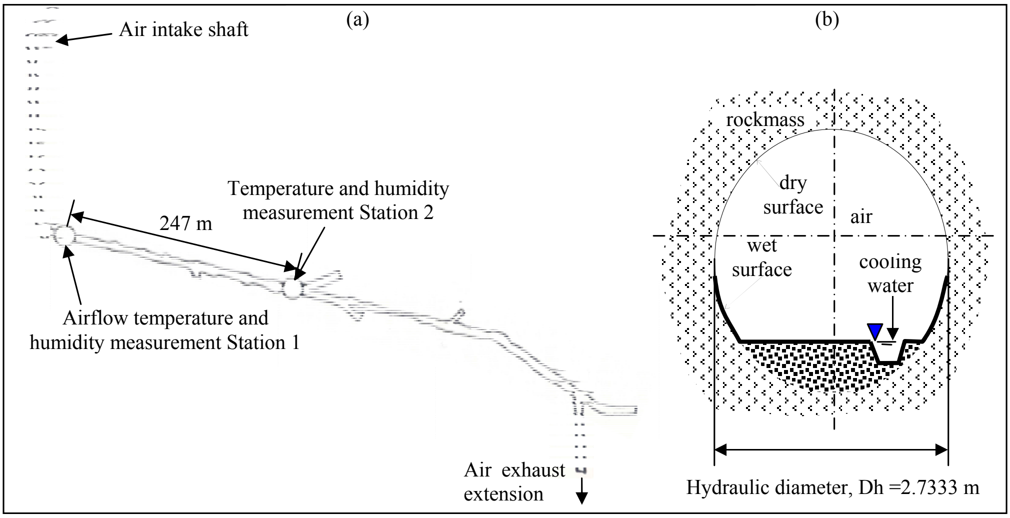

Figure 10.21. Plan view (a); and cross sectional view (b) of a 247-m drift segment in the 2350 m level drift segment.

$$qh = qm.c_w.(T_2 - T_1)$$

where *qm* is water flow rate (kg/s),
T_2-T_1 is temperature rise between the two stations (°C), and
c_w is specific heat of water (4187 J/kg-°C)

In the original CLIMSIM software verification, this heat removal was used as negative linear heat source along the 247 m drift section, varying between 2.8 and 16.7 KW. The rock mass surrounding the drift was assumed to be conduction-only. Water was assumed to be only on a portion of the drift surface expressed by the wetness factor. The far-field rock temperature, called the Virgin Rock Temperature (VRT), was estimated to be at 48 °C. Other rockmass thermal properties and drift geometry are summarized in Table 1. The age parameter refers to the time period for which the drift has been open. A model configuration provided prepares all the input files, including the CFD and NTCF models to be used in the MF model. The surface wetness factor provides an unlimited moisture source at 100% relative humidity for a given fraction of the drift perimeter. Table 2 summarizes the measured temperatures at the entrance of the measurement drift section together with airflows and cooling effect of the cold water drainage channel.

The results of the CLIMSIM prediction of the wet and dry bulb temperatures of air are given in Table 3 for comparison purpose. It was pointed out that all the wet bulb temperatures were predicted within 0.5 °C of measured values with average error of about 0.17 °C. The dry bulb temperature prediction error was slightly higher, -0.9 to 1.1 °C with air average absolute error of about 0.58 °C. Although the errors are small, the CLIMSIM predictions of dry bulb temperatures were slightly lower than the measurement values during the time period of cold water operation. After stopping the cold water flow the errors become positive, an indication that the CLIMSIM model overestimated the air temperatures. These results should be considered when the MF results are compared against the measurement and also against the CLIMSIM predictions.

Table 1. The physical data for the CLIMSIM [3] test case

Length:	247	m
Cross sectional area:	6.687	m^2
Perimeter:	9.786	m
Airway Friction factor:	0.012	kg/m^3
Age:	2	years
Wetness Factor:	0.25	
Pressure:	110	kpa
Virgin Rock Temperature: (VRT)	48	°C
Thermal Conductivity:	4.82	W/m°C
Thermal Diffusivity:	2.1083e-006	m^2/s

4 Simulation Results from MF

The model configuration of MF followed the geometry and input data given in Figure 1 and Table 1. A linear NTCF model was used, based on a single step change response function calculation, applying TOUGH2 [6]. Another alternative NTCF model was also used applying NUFT [10] for the input data generation for the NTCF model. A partially wet tunnel surface with a wetness factor of 0.25 was assumed, adding liquid water to the wet surface directly for evaporation in the model. Therefore, no hydrologic model was needed, and the TOUGH2 model was configured as heat conduction only [6]

Table 2. Air temperatures measurements at drift entrance [3].

Air input data at drift intake				Sensible Heat
Date	Quantity	Dry Bulb	Wet Bulb	
	[m^3/s]	[°C]	[°C]	KW
3/10/1984	3.97	30.8	27.1	-3.14
3/27/1984	3.69	32.2	29	-8.98
4/10/1984	4.05	32.3	28.6	-2.81
4/17/1984	4.56	32.1	28.8	-2.81
4/24/1984	4.25	32.1	28.9	-9.54
5/1/1984	4.25	31.4	28.5	-16.71
5/9/1984	7.38	31.5	28.6	1.07
6/4/1984	5.82	32.4	29	0
6/12/1984	4.16	32.7	29.7	0
6/21/1984	3.79	33	30.2	0
6/26/1984	2.98	33.4	30.7	0
7/3/1984	3.25	34.2	31.3	0
7/10/1984	3.8	33.7	31.3	0
7/26/1984	3.62	33.5	30.8	0

Table 3. Air temperature measurements at drift exit.

Date	measurements		CLIMSIM prediction		CLIMSIM prediction	
	Dry Bulb	Wet Bulb	Dry Bulb	error	Wet Bulb	error
	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
3/10/1984	33.3	29	33.37	0.07	29.01	0.01
3/27/1984	34.3	30.5	33.93	-0.37	30.5	0
4/10/1984	34.4	30.3	34.41	0.01	30.26	-0.04
4/17/1984	34.2	30.2	34.14	-0.06	30.29	0.09
4/24/1984	34.1	30	33.52	-0.58	30.22	0.22
5/1/1984	33.2	29.2	32.24	-0.96	29.63	0.43
5/9/1984	33.5	29.5	33.12	-0.38	29.7	0.2
6/4/1984	34.7	30.4	34.07	-0.63	30.26	-0.14
6/12/1984	34.4	31.1	35.27	0.87	31.29	0.19
6/21/1984	35.4	31.5	35.81	0.41	31.85	0.35
6/26/1984	35.8	32.1	36.79	0.99	32.63	0.53
7/3/1984	36.5	33	36.99	0.49	32.99	-0.01
7/10/1984	36.2	32.7	36.46	0.26	32.8	0.1
7/26/1984	35.5	32.6	36.32	0.82	32.43	-0.17

The MF results shown in Figure 2 and 3 are generally in excellent agreement for both reference temperatures and relative humidity variations with time against the published results. Table 4 summarizes the RMS error of fit between the measurement data and the simulation results, for three different simulations: (1) CLIMSIM, (2) NUFT-based MF (using NUFT for NTCF model) and (3) TOUGH2-based MF (using TOUGH2 for NTCF model).

As seen, CLIMSIM fares somewhat poorer against measurement data that MF, yet the CLIMSIM agreement was accepted as good in its qualification document from which the data came from for this test case. The NUFT-based or TOUGH 2-based MF models give about the same quality of agreement.

Table 4. RMS error of fit

	RMS error of fit		
	CLIMSIM	NUFT-based MULTIFLUX	TOUGH2--based MULTIFLUX
Temperature (°C)	0.5874	0.2929	0.2923
Relative Humidity (%)	3.5021	1.6718	1.6902

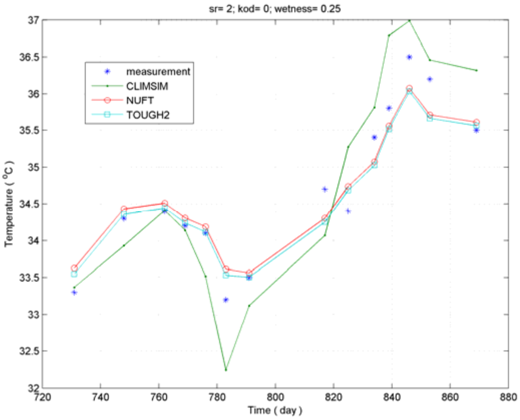

Figure 2. Air temperature at drift exit

5 Concluding Remarks

MULTIFLUX, a general-purpose thermal-hydrologic-air flow model and software is in its qualification and verification phase for the simulation of heat and moisture flows in and around subsurface openings. The software is designed with great flexibility for solving large-scale problems such as a ventilated underground mine or a high-level nuclear waste repository.

The software can be used to solve for the coupled (1) thermal, (2) hydrologic and (3) air flow problems simultaneously. All relevant processes of the multi-physics problem are modeled in air space [6]: (1) heat conduction, radiation, convection, latent heat, viscous dissipation, auto compression for heat; (2) moisture convection, diffusion, dispersion, condensation evaporation for moisture; and (3) laminar or turbulent, powered or natural flow for air flow.

Several test cases including unit tests and integrated tests (84 cases altogether) have been performed during the software qualification activity [6]. One of the tests is included in this paper for a subsurface mine climate application.

The test case shows that MF captures the relevant heat and moisture transport processes excellently.

A simple application example of MF is given in the paper as a debuttal for mining applications. However, MF is designed to solve tasks of large size and complexity [6].

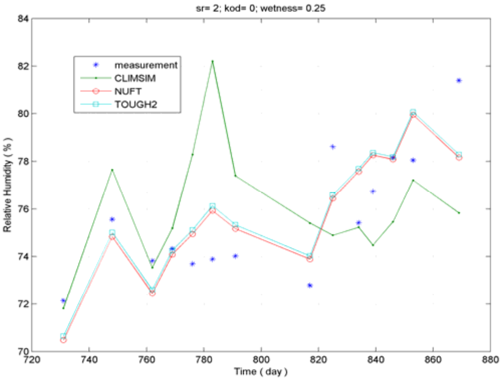

Figure 3. Relative Humidity at drift exit.

For example, a 760m-long emplacement drift with hundreds of heat sourced with it, has also been modeled with MF for the proposed nuclear waste repository at Yucca Mountain [13-15]. In the complex task, the operating regime is over the boiling temperature of water, and the drift is surrounded by a mountain size of heterogeneous, porous and fractured rockmass which is hydrothermally active. The MF model in this complex application involves active nodes for heat, 8172 active nodes for moisture, and 8172 active nodes for the air flow sub-models within the air space. Multiple connection branches are defined between the model for all three sub-models. The rockmass model is TOUGH2 itself also includes several thousands of discrete domains around the drift [16]. The MF model provides converging results including the calculation of the natural, buoyancy-driven air flow field, temperature, and humidity distributions for the task using a personal computer [6]. Such a solution capacity of MF may well serve the mine climate and air quality simulation requirements of complex, hot and wet deep underground mines

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Appendix 1. User Activity Diagram for a Complete MF Application