Determination of Temperature and Velocity Fields in a Corridor at a Central Interim Spent Fuel Storage Facility Using Numerical Simulation

V. Salajka, J. Kala and P. Hradil

***Abstract*—**The presented article deals with the description of a numerical model of a corridor at a Central Interim Spent Fuel Storage Facility (hereinafter CISFSF). The model takes into account the effect of air flows on the temperature of stored waste. The computational model was implemented in the ANSYS/CFX programming environment in the form of a CFD task solution, which was compared with an approximate analytical calculation. The article includes a categorization of the individual alternatives for the ventilation of such underground systems. The aim was to evaluate a ventilation system for a CISFSF with regard to its stability and capacity to provide sufficient ventilation for the removal of heat produced by stored casks with spent nuclear fuel.

***Keywords*—**Temperature fields, Spent Fuel, Interim storage facility, CFD.

I. Introduction

INTERIM storage of spent fuel offers a safe, flexible, and cost-effective near-term approach to spent fuel management that may be attractive regardless of a particular country's perspective on the continuing debate over whether spent fuel should ultimately be reprocessed or disposed of as waste. Today, in fact, there is less divergence among countries in what is actually done with spent fuel than official policy statements concerning reprocessing and direct disposal might suggest. With most of the spent fuel generated each year remaining in storage, a quiet consensus has developed that for the near term, simply storing spent fuel while continuing to develop more permanent solutions is an attractive approach.

The presented article deals with the description of a numerical model of a corridor at a Central Interim Spent Fuel Storage Facility (hereinafter CISFSF). The model takes into account the effect of air flows on the temperature of stored waste. The computational model was implemented in the ANSYS/CFX programming environment in the form of a CFD task solution, which was compared with an approximate analytical calculation. The article includes a categorization of the individual alternatives for the ventilation of such underground systems. The aim was to evaluate a ventilation system for a CISFSF with regard to its stability and capacity to provide sufficient ventilation for the removal of heat produced by stored casks with spent nuclear fuel.

The CISFSF comprises a complex structure of underground corridors. The fuel stored there is a significant source of heat which needs to be removed. The ventilation options are:

a) artificial ventilation with the aid of mechanical pressure units,

b) natural ventilation using the thermal energy produced by the stored SNF.

ad a) Artificial ventilation of a CISFSF can take place with the help of a ventilator with characteristics suitable for the creation of sufficient depression and volumetric flow for the removal of heat. The suggested placement of the ventilator is in the vent connecting the parallel entry into the storage facility with the repository corridor. The ventilation is designed so that the CISFSF is ventilated by means of overpressure.

ad b) A CISFSF can be ventilated naturally on the basis of the heating of the air flow via thermal uplift from the residual heat produced by the stored SNF. One of the safety conditions for the operation of a CISFSF is its ventilation without requiring the mechanical pressure units of ventilation systems, i.e. a natural means of ventilation via thermal uplift from the warming of air flows by the stored nuclear waste. It is also a basic requirement of the submitter of this project for the provision of ventilation.

Temperature changes in the air flows passing through the nuclear waste storage facility are dependent on the original temperature of the rocks in the surroundings of the facility and on the capacity of the heat source, i.e. the stored nuclear waste in this case. The temperature changes in the cooling air flows were calculated with the help of methodology and the ANSYS/CFX computer programme.

The calculated air flow temperatures are then used as basic input data for the calculation of the magnitude of the natural depression in the given geometrical configuration of the assessed CISFSF and the volumetric flow of the air flows caused by the depression as they pass through the facility.

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II. Determination of Temperature Changes in Air Flows in a SNF Storage Facility

Thermodynamic changes in the climate within the mined corridors that make up the facility are influenced by many factors – in this case, the focus is on heat and humidity.

The main sources of heat in the SNF storage facility are the stored casks, the rock massif and the installed powered systems (cranes, etc.). Auxiliary sources of heat with a negligible thermal output such as pipelines, lights and metabolism aren't included in the calculations [1].

The relationship used for the calculation of the amount of heat released or absorbed by the rock massif is based on the concept of air flow through a corridor with an equivalent circular cross section and a homogeneous isotropic environment. This assumption enabled the application of Newton's law of cooling and Fourier's law of non-stationary heat conduction via the resulting equation in the following form:

$$t = t_p - (t_p \pm t_o)\exp\left(\frac{A\alpha_0 C}{Q_m c_p}\right) \tag{1}$$

where

t - the calculated air flow temperature at the end of a given corridor, °C

t_p – the temperature of the surface of the corridor wall, °C

t_o - the temperature of air flows at the entry to the corridor, °C

A – the thermal coefficient of humidification

α_o - the heat transfer coefficient between the rock and the air flows, $Wm^{-2}K^{-1}$

C – the circumference of the corridor, m

Q_m - the mass flow rate of air flows through the corridor, kgs^{-1}

c_p – specific heat of air, $Jkg^{-1}K^{-1}$

The non-stationary character of the thermodynamic processes is expressed in equation (1) by parameter tp (the surface temperature of the walls). Its calculation is based on the definition of the dimensionless temperature of the walls of the mine workings and takes account of the physico-thermal parameters of the surrounding rock, the character of the heat transfer between the rock and the air flow and the influence of time factors on the intensity of this transfer.

The significance of the heat transfer coefficient is a theme given extensive coverage in the specialist literature. The following relation was used to obtain an approximate calculation:

$$\alpha = 3.65 v^{0.8} (2r_0)^{-0.2} \tag{2}$$

where

v - the velocity of air flow, ms^{-1}

r_0 - the equivalent radius of the corridor, m

In equation (1) parameter A (the thermal coefficient of humidification) is of great significance, as it expresses the influence of humidity on the resulting temperature change. Its value is typical and constant for the given type of mine workings and expresses the proportion of the sensible component of heat in the air with regard to the total heat content:

$$A = \frac{c_p dt}{c_p dt + l_v dx} \tag{3}$$

where

c_p - the specific heat of air, $Jkg^{-1}K^{-1}$

d_t – the difference in heat between the beginning and end of a given corridor, K

l_v – the latent heat of water evaporation, Jkg^{-1}

dx – the difference in specific humidity between the beginning and end of the corridor, kg.kg-1.

In the case of prognostic calculation methods this is the only parameter whose value was determined from a large set of thermal balance measurements in mines using statistical methods. Typical values lie in the interval 0 to 1, while in mines the values tend to be 0.2 to 0.3 regardless of geological conditions. This means that only 20 to 30 % of the heat accepted by the air flows causes their temperature values to rise and up to 70 or 80% of that heat causes a rise in moisture content. In the case of an SNF storage facility coefficient A was determined analogically to have a value of 0.5 - 0.6 [2]. Classification heat sources in the warehouse into the equation calculating the temperature change of the winds was the equation of the form

$$t = t_p - (t_p \pm t_o)\exp\left(\frac{A\alpha_0}{Q_m c_p}\right) + \left(1 - \exp\left(\frac{A\alpha_0}{Q_m c_p}\right)\right)\frac{\sum Q}{\alpha_0} \tag{4}$$

where ΣQ expresses the quantity of heat released its source except the massif.

III. The Assessment of Ventilation at a CISFSF

From the point of view of aerodynamics the assessed interim storage facility creates an air flow network underground. The air flow network is composed of the repository entry corridor, which is 504 m in length and has a cross-sectional area of 56 m^2, and four storage corridors with a cross-sectional area of 129.5 m^2 and lengths of 161.9 m (2 corridors) and 137.8 m (2 corridors). The storage corridors are connected at the exhaust side. This is achieved by 15 m long exhaust shafts with cross-sectional areas of 28.3 m^2 and by exhaust air lines 27.5 m in length with a cross-sectional area of 27.7 m^2 leading to two upper exhaust air lines, one being 167 m and one 137 m in length, both with a cross-sectional area of 53 m. The heated air flows are conveyed by the exhaust air lines into a single 75 m long exhaust shaft with a cross-sectional area of 42.7 m^2.

A basic schematic diagram was prepared for the presented disposition plan. It clearly shows the complexity of the chosen air flow network at the CISFSF. The regulation and management of this air flow network will be relatively demanding and it is recommended that difficulties be minimised by filling the four storage corridors equally. Regulation of the air flow network in the sense of raising or lowering the aerodynamic resistance in some of its branches (most advantageously in the air flow exhaust shafts) will be necessary for dealing with any emergency situations that might arise in the storage corridors (e.g. an oil fire). It is recommended that an emergency plan be prepared to solve hazardous situations connected with the outbreak of fire [3].

In order to plan the disposition of the underground storage areas the volumetric flow rate of the air flow was calculated depending on:

a) the configuration of the storage facility,

b) the changing aerodynamic resistance of the underground workings during the gradual filling of the storage corridors,

c) the value of the heat produced gradually by the spent nuclear fuel storage casks,

d) changes in the heat and humidity parameters of the climate on the surface during the year.

IV. Description of the Computational Model

A. Boundary Conditions

The top and the bottom of the investigated domain were considered constant temperature boundaries as indicated in Fig. 2 and set according to the geothermal conditions. The assumed constant temperature at the top of the domain (i.e. earth surface) is 20 °C. The geothermal gradient was assumed to be 30 °C/km. The investigated domain extends to a depth of 1000mbelow the repository level. The depth at which a natural temperature of 66 °C exists is expected to be about 1509 m.

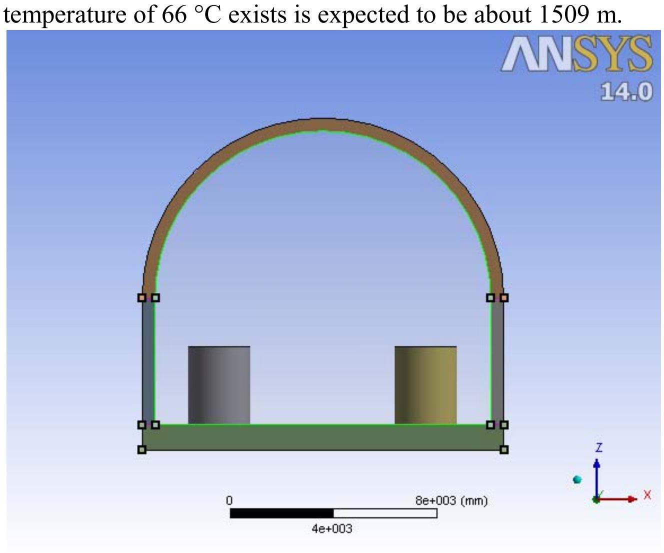

Fig. 1 Computational model – front view

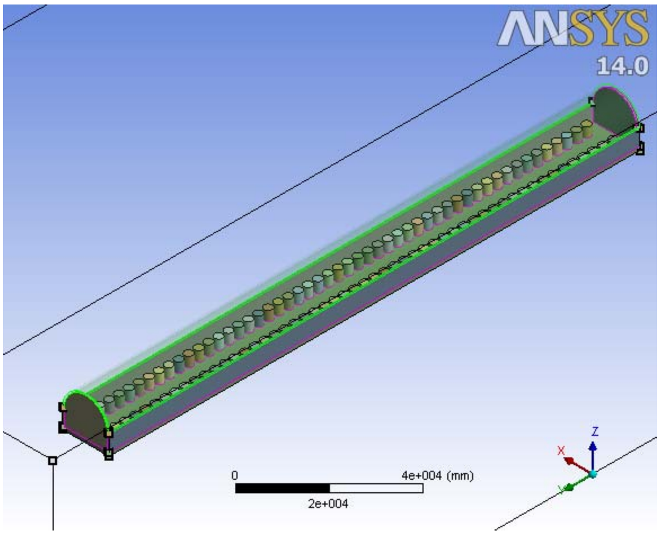

Fig. 2 Computational model - general view

The initial undisturbed rock temperature was set at an average of 45 °C. The investigated domain (Fig. 2) is limited by vertical planes passing through the center of the canister, half distance between the adjacent tunnels and half distance between the adjacent canisters. For the reasons of symmetry, the lateral Aires boundaries of the domain were considered insulated (zero heat flux) boundaries. This implies that the canister is in the center of the repository and surrounded by canisters of equal output. Thus, it accounts for the effect of all canisters contained with in the repository.

In fact, this assumption applies to a repository of infinite extent. Obviously, the canister in the center of the repository will have higher temperature than the canisters located close to the boundaries.

B. Input Parameters of Air

During the calculation of temperature changes in the air flows in the SNF storage facility the minimum entrance air flow temperature was assumed to be 1 °C and the maximum was 25 °C. The maximum average monthly temperature was specified as 17.4 °C and the average yearly temperature is 7.1 °C. . It was assumed that a straight corridor 80 meters in length is ventilated by an air flow with a volume of 5 $m^{-3}s^{-1}$. The total heat output of the stored waste was 11.65 kW divided equally among all casks.

The entrance air flows must be heated to the minimum temperature of 1 °C during the winter in order to avoid icing in the repository corridor.

C. Numerical Model

To determine the temperature fields in the area of a storage facility corridor, numerical simulations of the flow continuum were performed in the ANSYS/CFX programming environment. The calculation included modelling of the underground structure, the casks in the storage facility corridor and the air volume in the corridor.

The series of cans in a canister was modelled as a continuous cylinder with a uniform volumetric heat flux. The effective thermal conductivity for the overall waste was approximated by volumetric fraction weighting of the thermal conductivities of the constituents. In order to handle abrupt changes in thermal conductivity at the material interfaces without requiring an excessively fine grid, the harmonic averaging of the diffusion term in the heat transfer equation was implemented in the calculations.

The air volume was dealt with as a CFD problem with levels of freedom for flow velocity, pressure and temperature. The RNG k-ε model of turbulence in air flow was used. In the other parts of the model only temperature was calculated

V. Conclusion

The aim of this work was to assess the ventilation at a Central Interim Spent Fuel Storage Facility from the perspective of the provision of adequate and stable ventilation capacity for the removal of the heat produced by stored casks of spent nuclear fuel.

The calculation of temperature changes in the air flows was performed for the gradual filling of the CISFSF with casks expressed via their heat output in kW. This heat output generated a volumetric flow rate for the air flows of Q = min 5 m^3s^{-1} in the modelled storage corridor with a maximum outside air temperature of 15°C. When the outside air temperature is higher than 15 °C, Q progressively falls, and at a temperature of 25°C ventilation will only be intermittent, with the remaining heat in the casks accumulating in the rock.

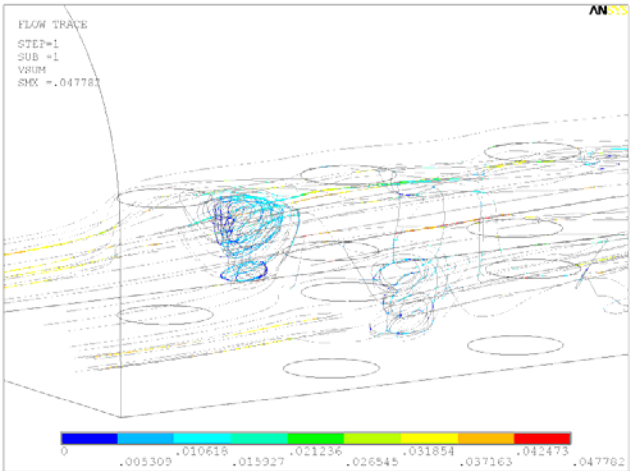

Fig. 3 Flow trace over casks

The calculated values of the natural depression will fully ensure the stability of the air flow network and the direction of air flow.

On the basis of the methods described in this article the aerodynamic resistances of the individual underground corridors that comprise the assessed CISFSF were calculated and a computational model of a corridor with appropriate input parameters was configured.

During the configuration of the parameters of the air flow network consideration was given to the changing aerodynamic resistances of the storage corridors in connection with the gradual depositing of casks within them.

Temperature changes in the air flows passing through the storage facilities were calculated with regard to the amount of casks stored in the individual storage corridors.

The issue of ventilation by natural means was evaluated, as was the necessity of installing ventilation equipment at the CISFSF for the resolution of potential accidents.

Acknowledgment

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