Field and numerical studies of water stratification in flooded shafts

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Abstract

Using the Computational Fluid Dynamics simulator routine CFX, a special version with technical program adaptations, and the compiled model input data (i.e. velocity, temperature and electric conductivity measurements), numerical models of flooded shafts have been established. The numerical model runs successfully show convection cells, which results in homogenous water characteristics (temperature, mineralization) in some shafts. The model calibration allowed an improved understanding of the flow processes in flooded shafts. In addition, model simulations suggest means by which it may be possible to isolate highly mineralized water within the lower shaft area.

1 Introduction

For a better understanding of problems associated with ascending mine waters a systematic study of site conditions, temperature and salinity profiles was conducted with the support of the North-Rhine Westfalian mine supervisory board. This study was conducted predominantly at former hard coal mine sites. The measurements confirm that columns of water in flooded shafts display stratification, with distinct boundaries between individual, homogeneous layers. Stratification was found both between water layers with very great differences in mineralization and temperature, as well as between layers with only very minimal differences. A comparison with previous measurements shows that layering persisted over a period of at least 9 years. The approach taken is to prove, by suitable numerical calculations, that stratification is stable over a very long period of time. A simulator routine was applied which allows the calculation of convection cells and layering during and/or after shaft flooding.

2 Field Studies

2.1 Temperature and salinity profile

By means of a probe continuous salinity (electric conductivity)- and temperature-logs were executed from a special vehicle at ground level.

The conductivity- and temperature-profile represented in Figure 1 is from the abandoned shaft Hermann 1 in the northern coal-mining district of the Ruhr. The shaft was already flooded in 1926. The carboniferous strata were reached at a depth of about 800 m below ground level. The 1st level (850 m-level) is situated at a depth of approximately 850 m.

The water table in the shaft is located at a depth of 315 m below ground level. From the water surface to approx. 850 m depth, i.e. over about 500 m, constant conditions have formed. This applies to both the conductivity (about 7000 µS/cm) and the temperature (about 29 °C). Below 850 m conductivity and temperature show a distinct, significant increase, up to approximately 148000 µS/cm and 41.4 °C respectively. Such strong thermal and chemical variations are limited to the boundary between the two water columns. This boundary layer itself has a thickness of only about 1.3 m (Fig. 1). Boundary layers are often related to “anomalies”, such as individual working levels, where a change of hydraulic conditions is possible.

The rock temperature and, in parallel to it normally, also the groundwater temperature increases with depth. The standard temperature increase amounts to approximately 3.7 °C per 100 m depth in the Ruhr area (after Leonhardt, 1983). This is indicated as the dashed line in Figure 1 (with an assumed groundwater temperature of 9 °C within the area of the neutral zone). In 2003, the temperature measured in the water column of the upper shaft increased from 28.7 °C to 29.3 °C over a total vertical distance of approximately 530 m. This translates into an increase of about 0.11 °C/100 m. The geothermal gradient is therefore largely eliminated within the homogeneous water layer.

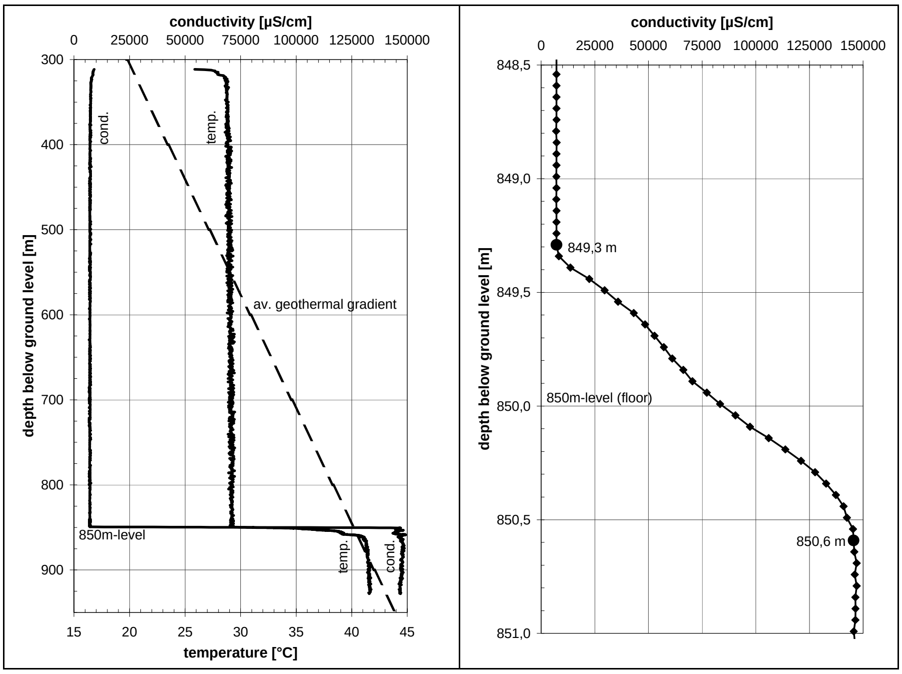


Fig. 1. Data profiles for layering in the abandoned flooded shaft Hermann 1 (left: overview, right: detail boundary layer)

A previous measurement from 1994 shows nearly the same situation, so the layering remained constant over a period of at least 9 years, and conceivably very much longer.

The homogeneity over the depth is explicable only by convective flow (thermal compensation flow), and the triggering force for this is the geothermal gradient.

The presumed flow pattern was the following (Czolbe et al. 1992): at the shaft-walls the water column is heated by the rock formation. This warmed up and somewhat lighter mine-water therefore moved upward along the shaft walls, cooled down, and in the area close to the surface of a water column sank downward again at the middle of the shaft. As soon as the water increases in temperature, and hence decreases in density, while sinking back into the shaft again, the convection cycle begins again. Different anomalies, primarily hydraulically effective levels in the shaft, can divide the liquid movement into several independent convective cells, which stabilize themselves as homogeneous areas.

2.2 Velocity measurements with an acoustic current meter

The supposed flow pattern described above had to be proved *in situ*. After the conductivity- and temperature-measurements three-dimensional current measurements were carried out in the water column of the shaft.

An acoustic probe was used for this purpose. An acoustic pulse travelling between a stationary source and receiver will arrive in a shorter time if there is a mean flow in the direction of propagation than if there is a mean flow in the opposite direction. This difference in travel time is proportional to the mean velocity averaged along the acoustic path. In the probe there are four acoustic paths, arranged in an array to provide a redundant, 3-component velocity measurement. Unlike in the salinity- and temperature-probe continuous depth profiles are not possible, but it was possible to hang the probe in the desired depth position, and record current flow-speeds and flow-directions over several minutes (up to a maximum of 1 hour), in 1-second pulses.

Because of the considerable depth of the water columns, measurements were taken only in the form of spot checks in the upper and lower water body, and the boundary layer. Areas directly above and below the boundary were measured in greater detail (Fig. 2).

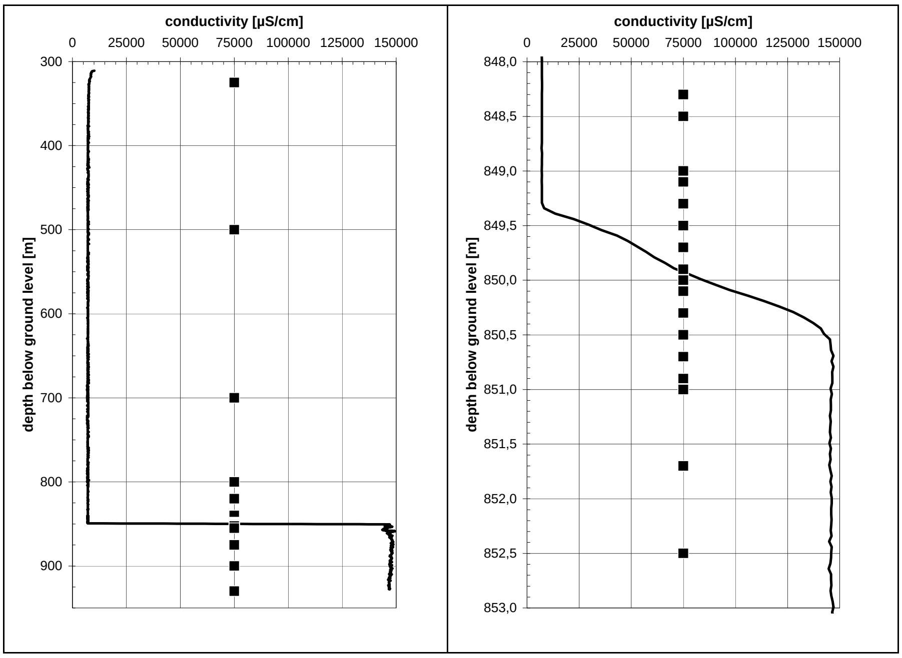


Fig. 2. Measuring points for 3D current measuring in the shaft Hermann 1 (left: overview, right: detail boundary layer)

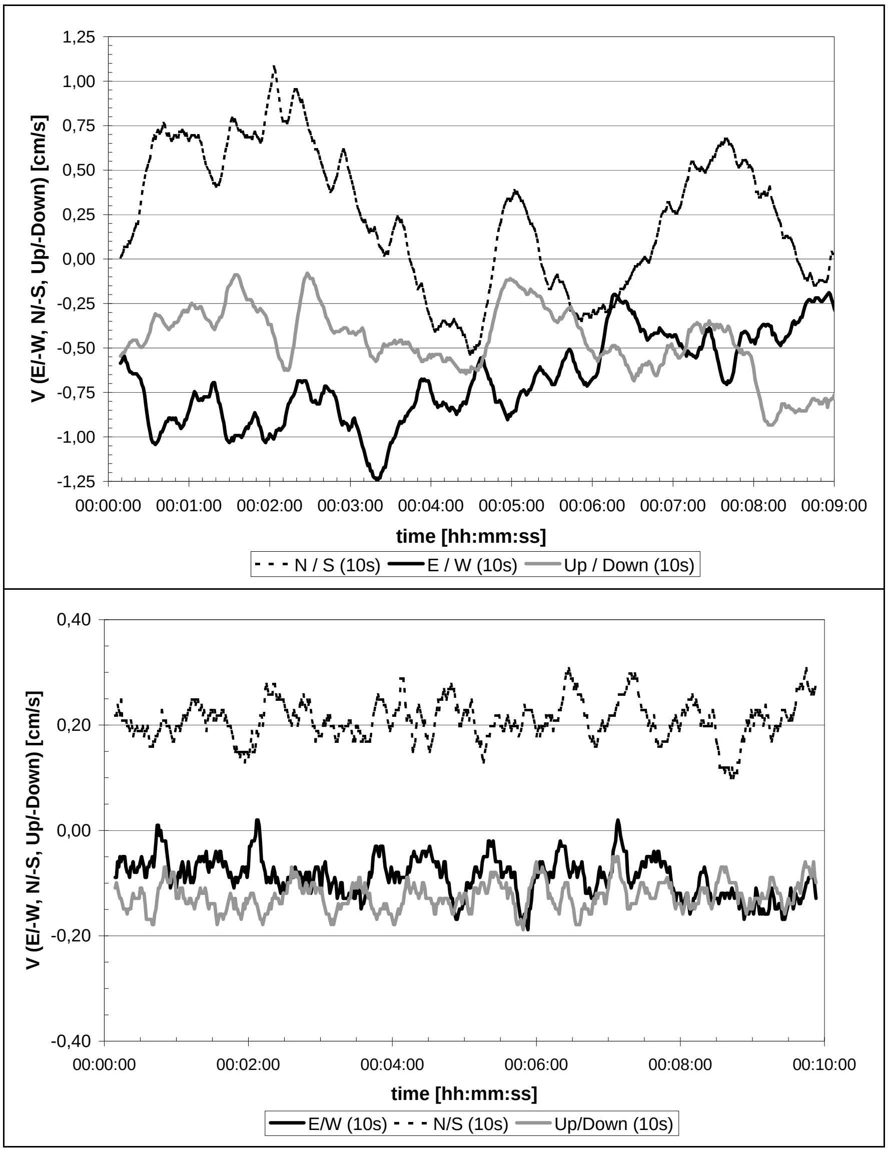


Fig. 3. Velocity measurements at depths of 500 m (above) and 849.9 m (below) below ground level in East-, North- and Upwards-Direction; negative values stand for the countermovement (West, South, Downwards). For a better overview instead of individual values per second the sliding averages over a period of 10 seconds are shown. The different scaling in the two illustrations is to be noted.

The interpretation of the measuring data at the different measuring points showed that at the respective measuring points a steady current is not present (neither in terms of speed or direction). In fact a more or less rhythmical increase and decrease of the current speeds, and a rhythmical change of current direction, dominates (Fig. 3). Generally all curves show a similar behaviour. In the area of the boundary layer the curves run nearly smoothly, i.e. a calm, even current with low velocities predominates (when comparing the two graphs in Figure 3 the different scaling should be noted).

In summary the following current events result: single, circular current bales undulate chaotically within the water body and thereby cause mixed, homogeneous conditions within a convection cell. Each convection cell appears to be a distinct unit, with individual current bales remaining within a cell, and current velocities at boundary layers being minimal. The average total are between 0.16 cm/s and 2.16 cm/s.

These data are used for calibration of the numerical models of the flooded shafts discussed below. Therefore the numerical models were modified until the model calculations fitted very well with the actual measurements obtained above i.e. temperature, salinity, flow-speed, flow-direction.

3 CFD-simulations

3.1 Description of the model

All calculations of water flow in the shaft were conducted with the commercial CFD-code CFX5.6. Additional library functions describing a buoyancy-model with specific functions for the fluid properties were implemented in order to describe the complex influence of temperature, pressure and salinity. These fluid properties can be expressed as functions for density, specific heat capacity, thermal conductivity and dynamic viscosity - each of them with dependencies of local salinity, temperature and/or pressure.

dynamic viscosity η:

$\eta = 1350 + 13x - 250y + 16y^2 + (180 + 0.62x^2)/y$

specific heat capacity Cp:

$Cp = 4.22 \cdot 10^{-12}s^2 - 5.30 \cdot 10^{-6}s + 4.19$

thermal conductivity κ:

$\kappa = 0.563 + 0.0019 \bullet (T - 274.650) - 0.0009x + 7.,0 \bullet 10^{-10} \bullet (p - 101325)$

density ρ:

$\rho = 1.005 + 0.0065x - 0.0030y - 0.00006xy$

where:

η = dynamic viscosity	in 10^{-6} Pa•s
Cp = specific heat capacity	in kJ/(kg•K)
κ = thermal conductivity	in W/(m•K)
ρ = density	in g/cm^3
s = salinity /salt concentration	in mg/l
T = temperature	in K
p = pressure	in Pa
$x = s/10000$	
$y = (T - 273.15)/10$	

Furthermore the simulation model considered the following effects:
- two- or three-dimensional steady or unsteady turbulent fluid flow
- mixing of water with locally different salinities
- heat transfer from the shaft masonry to the fluid
- heat conduction based on the geothermal gradient through all solids
- specific properties of different solid materials
- possible hydraulic influence of water inflow and outflow across levels

The principle of heat transfer mechanisms is shown in Figure 4.

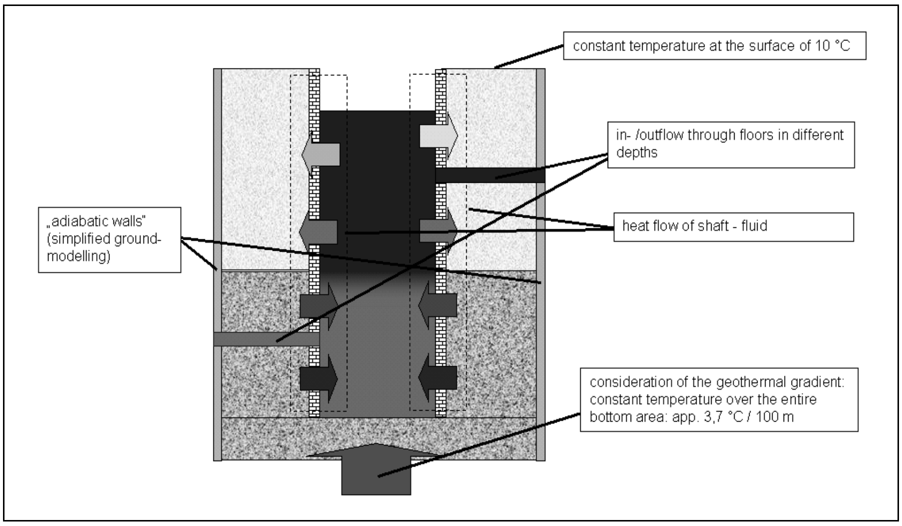


Fig. 4. Principle of modelled heat flow

3.2 Steady state tests

In order to demonstrate the general modelling capabilities, the CFX-code was validated against some experimental data relating natural convection problems. After implementation of a modified buoyancy model for mineralized water first calculations were done with a 450 m-shaft and some simplified 2D-models with steady state CFX-solver controls. The main goal was to investigate the possibility of using a calculation method with significantly reduced turn-around-time compared with unsteady calculations (because it turned out that the typical dimensions of a shaft requires large 3D-calculation-grids with a number of nodes greater than 500000). This would lead to large calculation times during an unsteady calculation if a simulated period of days, weeks, or up to several years is desired for a long-term prognosis.

Generally it turned out that convergence and balanced results are very difficult or even impossible to obtain during steady state calculations due to unsteady velocity fluctuations in the water column. It was therefore decided to choose the transient solver for subsequent calculations despite long turn-around times for each calculation. Some tests showed that the transient fluid flow and the fluid characteristics converge relatively quickly to steady state conditions.

3.3 Investigation of possible boundary conditions for simulation of real shafts

For the simulation of conditions in real shafts a definition of firm boundary conditions at the model borders is necessary in order to restrict model-technical expenditure. Particularly in the case of level connections at different depths in the shaft the determination of model boundary conditions represents an extraordinary problem, since no measurement data are available for these locations. The model calculations must cover a certain spectrum of plausible variations of the boundary conditions, which lead then in combination with the measuring data, to derive a conclusive overall view.

In the case of existing level connections it is necessary to define proper inflow and outflow boundary conditions in addition to the thermal boundary conditions described above. Several cases are conceivable, which were investigated with the help of a simplified 2D-model. Special emphasis was given to the behaviour of the initial sharp salinity jump midway down the shaft. The results presented are an extract of the whole investigation, containing only the calculations of some key variants.

All 2D-variants had some initial conditions which served as “start-up solutions” (Table 1). An overview of the principle of a 2D-model is shown in Figure 5.

Table 1. Initial conditions for 2D-variants

Initial conditions for all cases	
Homogenous temperature of water	10 °C
Geothermal gradient	0.037 °C/m at the shaft walls
Temperature at the top	10 °C
Temperature at the bottom	14.07 °C
Initial velocity	0 m/s
Salinity of low mineralized water	10000 mg/l NaCl
Salinity of high mineralized water	170000 mg/l NaCl

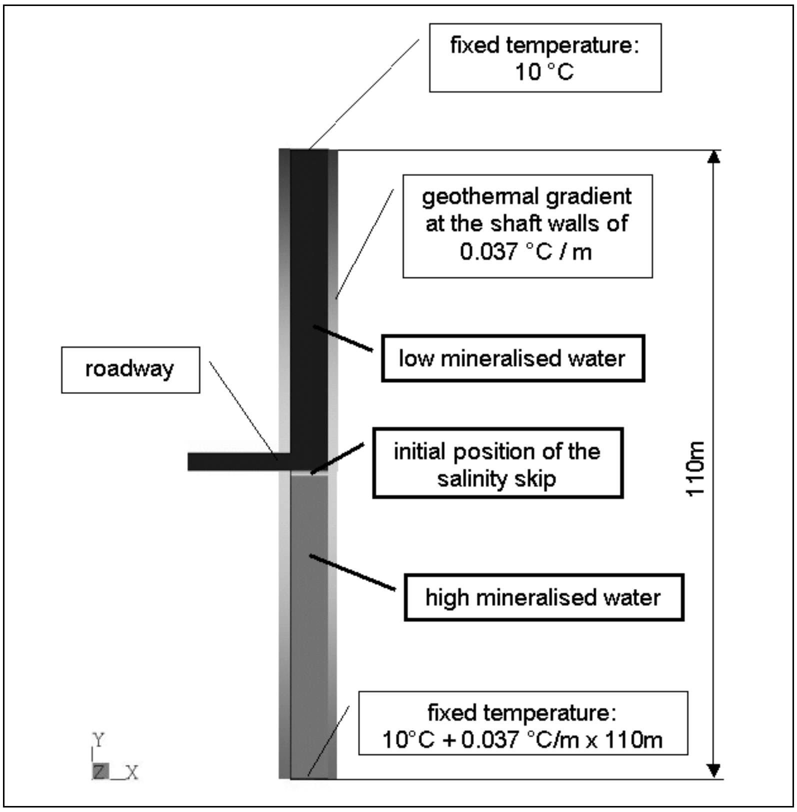


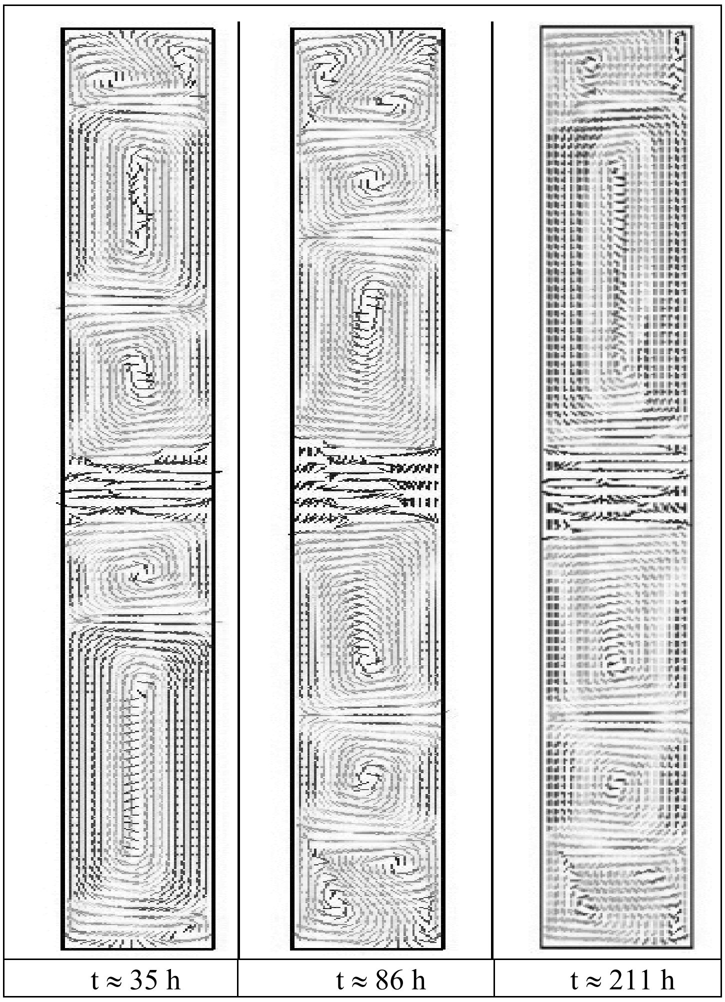
Fig. 5: Overview of the principle of the 2D-model, including one level connection

3.3.1 Variant without levels and additional inflow or outflow

This variant consisted of a 110 m-shaft without in– or outflow conditions. The sharp initial salinity jump was set at a depth of 55 m. The unsteady fluid flow was calculated for a period of more than 200 hours. The results of the unsteady simulations proved the slow convergence of fluid flow and fluid characteristics to a stable state. The calculated temperature line in the middle of the shaft shows a jump in the fluid-temperature from 11.4 °C to 12.7 °C in the vicinity of the salinity jump.

The velocity vectors at different times (Fig. 6) show the following effects:

1. Low velocity values in the vicinity of the salinity jump
2. Fluctuating velocity profile with the convection cells



t ≈ 35 h | t ≈ 86 h | t ≈ 211 h

Fig. 6. Velocity vectors at different times

With the help of additional simulation variants the influence of fixed boundary conditions, especially inflow and outflow of water across level connections, could be identified.

3.3.2 Variant with continuous filling with fresh water without other inflow

Fresh water filling from the top of the shaft (Fig. 7) should lead to a displacement of highly mineralized water (the lighter areas in the figures are more mineralized) without disturbance of the stable layering (Fig. 8).

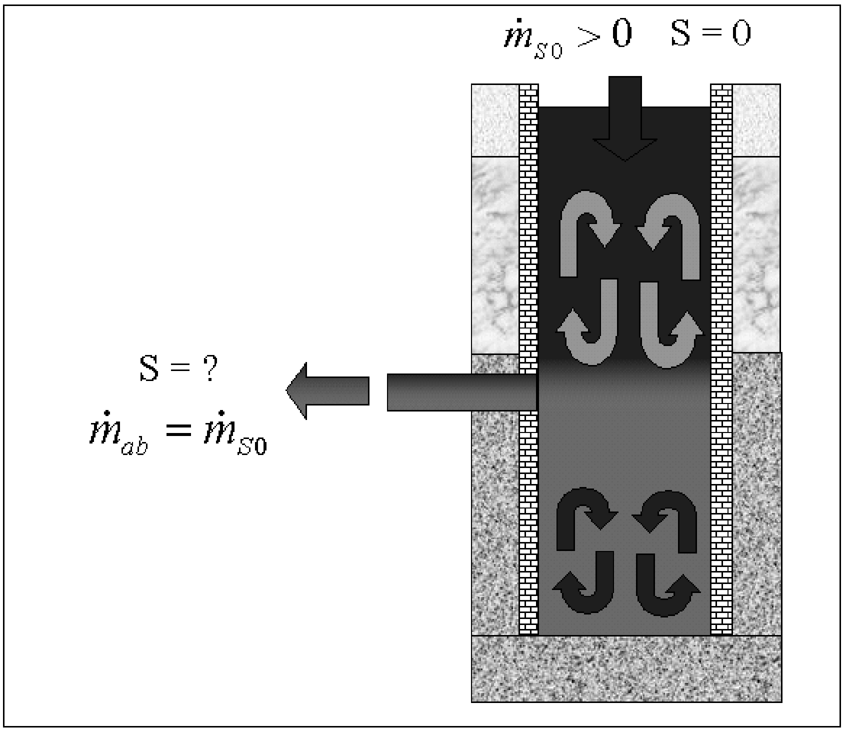


Fig. 7. Fill up with fresh water

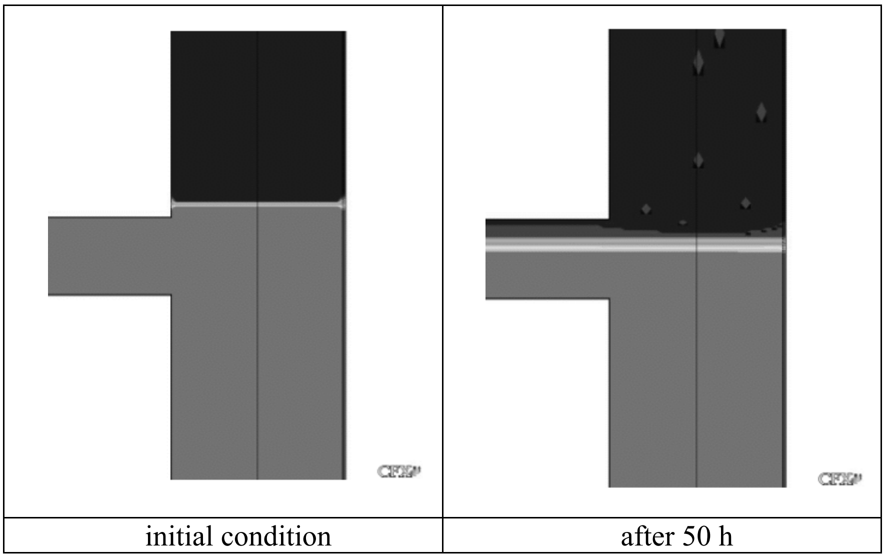

initial condition
after 50 h

Fig. 8. Mass fraction of high mineralized water

Other variants were calculated with or without inflow of fresh water and / or inflow of highly mineralized water from the bottom of the shaft (simulating a continuous supply of mineralized water from a deeper level). It was possible to model the main effects, which generally correspond with the measured data described above.

In summary the following phenomena were noted:

- Very slow mixing of low and high mineralized water cannot be excluded. The time it takes for highly mineralized water to penetrate into surface waters depends on the amount of differently mineralized water and on the concentrations within each layer.
- A continuous supply of fresh water to surface layers can permanently preclude highly mineralized water from upper layers of the shaft.
- The thickness and location of the salinity jump depend on the proportions and directions of the different water flows.
- It doesn't seem to be realistic that a forced convection effects the layering.

3.4 Simulation of shaft "Hermann 1"

The data collected, and described, above were used to define probable boundary conditions for the simulation of an existing shaft, "Hermann 1" (see Chap. 2). An unsteady calculation was derived for a simulated time interval of 3 hours. The model consisted of more than 1.15 Mio. nodes and was calculated on an 8-PC-cluster in parallel. The initial salinity jump was located at the 850 m-level at the beginning of the unsteady calculation.

3.4.1 Model-structure and boundary conditions

The structure of the model is shown schematically in Figure 9. The model is based on the actual situation in the Hermann 1 shaft. It should be noted that the roadways on the 850-m- and 950-m-level are combined with so-called by-passes. They play an important role for the mine water in the shaft. In Figure 10 the boundary conditions corresponding to the calibrated model are shown.

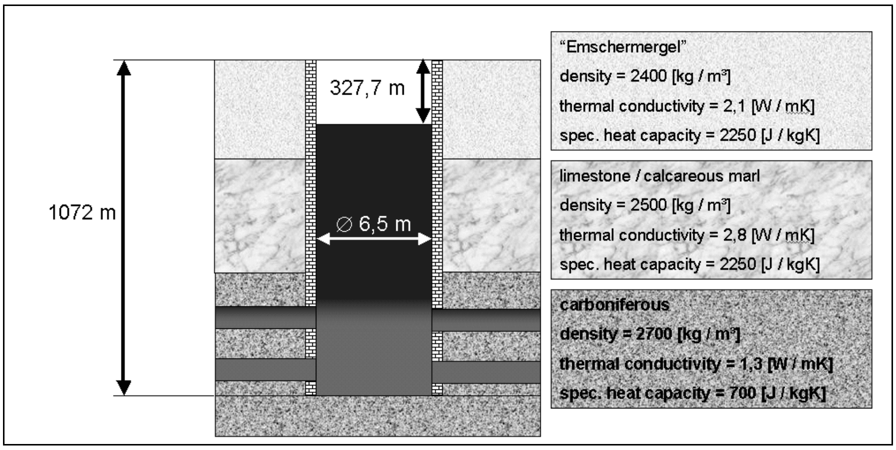


Fig. 9. Dimensions and material properties

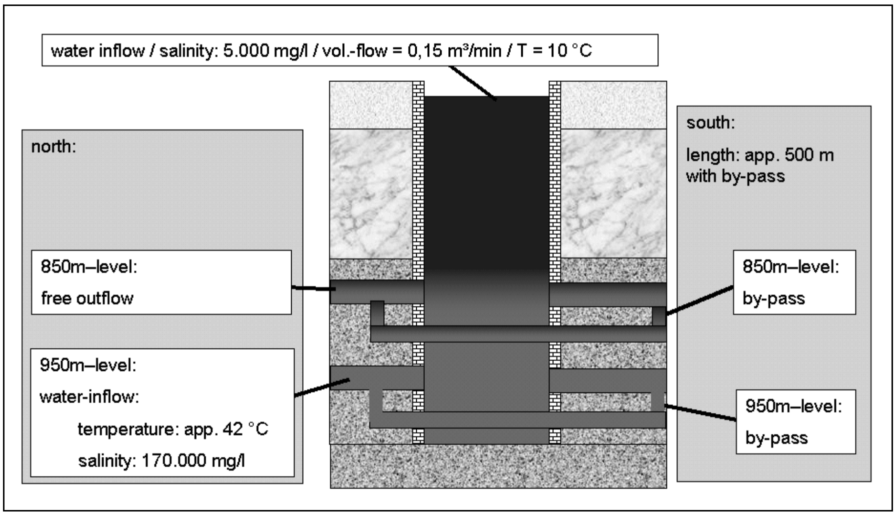


Fig. 10. Boundary conditions

3.4.2 Model calibration

After building up the numeric model for the Hermann 1 shaft it was necessary to calibrate the model, that means to modify the model. The most sensitive model data are the boundary conditions, especially the flow rates at the 850-m-level and at the 950-m-level. These are the only two levels present in the mine. It was initially felt that flow-rates along these levels were low or non-existent. However, the simulations showed that there must be an inflow of fresh water from the top of the shaft. This water leaves the shaft at the 850-m-level together with a certain volume of highly mineralized water from the 950-m-level. Only by using this configuration of boundary conditions could the model recalculate the measured data.

A review of old reports and data for the mine confirmed that this configuration of boundary-conditions was plausible, and coincided well with the observation of water running downwards from the head of the shaft. The model precisely calculated the temperature- and salinity-jumps at the 850-m-level (Fig. 11, 12).

The results show a temperature- and salinity-jump at the height of the 850 m-level in the Hermann 1 shaft and furthermore low velocities (Fig. 13) corresponding to the position of the salinity jump. The initial sharp salinity jump expands within a time period of approximately 20 minutes. The next time steps, up to 3 hours, show constant salinity and temperature distribution, suggesting steady state conditions.

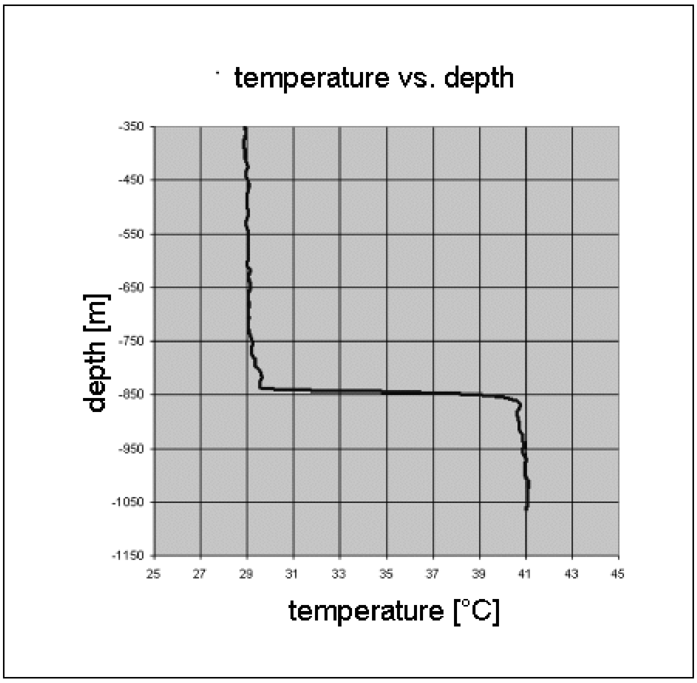
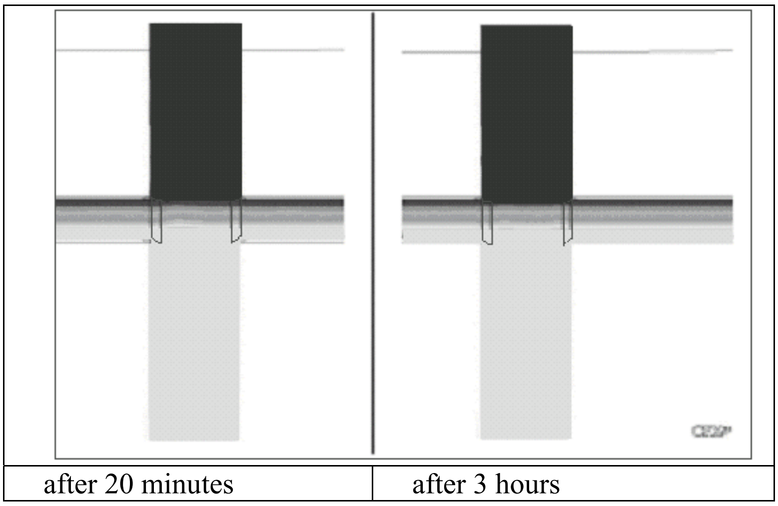


Fig. 11. Temperature in the middle of the shaft – after 3 hours, calibrated model



after 20 minutes | after 3 hours

Fig. 12. Mineralization of the mine water at the 850 m-level at different times, calibrated model (the lighter areas are more mineralized)

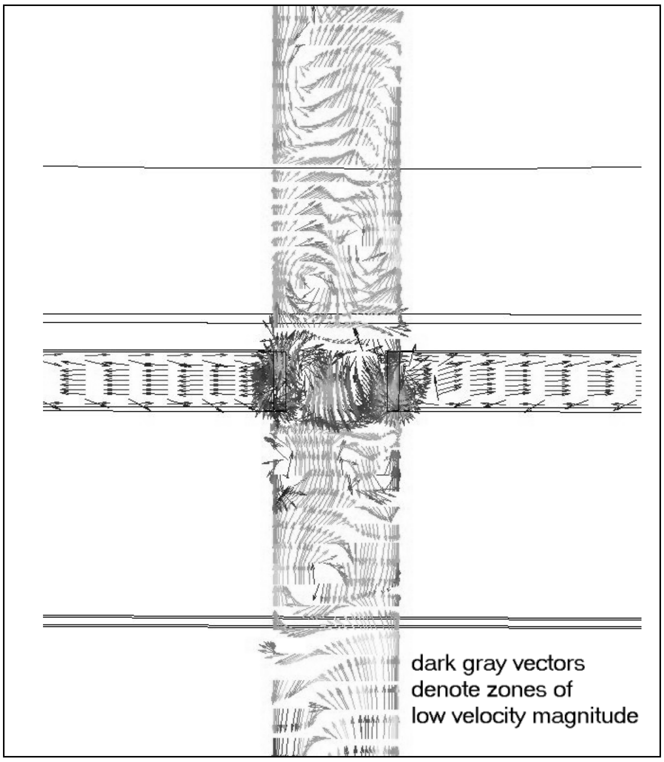


Fig. 13. Velocity vectors at the 850 m-level – after 3 hours, calibrated model

The Herman 1 shaft appears to be a typical example of stratification of the form of fresh water overlying saline water. It is thought that this situation will persist as long as there is an inflow of fresh water.

The key to understanding the flow system in the flooded Herman 1 shaft, and for calibrating the model, was regarding the influence of the water flow in the roadways of the whole mine and the contact to the surrounding rock.

4 Conclusions

Layering in water filled shafts is fairly easily characterised by electric conductivity and temperature profiles. What appear to be large steady state flow cells are in fact made up of numerous small chaotic flow “bales”. This was demonstrated using a probe selected to measure the flow velocities in three spatial directions. Specific software, applied in computational fluid dynamics, is adequate to model this type of flow behaviour. Steady state simulations are difficult to handle due to numerical stability problems but transient simulations result in excellent agreement with field measurements. We were able to simulate the actual flow conditions within the Hermann 1 shaft and, therefore, we are confident that the software provides us with a reliable opportunity to predict layering effects in the long-term. In the case of the Hermann 1 shaft ought that the layering will persist since the continuous recharge of “fresh” water is sufficient to stabilize the warmer highly mineralized mine water at a distinct level. Other model runs have also demonstrated that continuity of fresh water recharge is of decisive in retaining a stable layering effect. Thus, the layering effect can be enhanced by natural and artificial fresh water recharge.

The model will provide a good planning tool to determine adequate quantities and the geometries of flow patterns. It is our conclusion that even for abandonment of large coalfields careful planning may result in maintenance of beneficial stratification i.e. highly mineralized water kept at depth.

References

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