COMPARISON OF MINE VENTILATION SOFTWARE TOOLS FOR UNDERGROUND COAL MINES IN HARSH CONDITIONS

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ABSTRACT

Specific conditions of underground coal mines at great depth, such as high temperatures, high rates of methane inflow and natural ventilation pressure provide considerable challenges for the reliable design of appropriate mine ventilation systems. For decades coal mining in Germany has coped with these extreme circumstances. Based on these experiences appropriate software tools for simulating mine ventilation networks have been developed and continuously enhanced. This paper examines differences in the simulation results and underlying calculation methods of two software solutions. The analysis is based on the comparison of FlowNet™ and VentSim Design™ (Version 5.1) regarding the accurate prediction of fluid mechanical quantities and their validation with real measurements. A special focus lies on exceptional ventilation scenarios typical for deep coal mines, like gas inflows, fire events and buoyancy effects. The purpose of the comparison is the future utilization of the experiences gained during mining at up to 1,500 m depth for state of the art ventilation design.

KEYWORDS

FlowNet™, VentSim Design™, Ventilation simulation, Computerized model analysis, Computer ventilation software, Mine ventilation systems

INTRODUCTION

Ventilation is an essential component of mine operations - as providing fresh air to workplaces, diluting and removing explosive, toxic or asphyxiating pollutants and assuring sufficient climate conditions. On the other hand, the costs of ventilation contribute to a large extend to the overall operating costs of a mine, as the share in the energy consumption of a mine may be in the range of 25-50 % (Belle, 2008). Accordingly, proper design of ventilation systems has been a task since early times. Consequently software for modelling of ventilation networks has been developed in order to improve efficiency and accuracy of calculations (Maleki, 2018).

Compressible flow has not been considered by initial ventilation modelling software tools. In Germany, the consideration of changes in airflow density - depending on pressure and temperature - in the algorithms of ventilation simulation software has been started in 1974 by Duepre & Hofbauer. This development had been continued by the Pruefstelle fuer Grubenbewetterung (Test Centre for Mine Ventilation) and resulted in the release of a computer ventilation software named “Wetter”. The mine inspectorate of the German state of North Rhine-Westphalia, which supervises the major coal mining district in Germany, declared ventilation simulation based on compressible flow being “state of the art” in 1985 (Pollak, 1985). This approval made allowance for assessing the consequences of underground fires and downtimes of main fans based on advanced software solutions.

The early consideration of compressible flow has been demanded by the enormous depth of German hard coal mines. This in turn resulted in high differences in temperature due to auto compression and heat absorption from rock strata (McPherson, 2012). The average depth reached 900 m in 1985 and a maximum depth of 1,500 m has been exceeded at Ibbenbueren Mine a few years later. Known as the deepest coal mine worldwide for a long time, operations at the largest German coal fields, the Ruhr and Saar Basins, reached the same depth during the following decades. An additional requirement resulted from the expansion and merger of mine complexes, each operating multiple longwall faces and multiple main fan stations. The initial ventilation software "Wetter" has been integrated in the mine planning software package used by the largest mine operator RAG. The ventilation simulation modules have been improved and are known as GRUBE-W (Reimers, Lorbach, Shumacher & Huenefeld, 1998), later GTP-W (Langefeld, Guder, Rainartz & Huenefeld, 2001) and today FlowNet™ (Kuepper, T. & Huenefeld, R., 2008). FlowNet^{TM} uses AutoCAD^{TM} as a powerful tool for network construction and generation of structured and clearly laid out maps. However, compressible flow has been incorporated in other ventilation software products later on, namely VUMA^{TM} by Bluhm Burton Engineering and VentSim^{TM} by Chasm Consulting (today Howden) (Danko et al., 2017). This development reflects the increasing demand of accurate ventilation modelling over the last decades.

OBJECTIVE

FlowNet^{TM} and its predecessors have been used by the Pruefstelle fuer Grubenbewetterung (today part of DMT). With the original focus on serving the German hard coal industry, the assessment of the stability of ventilation networks has been a major topic of DMT. Due to the risks in coal mining, especially the risks of explosions and spontaneous combustion, the reliability of ventilation systems is essential and requires most accurate planning. "Wetter" (today FlowNet™) has been accepted by the mine inspectorate and the industry as matching these requirements since its introduction. With the decline of underground coal mining in Europe, DMT has diverted its business activities during the recent decades and today provides engineering services to international clients. While FlowNet^{TM} has been a ventilation simulation software being basically established in Germany, VentSim^{TM} and VUMA^{TM} became the most used comparable products on an international scale. Accordingly, DMT uses VentSim^{TM} as an additional tool in order to fulfil the demand of individual clients. The selection of a suitable software for a project depends on factors like interfaces for utilizing input and output data, requirements of documenting the results and the acceptance of the respective software tool by local stakeholders.

The end of underground coal mining in Germany in 2018 gave reason to reassess the performance of FlowNet^{TM} and to check possibilities of utilizing the experience gained in Germany during decades in conjunction with internationally established modelling software. Buoyancy effects are crucial especially where low air flow quantities occur. In the history of German coal mining, there have been several examples of natural ventilation being a main driving force for ventilation. Thus, effects as e.g. seasonal changes of air quantities, reversion of air flow within individual mine workings, or buoyancy being higher than fan pressure, have been observed. Generally, the importance of natural ventilation may increase wherever pressure drops and air quantities are reduced, for example in the course of mine closures or in case of ventilation on demand (VOD) applications.

The prediction of such occurrences require accurate preparation and processing of input data in addition to a suitable numerical algorithm used in the respective software. The quality of input data and input options are crucial influential factors for a reliable simulation (Maleki, 2018). In order to investigate differences in simulation results and underlying calculation methods of two software solutions, a rather simple system consisting of two 1,000 m deep shafts and about 1,000 m of lateral roadways has been selected. The specific situation at the selected mine results in natural ventilation providing over 90 % of total ventilation pressure. The purpose of the comparison is the future utilization of the experiences gained during mining at up to 1,500 m depth for state of the art ventilation design.

METHODOLOGY

The emphasis in this research work lies on the comparison of a ventilation simulation and the analysis of the results. The simulation was conducted with the ventilation software tools FlowNet^{TM} and VentSim Design^{TM} (Version 5.1). Both tools are designed to investigate fluid mechanical phenomena with the emphasis on a mining environment. Beside the simulation of ventilation flows, tools for fire events and distribution of contaminants like methane or carbon dioxide are provided as well (VenSim™ User Guide Version 5.0 & Pollack, 1985). Due to the extensive physical description of flow properties, FlowNet^{TM} additionally provides the possibility to simulate various flow networks outside the mining environment and e.g. has been used for the design of venting large-scale sewer systems. After completion of the simulation process, both programs provide detailed data like the quantity of airflow, temperature and frictional pressure drop for further analysis. In a first step, a suitable case study was selected and AutoCAD^{TM} was used to design a three-dimensional geometric model of the coal mine. The number of airway branches was reduced in order to keep the considered ventilation model as simple as possible. This approach makes the editing and analyzing process much easier and helps to keep the focus on crucial aspects of the simulation and data evaluation. In order to obtain reliable results, the input data as airway attributes, resistances, temperatures and fan characteristics are of vital importance. The designed computer model has to reflect reality with regard to geometry, defined boundaries and initial settings in an appropriate manner (Eckart, 2018). Therefore, before starting with the simulation, appropriate attributes were allocated to nodes and airways and suitable initial settings were defined. Finally, the simulation results obtained from both programs were compared and analyzed in detail.

CASE STUDY

The coal mine selected for this case study is located at Germany's largest coal basin. During its active period, the mine was one of the largest in the world. A total of 240 million tons of coal have been produced during 130 years before the mine ceased operation in 1986. Due to multi-seam mining, the entire production was from a relatively small license of approximately 13.2 km^2. The downcast shaft (No. XII Shaft) depicted in Figure 1 was sunk between 1928 and 1932 and reached a depth of roughly 1,000 m later on. One characteristic of the mine is an underground connection to a neighbor mine at a depth of 1,000 m and a total length of more than 3,000 m. During its final production period, the mine has been operated as a complex of several formerly independent mines. The coal extracted from that linked mines has been conveyed to the No. XII Shaft and moved upwards by skips.

After coal production ceased, the drainage of mine water had to be continued in order to prevent flooding of surrounding active mines. For this purpose, the original mine workings have been reduced to a minimum. This includes two shafts, the connection between the shafts with the main pump room and part of the aforementioned connection to the neighbor mine. Latter is served by auxiliary ventilation in order to maintain access to a bulkhead. Abandoned workings have been closed by explosion proved sealings. Mine water is collected from these sealed areas and piped to the main pump room. A total volume flow of about 15 m^3/min is pumped to the surface through pipes in the second shaft, known as No. II Shaft. A major fraction of the water is drained from the connection to the neighbor mine. The water is transported to the pump room through a 600 m long pipeline. Due to a water temperature of more than 40 °C, considerable additional heat is provided to the airflow within this section.

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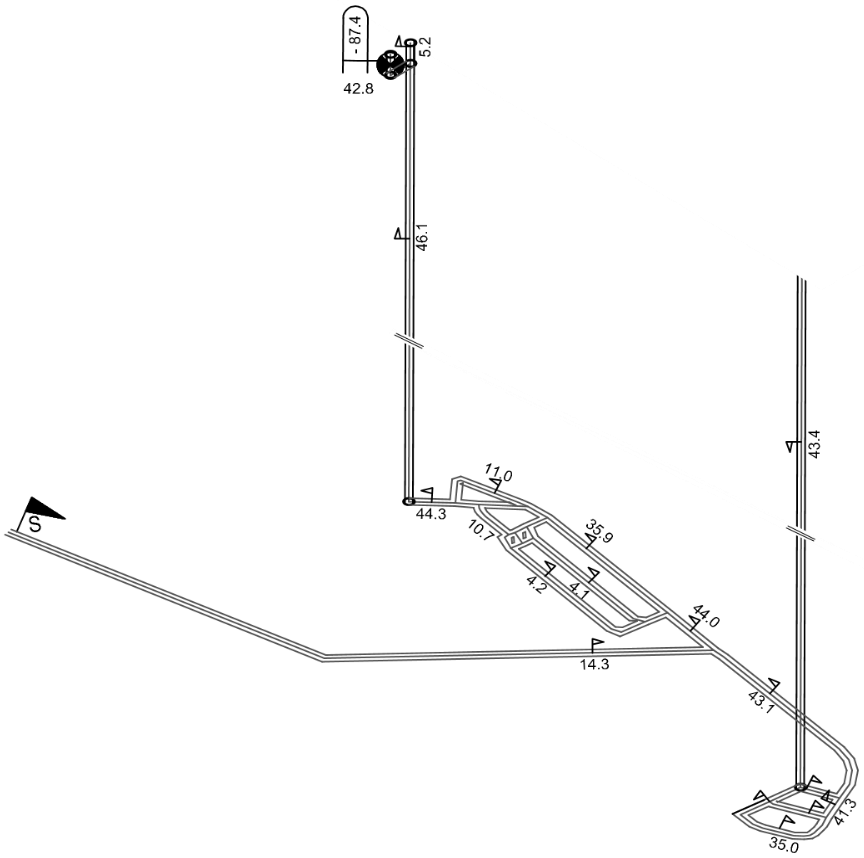

Figure 1. Mine ventilation plan of the case study including No. II and No. XII (front) shafts, including airflow distribution (m^3/s) created in FlowNet^{TM}.

The main characteristic of the ventilation circuit of this mine is the fact that natural ventilation is the main driving force. Generally, exhaust ventilation has been applied at all German coal mines and maintaining stable ventilation has been a prime target. However, the air quantity at the water drainage stations at older mine sites has been reduced to a minimum in order to keep operational costs on reasonable levels. In case of the selected mine, natural ventilation is higher than the fan pressure due to high differences in temperature and the considerable depth of 1,000 m. This is acceptable, as the actual operation is limited to water drainage and gas emissions are close to zero due to intense gas extraction from the surrounding abandoned mine workings.

MODELLING AND DESIGN

A ventilation network model was set up in each program (FlowNet^{TM} and VentSim^{TM}), implementing actual on-site measurement data from the selected mine. Both models were constructed based on centerlines from CAD file imports. As VentSim^{TM} does not allow for curved segments, the model comprises considerable more nodes. Therefore, after simplifying the model by a reasonable reduction of nodes, the lengths of some airways had to be readjusted - according to the real measurements - using the length input option in the edit box. The airways in the mine workings have arch shaped profiles. This is considered in the ventilation model by using an appropriate shape factor. Standard resistance values, based on the standard reference density of 1.292 kg/m³ being common in German coal mining, were available from pressure surveys for each airway. In order to cope with airways consisting of several segments in the VentSim^{TM} model, linear resistances have been applied. The main input data are summarized in Table 1. For simplicity reasons only information for airways in the main path of airflow are displayed.

Table 1. Basic parameters of airways

Airway Name	Node Entry	Node Exit	Length (m)	Area (m^2)	Standard Resistance (Ns^2/m^8)
ZV010	1	2	999.70	18.0	0.07700
1	2	3	27.37	25.0	0.00050
ZV001	3	4	109.74	18.1	0.01020
ZV002	4	5	25.00	12.7	0.02130
ZV003	5	6	200.14	13.2	0.02140
4	6	7	10.00	12.9	0.00004
ZV004	7	8	56.52	12.5	0.05330
5	8	9	142.41	13.0	0.02960
6	9	10	18.97	13.0	0.00310
7	10	11	34.83	18.0	0.00520
ZV008	11	12	17.81	16.5	0.02900
8	12	13	12,38	22.0	0.00040
ZV020	13	22	977,60	18.0	0.07500
21	22	24	20,00	3.0	0.05440
22	24	25	20,00	3,0	0,00000

When comparing two simulation programs with different interfaces and algorithms, a major challenge is to produce two sets of equivalent input data. Input temperatures for FlowNet^{TM} are expected to come from real measurements. Between the points of measurements, a linear temperature profile is applied. Whereas, in VentSim^{TM} heat simulation is a substantial part of the network calculation. Temperatures can be adjusted manually to match actual measured data within a certain range. Nevertheless, the program cannot cope with great deviations of these adjusted temperatures from those determined through the base settings (e.g. geothermal gradient, conductivity, age or wetness of rock). In this specific case study, a major source of heat is the mine water inflow from abandoned neighbor mines. VentSim^{TM} requires a detailed modelling of this heat transfer. These heat sources, unlike technical sources, have no defined amount of fixed energy transfer being expressible in kilowatt. Like any heat transfer (e.g. from rock strata), the heat exchange from hot water pipes, depends on the temperature difference and might vary with changing environmental conditions. For these reasons, heat transfer from dewatering pipes has not been modeled as a linear source of heat, but through virtual equivalent rock surface temperatures. By modifying the airway ages of segments close to the bulkheads, exposed surface temperatures where raised, without changing the virgin rock temperature. As the ventilation system of this specific mine is very sensible to temperature changes, investigating the input parameters for the heat simulation to exactly match the actual data is difficult at reasonable efforts. Therefore, in a pragmatic approach, the actual temperature data was matched as close as possible with an accuracy of ±1 °C, while keeping the number of airways with manually altered rock properties to a minimum. This new temperature distribution was then used in the input file for the FlowNet^{TM} model in order to realign the two models. The temperature distribution received from the heat simulation in VentSim™ is depicted in Figure 2.

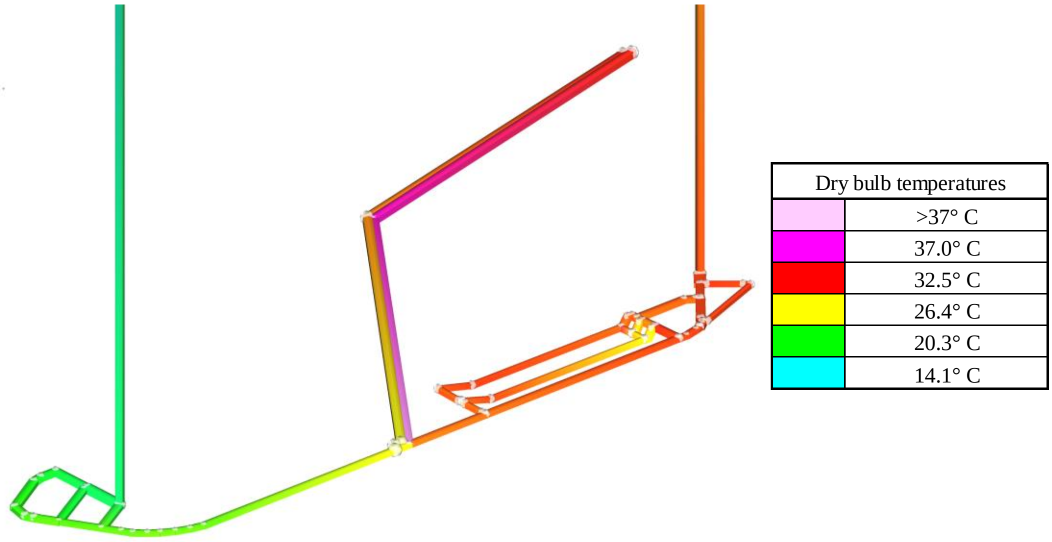

Figure 2. VentSim™ temperature distribution through heat simulation.

Fan curves have been constructed in both programs from seven fan duty points. An axillary fan was implemented by means of a fixed volume flow. The duct of the auxiliary ventilation was modeled as a parallel airway. Other relevant simulation settings and environmental conditions are shown in Table 2. FlowNet^{TM} does not consider changes in moisture content and uses a constant specific heat capacity for mine air throughout the network. In the model, the specific heat capacity for dry air was utilized. Moisture content cannot be omitted in VentSim^{TM} as it is an essential parameter for heat simulation, while its influence on the actual airflow calculation is rather low. Information on moisture content enters VentSim^{TM} through wet bulb temperatures.

Table 2. Relevant settings of the models

FlowNet^{TM}		VentSim^{TM}	
Accuracy	±0,01 Pa	Accuracy	High
Specific heat capacity	1004 J/kg/K	Wet bulb temperature	1 °C
Specific gas constant	287.1 J/kg/K	Geothermal gradient	3.5 °C/100m
		Rock wetness fraction	0.15
Both programs			
Barometric pressure	101.325 kPa		
Dry bulb temperature	8 °C		
Reference surface elevation	49.6 m		
Airway shape	Arched		

RESULTS

The outcomes from both programs are in a similar range, as depicted in Figure 3. The distribution of the barometric pressures - shown on the left - in the mine diverge by maximum 12.8 Pa between the models. In general, the barometric pressure in the Ventsim™ model is higher throughout the network. Even though the moisture content of air changes in VentSim™, the mass flow rate does not. Both programs utilize a constant mass flow throughout the network. In the VentSim™ simulation the mass flow rate is 56.8 kg/s and in FlowNet™ 57.5 kg/s.

Figure 3 on the right provides some additional information on relative static and total pressure taken from the VentSim™ model. The rates only diverge in the area of the main fan, where velocity increases significantly due to the smaller diameter. As can be derived from the diagram, the main fan has no substantial role in the ventilation system. It only diverges the airflow around the shaft house.

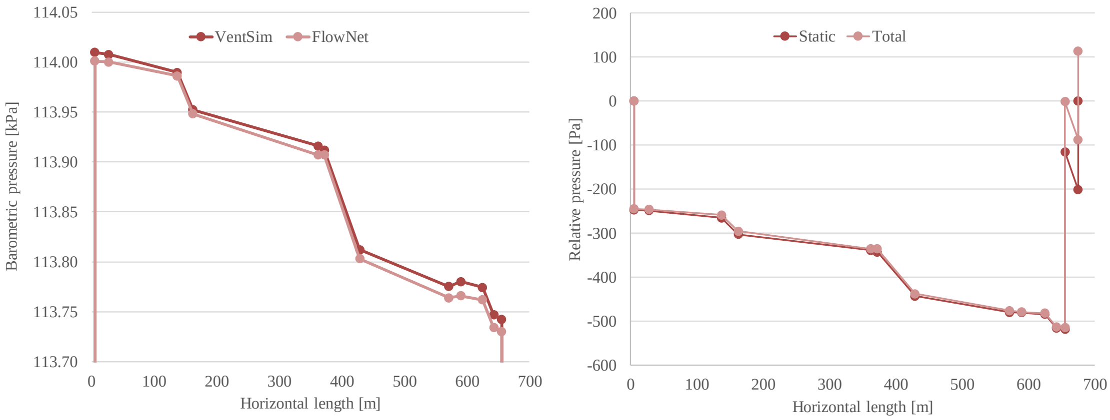

Figure 3. Resulting pressure distribution along the main path of airflow. Left: Comparison of barometric pressure in VentSim™ and FlowNet™. Right: Static and total pressure of VentSim™ simulation.

As a result, it can be stated that both programs deliver reliable and comparable output, even though their input differs slightly. Both programs seem to follow equally successful approaches for considering compressible airflows and natural ventilation pressure. As there is no great difference in the results, it seems reasonable for example to disregard the effect of moisture on the density of airflow.

Apart from the simulation results, also the handling of the programs is of interest. In VentSim™ parameters like specific temperatures, constant moisture content, cross sections or total airway resistances (without adding wall friction) are calculated internally, without an option to directly define these data. In FlowNet™ input parameters can be defined directly, while on the other hand it provides less checking for consistence and plausibility of input data.

Due to the afore mentioned inability to process fixed temperatures in combination with the steady state nature of the simulation, in VentSim™ it takes some effort to calculate short term fluctuations in outside temperature (where temperatures in the main parts of the mine workings remain unchanged). The effect on underground temperatures can be seen in the new annual thermodynamic flywheel feature, whereas the link to airflow changes is not available yet.

Results from a second simulation run exemplify the difference in the two approaches. Outside surface temperature was set to 25 °C in both models, while keeping all other settings unchanged. In the FlowNet™ model air flow drastically decreased by 68% (when compared to the base case of 57.5 kg/s at 8 °C) resulting in a mass flow of only 18.28 kg/s. In contrast, the decrease in the VentSim™ model was merely 32% with a mass flow of 38.6 kg/s. It is important to note that due to the change in outside temperature in fact two very different situations have been modeled. VentSim™ with the underlying steady state temperature simulation considers a long period of warm temperatures (“all year summer”) where the mine has had enough time to heat up. In FlowNet™ temperatures in the mine did not change, so the corresponding scenario would be a sudden rise in outside surface temperature after a long period of cold weather (“one summer day”).

CONCLUSIONS

The ventilation simulation software FlowNet^{TM} and VentSim^{TM} have been compared with special consideration of aspects being relevant in modelling deep mine ventilation networks, namely compressible flow and natural ventilation. While FlowNet^{TM} is most common used in Germany, VentSim^{TM} is one of the worldwide most popular mining ventilation modelling products. Due to the high depth of German coal mines, compressible flow has been considered in early stages of software development with its roots in 1974. For this research paper a former coal mine still being used for water drainage has been selected as case study. The reason for the selection was a significant impact of natural ventilation on the ventilation circuit and the main fan's duty point.

Although simulation results received from both simulation programs are comparable, there are considerable differences. FlowNet^{TM} has been developed based on mine planning software packages used by the main German coal miner RAG. This includes interfaces to other software tools being used in German hard coal mining. Furthermore, AutoCAD is utilized for network construction and output of ventilation maps. As a full scale drawing program, it is a multifunctional and powerful tool. Compared to VentSim^{TM}, complex structures with curves and polygon shaped mine workings can easily be constructed and parametrized as single airway in FlowNet™. Finally, advantages and disadvantages of both software's construction tools depend on the available input data like coordinates, analog or digital mine maps or 3D mine models as well as on the shape and layout of mine workings.

Output from FlowNet^{TM} are tables with selectable parameters which can be used for further processing or documentation, but also maps, created by AutoCAD. Due to the history of the software they are in line with further standard mine maps visualizing e.g. locations of ventilation and gas monitoring devices, ventilation control devices, sealings of abandoned workings and other objects being relevant to mine ventilation. Visualization is usually three-dimensional and contains selectable information as flow direction, air quantities, concentration of contaminants, pressure losses, relative pressures, locations of fans, regulators and air doors, etc. The compilation of clear and structured printable maps is a strength of FlowNet^{TM}. There are several examples where printed maps are essential and even mandatory for approval processes and documentation requirements. Furthermore FlowNet™ provides the opportunity to rely on a huge symbol library. Again, the work flow has to be considered which may include exchange of a network model within a company, to clients or contractors. The strength of models created in VentSim^{TM} is the widespread availability of the software allowing adaption and further development of the model by others.

While lots of relevant features like distribution of contaminants and simulation of underground fires are available in both software packages, FlowNet^{TM} does not contain heat simulation. The German hard coal industry used a separate software for heat modelling which has not been connected to FlowNet^{TM}. In practice, it is required to include heat data from calculations or measurements in the input data files. However, any assumed or measured temperature data can be allocated to both, the entry and exit node of airways without any automatic control or correction by the software. Although demanding good knowledge and careful work by the operator, it offers a high degree of freedom. This is usually advantageous if temperatures are established without knowing the exact sources of heat or in cases where complex mine layouts have to be simplified. It is sufficient to focus on relevant changes in temperature.

As a conclusion, FlowNet^{TM} and VentSim^{TM} both appear to be reliable simulators allowing the design and analysis of complex mine ventilation networks. The preference of the user definitely is determined by the available input data, interfaces for data exchange and finally the preferred or required form of output and documentation. At DMT, ventilation engineers continue to use the different simulation softwares depending on the project requirements.

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