COMPUTER PROGRAM FOR PLANNING OF MINE-VENTILATION SYSTEMS

by
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ABSTRACT

Today the application of computer programs for planning of mine-ventilation and for safety-analysis of ventilation systems is widespread practice in German mining.

The computer program for network calculation, developed at the "Mine Ventilation Testing Centre of the Westfalische Berggewerkschaftskasse" allows the distribution of airflow and pressure in mines to be calculated. In a physically well founded manner it takes into account the natural ventilation as well as changes of volume-flow in the mine, which both are dependent on pressure and temperature. Compared to an incompressible treatment of the mine air these circumstances are of increasing importance with the increase of depth, air temperatures and fan-pressures. This especially holds for the calculation of airflows during failures of fans or for assessing the influence of open mine-fires on ventilation.

The application of the program is very easy and its structure is made to fit the requirements of practice. For instance it takes into account the fan characteristics of all fans. For each planning calculated airflows in all mine workings are compared to those of an eligible basic calculation or to measured airflows. In addition for the simulation of mine fires any variation of temperature in selected galleries may be specified.

Finally with an additional program there is the possibility to plot the ventilation network. In this plot the main results of the calculation are recorded automatically.

Because of its comprehensive physical description of gas-flow the program meanwhile is also used successfully for planning of compressed air networks. The calculation of methane-drainage systems should be possible too.

The program has already been used for an Australian project, a commissioned study on the ventilation of the German Creek Central Colliery.

INTRODUCTION

In German coal mining, computer programs are in use since long time for calculation of air flow and pressure distribution within ventilation system planning. Without computer aid, the calculation of a ventilation network is nowadays almost impossible because of the increased size of mine workings. In the majority of programs, the ventilation air is assumed to be an incompressible fluid and, accordingly, the programs neither consider natural ventilation air draft nor the volume flow changes occurring within the mine workings. Both phenomena, however, gain increasing importance with penetration to greater depth, increasing fan pressure rates, and increasing rock temperatures. In this context the average

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depth of coalfaces in the Ruhr district increased by 220 m to 900 m in the course of the last two decades. The rock temperature increased accordingly by $8^{o}C$ to $40^{o}C$. The deepest coalfaces and headings are situated at present in depths of 1300 m where the rock temperatures are of $60^{o}C$.

For the above reasons a ventilation network program was developed which allows for the physical changes of the ventilation air caused by temperature and pressure, and accordingly, also for the volume flow changes and the natural draft. Particular efforts were made in view of drafting the project to the needs of practice and in view of easy application.

BASIC PHYSICS

The basic physical principles which apply to the flow of air through a mine working are

- the law of conservation of the mass,
- the law of conservation of the energy,
- the relation that describes the energy dissipated by friction,
- the equation of the state of the mine air, and
- the change of state of the mine air as a function of airway length.

According to the law of conservation of the mass the magnitude of the mass-flow $\dot{m}$ of the air does not change between the inlet and the outlet point of a working:

$$\dot{m} = A \cdot \rho \cdot v = \text{const} \qquad (1)$$

where ρ and v stand for the density and velocity of the air stream respectively and A for the cross-sectional area of the working.

When applying the law of conservation of the energy, the change of kinetic energy of the air flow may be neglected for mine ventilation systems. Accordingly, the following differential equation applies to mine workings without fan installations:

$$- dp/\rho = d\psi + g\, dz = 0 \qquad (2)$$

where p stands for the barometric pressure, g for the gravitational acceleration (9.81 m/s^2) and z for the geodetic height coordinate.

The specific energy $d\psi$ dissipated by friction in an airway section of the length dx, a perimeter U and a cross-sectional area A is calculated by the formula:

$$d\psi = \lambda \frac{U}{8A} v^2\, dx \qquad (3)$$

In fluid dynamics equation (3) defines the friction coefficient λ.

The air density, a function of the barometric pressure p and the thermodynamic temperature T is calculated quite accurately from the equation of state for an ideal gas:

$$\rho = p/ (R_F \cdot T) \qquad (4)$$

The gas-constant R_F in this case depends on the humidity of the mine air.

Eventually, an assumption has to be made of the variation of the state of air as a function of the airway length, e.g.,

$$\rho = \rho\ (x) \qquad (5a)$$

$$\text{or} \quad T = T\ (x) \qquad (5b)$$

Sufficient accuracy is obtained if the calculation is based on a linear variation in each airway. Furthermore, both assumptions are equally acceptable with respect to the possible accuracy of ventilation air measurements done underground. The solution of the differential equation 2, however, is much more complex when using assumption 5b instead of assumption 5a.

Therefore, the described set of equations

was solved for the assumption of a linear density change in the airway.

Considering now a mesh comprising several airways and fans, if the specific fan energies are denoted by w, the following may be deduced from equation 2:

$$\oint dp/\rho = \Sigma w - \Sigma \psi \qquad (6)$$

For a constant density ρ the left-hand side of this equation is equal to zero. In this case, the dissipated energy is equal to the fan energy and natural draft is inexistent. Therefore generally a natural-draft energy of a system is expressed by $\oint dp/\rho$. This value is only considered if the change of the physical state of the air is not neglected either.

BASIC RELATIONS OF THE PROGRAM

From the more or less generally valid physical laws referred to above the following basic relations for a ventilation network program may be derived. With respect to applicability in practice, the solution is based on quantitative values which underground can be measured, viz., pressures, temperatures, and air-stream velocities.

$$p_1 - p_2 = \Delta p_r + \Delta p_s \qquad (7a)$$

$$\Delta p_r = R_n \frac{\dot{m}^2}{\rho_m \rho_n} \qquad (7b)$$

$$\Delta p_s = \rho_m \; g \; (z_2 - z_1) \qquad (7c)$$

with $\rho_m = (\rho_1 + \rho_2)/2$

and $\rho_n = \rho(0^oC, 1013 \text{ m'bar})$

$= 1.292 \text{ kg/m}^3$

According to equation 7a the barometric pressure difference between the two ends of an airway results from the sum of pressure loss Δp_r and the static pressure Δp_s, the latter being caused by the weight of the air column in the working under consideration.

The pressure loss Δp_r is calculated by equation 7b which comprises the airway resistance R_n and an arbitrarily chosen reference-density ρ_n. Actually, for the mean density ρ_m the logarithmic mean of the density values ρ_1 and ρ_2 should be inserted into equation 7b. However, for practical application, the arithmetic mean assures sufficient accuracy when inserted into both the equations 7b and 7c. The density values ρ_1 and ρ_2 at the beginning and at the end of the airway are calculated by equation 4. The resistance

$$R_n = \lambda \frac{UL}{8A^3} \rho_n \qquad (8)$$

is a characteristic value for an airway which depends on the friction factor λ and the geometric data of the airway, viz., perimeter U, length L and cross-sectional area A.

For constant density all relations described are reduced to the slightly different conventional laws of ventilation.

In a complete network calculation the above-mentioned equations have to be fulfilled simultaneously for every branch of the mine workings under consideration. The mathematical method for solving the resulting comprehensive set of equations is not to be discussed in this paper. For iteration, a broadened version of the cross-method was chosen.

APPLICATION OF THE PROGRAM

For a complete network calculation

- the resistance, or

- a required constant air quantity, or
- for fans, a required constant fan pressure or the fan characteristics

are to be specified for every branch of the network.

Fan characteristics are specified by a set of points on selected characteristic curves available for various blade positions of the impeller. The computer by interpolation determines the correct operation condition corresponding to a chosen impeller blade setting.

In addition, the following input data are necessary for considering natural draft and changes in volume flow:

- depths of all junctions of the network, and
- temperatures at both ends of every branch.

The results of a network calculation are printed on clearly arranged lists, including the following quantity values for each of the branches of the network:

- numbers of junctions on both ends of the branch,
- the chosen name of the branch,
- airway type; this is only indicated for branches with required volume flow or for fans,
- volume flow at the beginning of the branch,
- resistance of the airway,
- pressure loss,
- air temperatures at both ends of the branch,
- mass flow of air,
- power dissipated by friction,
- pressure at the beginning of the branch, and
- differences of depth level between both ends of the branch.

Moreover, the network can be plotted. On such a graph, the main calculation results are introduced automatically. Fig. 1 shows - considerably reduced in scale - the perspective representation of a medium-sized mine with about 320 branches and 210 junctions.

The program is primarily used for ventilation planning. By that, the conditions for satisfactory ventilation are determined in advance. Thus, the program supplies the basis for arrangement and operations of air-locks and fans, for the network structure, and the necessary cross-sectional areas of the airways.

Beyond that, the program is used for studies with respect to mine safety. For instance, it is possible to determine ventilation status after a fan failure. The influence of open mine fires on ventilation is simulated by assuming arbitrarily a fume-temperature development in any selected airway. In such a simulation, the program caters also for buoyancy and throttling effect of the fumes. In a similar way, other ventilation trouble may be investigated thus creating the basis for air-flow stabilisation measures to be taken if necessary.

For all these investigations the program, if required, supplies a comparison of the calculated air flows against an arbitrarily determined basic ventilation status. This is of special importance in practice because in this way the resulting changes in any part of the network are recognised very quickly.

Eventually it should be mentioned that the program because of the comprehensive physical description of the motion of gases which it supplies can be used for compressed-air networks as well even though in such a case the pressure differences are considerably greater. For compressed-air system planning, the program is already used successfully. In addition, it is intended to use the program for calculation of methane drainage systems.

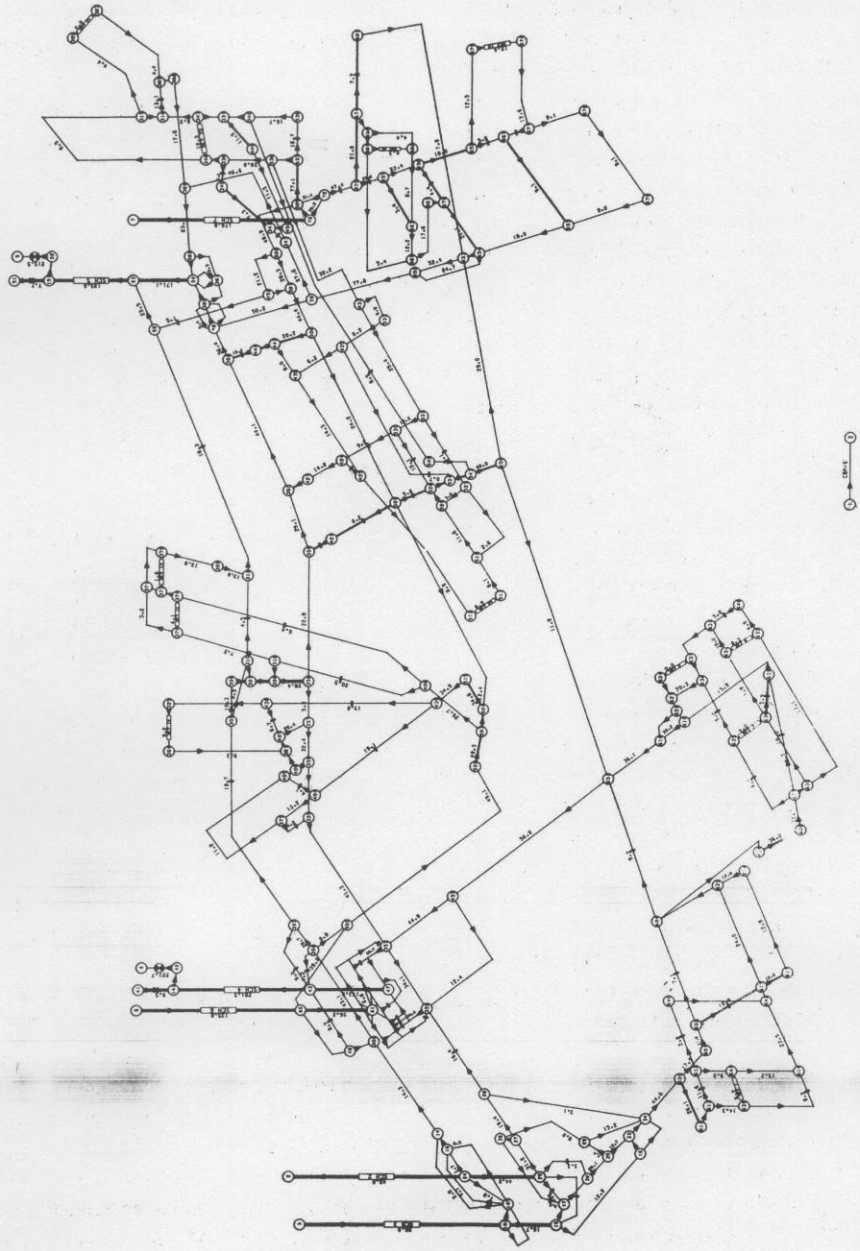


Fig. 1 Perspective Representation of a Medium-Sized Mine

INFLUENCE OF COMPRESSIBILITY

In order to demonstrate the influence of compressibility of air on the reliability of plannings, Fig. 2 shows a comparison of network calculations wherein air is in one case treated as a compressible fluid and, in the other case, as an incompressible fluid.

The example is based on a simple network of only one mesh. The assumed air temperatures are of $5^{o}C$ on the surface, rise to $30^{o}C$ in the mine workings and fall to $20^{o}C$ in the upcast shaft. The mine workings reach down to 1000 m of depth, and the resistances of the three branches are of 0.02 kg/m^7 each. For both calculations, the required airflow at the fan was of 350 m^3/s.

The results of the cases under consideration show differences of up to 17% for the volume-flows, of 20% to 52% for the pressure losses and the fan pressure, and of 26% to 55% for friction-dissipated energy and fan performance.

When summing up the energy-related data, it is confirmed that the contribution of natural draft to the airflow is catered for only when considering the compressibility of air. In the example, the corresponding value reads P_{NV}= 170 kW, and corresponds to approximately 10% of the fan performance.

It is clearly shown by this example that for ventilation planning it is necessary to allow for the compressibility of air in some way or other in order to make ventilation planning acceptably reliable.

EXAMPLE: MINE-FIRE

For conclusion, a case of ventilation system calculation for a simple network comprising 17 branches and 13 junctions may be discussed. The calculation was carried out for specified resistances and temperatures of all branches and for a known fan characteristic.

Fig. 3 shows the computer-drafted ventilation network plan with automatically plotted results of volume-flow and pressure loss calculations. Table 1 contains the complete set of ventilation data. From Table 1 may be read that the operating conditions of the main fan between junction 10 and junction 12 results from a fan blade position of 3°, a volume flow of 251 m^3/s, a fan pressure of 3440 Pa, and a fan performance of 853 kW.

By an additional calculation for the same network the influence of an open mine fire on ventilation was determined. The location of the fire was assumed to be in staple shaft 5-6 with fume temperatures gradually decreasing from $800^{o}C$ to $63^{o}C$.

The results are shown in Table 2. The last column contains the comparison of the air quantity data for this case with those of the normal ventilation situation. Accordingly, in the staple shaft 5-6 with descending ventilation the buoyancy of the fumes reduces the airflow to 5%.

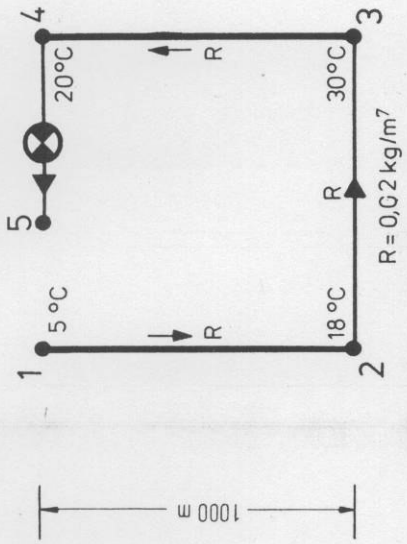
In almost all the other airways the influence of the fire on the stability of ventilation is negligible.

CONCLUSIONS

For the planning of mine ventilation systems the compressibility of air which depends on pressure and temperature should not be neglected. This applies in particular to deep mines, large variations in air temperatures, and high fan pressures.

The suggested method, by means of simple mathematical relations, allows very accurately for changes in volume flow and for natural ventilation.

This was the basis for development of a computer program for ventilation network calculation. All input data can be traced back to quantities measurable underground.



Airway	Δp in Pa		Difference
	air		
	compr.	incompr.	
1 – 2	1882	2450	30 %
2 – 3	1883	2450	30 %
3 – 4	2037	2450	20 %
4 – 5	-4842	-7350	52 %

Airway	P in kW		Difference
	air		
	compr.	incompr.	
1 – 2	578	857,5	48 %
2 – 3	579	857,5	48 %
3 – 4	678	857,5	26 %
4 – 5	-1665	-2572,5	55 %
P_{NV} =	170	0	

Point	$\dot{V}$ in m³/s		Difference
	air		
	compr.	incompr.	
1	316	350	11 %
2	299	350	17 %
3	316	350	11 %
4	350	350	0 %

Fig. 2. Comparison of Network Calculations

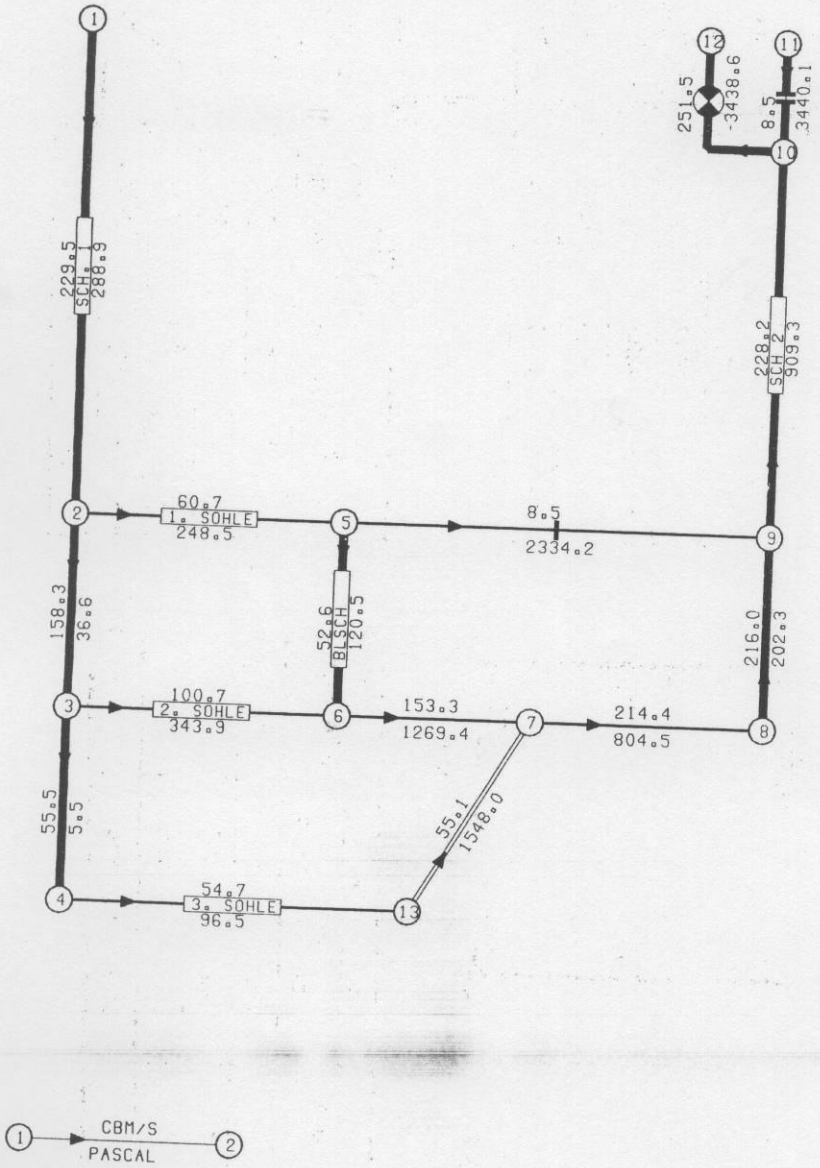


Fig. 3. Computer Drafted Ventilation Network Plan

DATUM: 7. 2. 83 UHRZEIT: 14.41

NETWORK CALCULATION FOR A SIMPLE MINE
NORMAL SITUATION OF VENTILATION

* PROGRAMM W E T T E R
* PRUEFSTELLE FUER GRUBENBEWETTERUNG
DATEI B.AU

AIRWAY FROM	TO	NAME	TYPE	VOL-FLOW BEGINNING	RESISTANCE RN	PRESSURE -LOSS	TEMPERATURE BEG.	END	MEAN DENSITY	MASS-FLOW	DISS. POWER	PRESS.	DIFF.OF DEPTH	MASS/ MASSB
				CBM/S	KG/M**7	PASCAL	GRAD C		KG/CBM	KG/S	KW	MBAR	M	-
1	2	SCH. 1		229.54	0.0060	288.9	15.0	21.0	1.238	277.46	64.8	1000.00	-600.0	0.00
2	3	SCH. 1		158.31	0.0015	36.6	21.0	22.0	1.276	200.57	5.8	1069.95	-150.0	0.00
2	5	1. SOHLE		60.69	0.0686	248.5	21.0	22.0	1.263	76.90	15.1	1069.95	0.0	0.00
3	4	SCH 1		55.46	0.0018	5.5	22.0	23.0	1.293	71.23	0.3	1088.34	-150.0	0.00
3	6	2. SOHLE		100.70	0.0340	343.9	22.0	23.0	1.280	129.34	34.7	1088.34	0.0	0.00
4	13	3. SOHLE		54.69	0.0319	96.5	23.0	25.0	1.297	71.23	5.3	1107.31	0.0	0.00
5	6	BLSCH		52.58	0.0450	120.5	22.0	23.0	1.268	66.23	6.3	1067.46	-150.0	0.00
5	9	DROSSEL		8.46	33.0000	2334.2	22.0	23.0	1.244	10.66	20.0	1067.46	0.0	0.00
					DROSSELANTEIL =	99. %								
6	7	H-STR		153.27	0.0543	1269.4	23.0	24.0	1.266	195.57	196.0	1084.91	0.0	0.00
7	8	H-STR		214.42	0.0181	804.5	27.0	27.0	1.240	266.80	173.1	1072.21	0.0	0.00
8	9	SCH 2		216.04	0.0045	202.3	27.0	26.0	1.225	266.80	44.1	1064.17	150.0	0.00
9	10	SCH 2		228.23	0.0180	909.3	26.0	21.0	1.180	277.46	214.0	1044.12	595.0	0.00
10	12	VENT.	HV-SCH 2 3.0 SKT	251.50	-0.0622	-3438.6	21.0	23.0	1.160	287.74	-853.0	966.18	5.0	0.00
11	10	WKZ		8.50	50.0000	3440.1	15.0	15.0	1.188	10.28	29.8	1000.00	-5.0	0.00
13	7	ABBAU		55.11	0.5000	1548.0	25.0	27.0	1.268	71.23	87.0	1106.35	150.0	0.00
12	1	AUSGL		229.54	0.0000	0.0	15.0	15.0	1.209	277.46	0.0	1000.00	0.0	0.00
12	11	AUSGL		8.54	0.0000	0.0	15.0	15.0	1.203	10.28	0.0	1000.00	0.0	0.00

Table 1 Network Calculation for a Simple Mine
Normal Situation of Ventilation

DATUM: 7. 2. 83 UHRZEIT: 14.56

NETWORK CALCULATION FOR A SIMPLE MINE
INFLUENCE OF AN ASSUMED MINE-FIRE IN STAPLE SHAFT 5-6 ON VENTILATION

* PROGRAMM W E T T E R
* PRUEFSTELLE FUER GRUBENBEWETTERUNG
DATEI:B.AU.B

AIRWAY FROM	TO	NAME	TYPE	VOL-FLOW BEGINNING	RESISTANCE RN	PRESSURE -LOSS	TEMPERATURE BEG.	END	MEAN DENSITY	MASS-FLOW	DISS. POWER	PRESS.	DIFF.OF DEPTH	MASS/ MASSB
				CBM/S	KG/M**7	PASCAL	GRAD C		KG/CBM	KG/S	KW	MBAR	M	-
1	2	SCH. 1		225.62	0.0060	279.1	15.0	21.0	1.238	272.73	61.5	1000.00	-600.0	0.98
2	3	SCH. 1		203.33	0.0015	60.4	21.0	22.0	1.276	257.63	12.2	1070.05	-150.0	1.28
2	5	1. SOHLE		11.92	0.0686	9.6	21.0	22.0	1.265	15.10	0.1	1070.05	0.0	0.20
3	4	SCH 1		58.93	0.0018	6.2	22.0	23.0	1.293	75.68	0.4	1088.21	-150.0	1.06
3	6	2. SOHLE		141.69	0.0340	681.7	22.0	23.0	1.278	181.95	97.1	1088.21	0.0	1.41
4	13	3. SOHLE		58.12	0.0319	109.0	23.0	25.0	1.297	75.68	6.4	1107.17	0.0	1.06
5	----	BLSCH	TEMP(X)	10.06	0.0060	0.1	800.0	540.0	0.403	3.49	0.0	1069.95	-20.0	0.05
----	----		-------	7.62	0.0090	0.2	540.0	300.0	0.555	3.49	0.0	1070.74	-30.0	0.05
----	----		-------	5.36	0.0120	0.1	300.0	140.0	0.779	3.49	0.0	1072.37	-40.0	0.05
----	6		-------	3.85	0.0180	0.2	140.0	62.9	1.014	3.49	0.0	1075.43	-60.0	0.05
5	9	DROSSEL		9.19	33.0000	2765.9	22.0	23.0	1.244	11.61	25.8	1069.95	0.0	1.09
					DROSSELANTEIL = 99. %									
6	7	H-STR		145.81	0.0543	1144.4	23.0	24.0	1.263	185.45	168.0	1081.39	0.0	0.95
7	8	H-STR		210.31	0.0181	772.1	27.0	27.0	1.237	261.12	163.0	1069.95	0.0	0.98
8	9	SCH 2		211.84	0.0045	194.2	27.0	26.0	1.223	261.12	41.5	1062.22	150.0	0.98
9	10	SCH 2		224.73	0.0180	880.0	26.0	21.0	1.178	272.73	203.9	1042.29	595.0	0.98
10	12	VENT.	HV-SCH 2 3.0 SKT	247.91	-0.0669	-3581.0	21.0	23.0	1.159	283.22	-875.0	964.76	5.0	0.98
11	10	WKZ		8.67	50.0000	3582.4	15.0	15.0	1.187	10.48	31.6	1000.00	-5.0	1.02
13	7	ABBAU		58.57	0.5000	1749.6	25.0	27.0	1.267	75.68	104.5	1106.08	150.0	1.06
12	1	AUSGL		225.62	0.0000	0.0	15.0	15.0	1.209	272.73	0.0	1000.00	0.0	0.98
12	11	AUSGL		8.72	0.0000	0.0	15.0	15.0	1.203	10.48	0.0	1000.00	0.0	1.02

Table 2 Network Calculation for a Simple Mine Influence of an Assumed Mine-Fire in Staple Shaft 5-6 on Ventilation

The examples demonstrate the efficiency of the program and the possibility to plot a complete network with automatically introduced calculation results. The program may also be used for other gas networks, e.g., compressed-air networks or methane drainage systems.