Calibration of LKAB’s Konsuln test mine ventilation model using barometer Pressure-Quantity (PQ) survey

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ABSTRACT: Ventilation projects such as installation of primary fans, refrigeration system, heating systems, and Ventilation of Demand (VOD) system require some simulations to ascertain their benefits and fulfilment of their purpose before the actual financial commitment is made to execute such projects. Ventilation models used for the simulations should provide some degree of accuracy to ensure that their results will reflect the actual mine ventilation circuit. This paper outlines a barometer Pressure-Quantity (PQ) survey that was done to calibrate the existing ventilation model of LKAB’s Konsuln test mine before it was used in a VOD design study to determine whether it will be feasible for Konsuln mine to install the system. The results show a good correlation between the simulated airflows in the calibrated model and the actual underground measured airflow quantities and primary fans pressure. This good correlation has validated the model for its use in Konsuln VOD design study.

1 INTRODUCTION

Ventilation simulation softwares enable ventilation engineers to carry out airflow, radon, pressure, heat, fire and several other simulations in a given mine ventilation model. These softwares also help engineers to model the ventilation circuit of a mine, have a thorough understanding of how the airflow will behave, the fan pressures and effects when certain activities such as fan installation are carried out in the mine.

Several simulation softwares have therefore been developed over the years such as VentSim Design, VuMa, and VnetPC. They have been proven to be of great benefit in the initial design of a mine ventilation circuit. They have also been useful in modelling the spread of blast fumes, heat and contaminants within the mine ventilation circuit. These softwares have also played key roles in accident control system by simulating several scenarios to support decision-making process in the event of incident in the mine to address various issues such as gas or fire control problems underground (Wu et al., 2019).

However, there is a high risk in using a ventilation model that has not been calibrated for ventilation planning and for ventilation projects that involve millions of dollars in capital or operating costs. Not only will there be losses in terms of cost, but it may also affect future mine production or result in serious occupational health and safety consequences associated with gases, fires, dust etc. (Brake, 2015). These produced ventilation models from simulation softwares should therefore be calibrated to ensure that the models are reasonably accurate to
give reliable simulation predictions of the performance of the actual mine ventilation system in their current state and for future ventilation planning, such as the situation in LKAB’s Konsuln test mine.

Konsuln mine is owned and operated by Luossavaara-Kirunavaara Aktiebolag (LKAB), a Swedish state-owned iron ore mining company. The mine is located just south of the famous Kiruna mine, the largest underground iron ore mine in the world in term of production, with the output of about 26.9 million tonnes per annum (mtpa) (LKAB, 2021). Konsuln orebody was extracted using open pit mining methods in the 1970s and underground mining in the 1980s. The mine was then closed because of unfavourable economic conditions. When LKAB set up its Sustainable Underground Mining (SUM) project (SUM, 2021), a new block of the mine underneath the old workings was developed 2018-2020 as a test mine for the project. Besides Kiruna and Konsuln, the company also operates 2nd largest underground iron ore mine in the world in term of production, Malmberget, and an open pit mine operation, Svappavaara. All of these operations are located in Malmfälten area in Northern Sweden inside the Arctic Circle. Products from these three mines are transported by rail to the exporting ports of Narvik in Norway and Luleå in Sweden where they are subsequently shipped to LKAB’s customers. Figure 1 shows the map of all mining operations and exporting ports.

Besides functioning as a test mine, the newly reopened Konsuln mine contributes ore production. The mine currently produces about 0.8 mtpa of iron ore. It is planned to increase it to a rate between 1.8 and 3 mtpa in the future. At the time of the writing of this paper, the new production rate was still being decided, but it will not exceed 3 mtpa. The mine uses the same mining method as in Kiruna mine, Sublevel Caving. The new block of the mine has three production levels: 436, 486, and 536. The deepest level, level 536, is about 390 m below

![Figure 1. Map of Northern Sweden, Norway, and Finland, which shows LKAB’s mining operations (Kiruna, Malmberget, and Svappavaara) and exporting ports (Narvik and Luleå).](image-url)
the surface. The ore is transported to the surface stockpile by diesel trucks via a ramp. This is different than the ore handling system used in Kiruna mine where shaft hoisting is used.

The ventilation and heating system is crucial to ensure safe and efficient operation of Konsuln mine. At the moment, the primary ventilation system is designed for a production rate of 0.8 mtpa. Due to a planned increase in the production rate mentioned above, a study was carried out to see whether employing VOD would avoid an expensive upgrade of the existing primary fans and the subsequent increase of their power cost. A major part of this study was to calibrate the existing ventilation model of the mine in order to make it fit for the purpose of designing a VOD system in Konsuln test mine. The original model was found to have some significant discrepancies with the ventilation survey results and therefore was deemed as not fit for the purpose.

This paper outlines the calibration work of the Konsuln ventilation model, which was done using a barometer Pressure-Quantity (PQ) survey method from April until May 2020. The aim of this PQ survey was to obtain the actual friction factor and shock loss factor of Konsuln’s airways, and also to check the accuracy of the primary fan curve that was used in the original model. Experience shows that these discrepancies are generally caused by the fact that the actual friction factor and shock loss factor are often different than the preset values generated by the simulation softwares. Simulation softwares have preset values of these parameters, which were obtained from literatures. However, the actual values are often different because these values were obtained from measurements in certain mines, which may have different geometry of airways compared to the simulated mine. Using inaccurate fan curves was also found as another main cause for these discrepancies.

The barometer method was chosen over the gauge and tube method because of its simplicity and practicality in the measurements, in particular when surveying airways that have some traffic in them such as the main ramp and footwall drives. Another reason for choosing this method was the time limitation to complete this calibration work. Due to its simplicity, the barometer method requires less time to complete the measurements than the gauge and tube method; and therefore was the better option to meet the deadline of this calibration work.

2 KONSULN MINE VENTILATION SYSTEM

Konsuln mine employs a combination of force and push-pull primary ventilation systems. The push-pull system is only used during the clearance of production blasting fumes. After production blasting is done on a certain level, two 22 kW fans, bolted to a bulkhead located in the connection drive to the exhaust raises, are turned on to pull the fumes from that level. After the fumes are cleared, these fans are turned off and the system runs only on “push” mode, which is the mode during the steady-state production. The primary intake fans are two 75 kW EOL Vent system inline axial fans installed in parallel. Both fans are equipped with Variable Frequency Drives (VFD) to vary their speed. These fans are located 52 m below surface and were designed to deliver 100 m³/s of fresh air to the mine. Due to extreme winter climate conditions where ambient surface temperatures can be as low as -40°C dry bulb (DB), the intake airflow must be heated during winter months. A direct-contact heating system, using electric coils, is installed on top of the fan intake raise. Figure 2 shows a schematic of the primary ventilation system, which includes dimensions of the primary airways. Figure 3 shows the ventilation model of the mine, which was created using VentSim Design software.

Primary airflow on each level is provided by 30 kW auxiliary fans bolted to a bulkhead located in the connection drive to the intake raises. Each fan is connected to a 1,000 mm diameter duct that extends to the level footwall drive. This air is then distributed to each crosscut (production drive) using a 11 kW auxiliary fan (called crosscut fan) connected to a 800 mm diameter duct installed in the access to each drive. Figure 4 shows a view of level ventilation in Konsuln mine.
Figure 2. Schematic of Konsuln primary ventilation system, with dimension of primary airways shown.

Figure 3. VentSim model of Konsuln ventilation system.

3 KONSULN VENTILATION MODEL CALIBRATION PROCESS

The existing ventilation model of Konsuln mine as of 2 December 2019 was obtained as the base case model for calibration. The model was created using VentSim Design software, a popular ventilation simulation software.

Due to time limitation, the survey was not done in all airways within the mine. Rather, some representative airways with similar characteristics were measured as follows:

- Airways that have the same dimensions and ground support on each level. For example, on level 436 and 486 only some parts of the footwall drive that have the same dimension and ground support were surveyed at the same elevation, instead of the whole footwall drive.
- Some sections in the main decline/ramp.
The survey was not done in the ventilation shafts and raises due to the limited number of personnel that could be involved. Only two personnel were available to complete the survey program; and they were required to stay together during the survey to follow safety protocols. Hence, surveying ventilation shafts and raises, which would have required two personnel at both ends simultaneously (total of four personnel), could not be done. Therefore, the calibration of their friction factor was done based on the calibration in other airways in the vicinity (i.e. after these airways were calibrated, the model was run and then the values of the raise airflow quantities were compared with those measured. If the difference was found to be less than 10%, it was then concluded that the preset friction factors in VentSim Design for shafts and raises was acceptable and could be used in the calibrated model).

It must be noted that level 536 was still being developed during the survey and no measurements could be done on this level. However, because parameters on level 536 are similar with those on level 436 and 486, the calibrated friction factor and shock loss factor on these levels can be applied.

4 THEORY OF BAROMETER PRESSURE-QUANTITY (PQ) SURVEY

PQ surveys play an important role in obtaining the frictional pressure drop and the corresponding airflow quantities needed for calibration and validation of a model. The parameters that are measured are airflow quantity, air pressure, and air temperatures. A guideline for survey execution to build and calibrate a given ventilation model has been presented by some practitioners (Prosser and Loomis, 2004; Prosser, 2020; Rowland, 2009, 2010, 2011).
In a barometer PQ survey, air pressure at two points within a uniform airway is measured simultaneously using a barometer. Airflow quantity, air temperatures (dry and wet bulb), and distance between these two points are also measured. When the two points are on the same elevation (i.e. inside a horizontal airway such as footwall drives), the pressure difference between these two points is the pressure loss of the airway between them. When the two points are not at the same elevation (i.e. inside an inclined airway such as ramps), a correction to the pressure difference must be made to exclude the weight of the air column. The correction is calculated by multiplying air density with elevation difference and gravitational acceleration. The elevation of each measurement point was obtained from the mine surveyors. The air density is calculated using psychrometric equations with air temperatures and barometric pressure as the input data.

The airway resistance can therefore be calculated using the following equation:

$$R = \frac{P}{Q^2}$$

Where:
- $P$ is the pressure loss of the airway between two measurement points (Pa)
- $R$ is the resistance of the airway between two measurement points (Ns$^2$/m$^4$, nicknamed as Gaul)
- $Q$ is the airflow quantity inside the airway between two measurement points (m$^3$/s)

After calculating the resistance of the airway between two measurement points, friction factor and shock loss factor between these two point can therefore be calculated using the following equation:

$$R = \left(\frac{kCL}{A^3} \times \frac{\rho}{1.2}\right) + \left(\frac{XP}{2A^2}\right)$$

Where:
- $k$ is airway friction factor between two measurement points (Ns$^2$/m$^4$ or kg/m$^3$)
- $C$ is the circumference (perimeter) of the cross-section of the airway between two measurement points (m)
- $L$ is the length of the airway (m) or the distance between two measurement points
- $A$ is the area of the cross-section of the airway between two measurement points (m$^2$)
- $\rho$ is the density of the air that flows inside the airway between two measurement points (kg/m$^3$)
- 1.2 is the density of air at sea level. The unit is kg/m$^3$
- $X$ is the airway shock loss factor between two measurement points (dimensionless)

5  MEASUREMENT OF PRIMARY FANS QUANTITY AND PRESSURE

Another PQ survey was done on the primary fans to determine their actual duty point and to check the accuracy of their curve in the original model. As mentioned previously, using inaccurate fan curves is another general cause of the discrepancies between the model and the actual condition. Figure 5 shows the layout of the Konsuln primary fans. It can also be seen in Figure 5 that the airflow delivered by the primary fans encounters two 90° (approximately) bends after the regulator, which will be removed in the future in order to achieve the design quantity of 100 m$^3$/s. The fan quantity was measured using a vane anemometer at the regulator in front of the outlet of the fans’ diffuser; and Fan Total Pressure (FTP) was determined by measuring the pressure across the fan bulkhead using a digital manometer. The pressure was then adjusted for shock loss caused by the expansion of the ejected air from the fans into the chamber using the following relationship:
Figure 5. Plan view of the installation of Konsuln primary fans during the PQ survey.

\[ P \text{ across fan bulkhead} = FTP - \left(1 - \left(\frac{A_1}{A_2}\right)^2\right) \times FVP \]

Where:
- \( A_1 \) is the cross sectional area of the outlet of fans' diffuser (m\(^2\))
- \( A_2 \) is cross sectional area of the fan chamber (m\(^2\))
- FVP is Fan Velocity Pressure (Pa)

6 INSTRUMENTS THAT WERE USED IN THE SURVEY

Following are the instruments that were used in the PQ survey to calibrate Konsuln ventilation model:
- 2 x GE Druck DPI800 electronic barometers, used to measure barometric pressures.
- 1 x Dwyer series 475 Mk. III digital manometer, used to measure pressure across primary fans bulkhead.
- 1 x TSI VelociCalc 5725 vane anemometer, used to measure air velocity in horizontal airways and in primary fans diffuser outlet.
- Kimo AMI 310 hot wire anemometer, used to measure air velocities in horizontal airways that have very low air velocity.
- 1 x Leica Disto D210 laser distancemeter, used to measure cross-sectional dimension of horizontal airways.
- 1 x Kestrel 5000 pocket weathermeter, used to measure air temperatures.
- 1 x Zeal whirling hygrometer, used to measure air temperatures.
7 RESULTS FROM THE MODEL CALIBRATION

After the model was calibrated using the calculated friction factor and shock loss factor, and the corrected primary fan curve, the simulation was ran and some of its simulated values were compared against the measured values and the simulated values from the original (uncalibrated) model.

7.1 Primary fans

The measurement of primary fans quantity and pressure found that an inaccurate plot of the supplied curve was used in the original model. The plot was subsequently corrected and then re-entered into the calibrated model. Figure 6 shows the comparison between the measured quantity and FTP of Konsuln primary fans and their simulated value in uncalibrated and calibrated models. It shows that the difference between simulated and measured values has been reduced substantially. However, the FTP in the calibrated model is still 135.2 Pa higher than the measured value (corresponds to 13% difference relative to the measured value). When the measured duty point was plotted on the supplied fan curve, it lays below the curve. This indicates that the actual fan curve is lower than the one supplied by the fans’ manufacturer. This situation is not unusual because the supplied fan curves are derived from the testing program done in a test chamber that is clean and dry; and during testing the air that flows through the fans is relatively clean (contains very little dust and moisture). However, in the mine, air that flows through the fans is usually dusty and moist, which can impact the actual fan duty point where it intersects the supplied fan curve.

7.2 Level 436 and 486 airflow comparison

The level survey data were also compared to the simulated modelled values, as shown in Figure 7 and 8. These figures show a comparison between airflow quantities in the uncalibrated model, calibrated model with flows that were measured at various measurement stations on level 436 and 486. It is clear from these figures that there is an improved correlation between airflow quantities in the calibrated model and the measured data after the calibration.

8 DISCUSSION

It can be seen in Figure 6 to 8 that the model has been successfully calibrated. The difference in primary fan quantity (relative to the measured value) has been reduced from 3.8% in the uncalibrated model to 1% in the calibrated model, whilst the difference in primary FTP (relative to the measured value) has been reduced from 24.6% in the calibrated model to 13% in the calibrated model. The difference between airflow quantities on level 436 and 486 has also been reduced substantially. For example, on level 436 (station S03), the difference in model quantity (relative to the measured value) has been reduced from 716.4% in the uncalibrated model to 0.6% in the calibrated model. Similarly, on level 486 (station S02), the difference has been reduced from 79% in the uncalibrated model to 3.1% in the calibrated model.

It must be noted that the main disadvantage of barometer method is the requirement to apply correction to the readings in inclined airways. This correction depends on the accuracy of the measurement of measurement points elevation and barometric pressure. Although this was not an issue in this calibration work, the use of gauge and tube method should be considered in the future calibration work because there is no need to apply correction when this method is used. However, a longer timeframe and more personnel than what was available for this calibration work would be required should gauge and tube method be selected in the future.
Figure 6. Comparison of primary fan performance before and after calibration.
9 CONCLUSION AND RECOMMENDATION

The work outlined in this paper shows the improvement of the Konsuln ventilation model after its calibration using the barometer PQ survey method. Even though the primary FTP in the calibrated model is still 135.2 Pa higher than the measured value, the airflow quantities in the calibrated model have become closer to the measured values after the calibration. The lower measured FTP compared to simulated value in the calibrated model indicates that the actual fan curve is lower than the supplied one, which is not uncommon as explained in Section 6.2. Therefore, the model can be considered as acceptable for designing the VOD system and other future ventilation design and planning work in Konsuln mine.
It is recommended that the model continue to be calibrated as conditions change in the future as mining progresses. The barometer PQ survey is useful not only to calibrate the ventilation model but also to get a snapshot of the actual condition in the mine ventilation circuit.

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