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Optimization of Underground Mine Ventilation Using Passive and Active Methods: Case Study of Chaabet El-Hamra Mine

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Dedication

We would like to dedicate this work to our parents, who have always been there for us with love, patience, and endless support,

To our friends, thank you for your kindness, your encouragement, and for being by our side during the hard times and the good one.

To our classmates and fellow students in the same field weve learned a lot together, and were grateful for every shared moment.

And finally, to everyone who helped us, directly or indirectly, thank you from the bottom of our hearts

Acknowledgment

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Finally, we dedicate special thanks to our parents, whose love, encouragement, and unwavering support have always been our greatest source of motivation, especially during challenging moments.

Abstract

This thesis focuses on optimizing the underground ventilation system of Chaabet El-Hamra mine using a two-stage approach: passive and active techniques. Passive optimization included geometric improvements such as the lining of KO and YK galleries, which significantly reduced resistance and pressure loss. Active optimization involved the installation of a secondary fan in the KO branch, resulting in a local power reduction of over 30% and an overall system energy savings of 3.4 kW. The combined strategy improved airflow balance and energy efficiency across the network.

Keywords: mine ventilation, optimization, lining, secondary fan, airflow resistance, energy efficiency

Résumé

Ce mémoire porte sur l'optimisation du système de ventilation de la mine souterraine de Chaabet El-Hamra en utilisant une approche en deux étapes : passive et active. L’optimisation passive a consisté à améliorer la géométrie des galeries KO et YK par un revêtement, réduisant significativement la résistance et la perte de charge. L’optimisation active a introduit un ventilateur secondaire dans la branche KO, ce qui a permis de réduire localement la puissance requise de plus de 30 % et d’économiser 3,4 kW au niveau du système global. La stratégie combinée a permis d'améliorer l'équilibre du débit d'air et l'efficacité énergétique.

Mots-clés: ventilation minière, optimisation, revêtement, ventilateur secondaire, résistance à l’air, efficacité énergétique

ملخص

يركز هذا البحث على تحسين نظام التهوية في منجم شعبة الحمراء تحت الأرض باستخدام نهج مزدوج: تقنيات سلبية ونشطة. مما أدى إلى تقليل كبير في المقاومة وفقدان الضغط. YKو KO شملت التحسينات السلبية تحسينات هندسية مثل تبطين فرعي مما أدى إلى تقليل استهلاك الطاقة المحلي بأكثر من 30٪ KO أما التحسين النشط فتمثل في تركيب مروحة ثانوية في فرع وتوفير 3.4 كيلوواط على مستوى النظام ككل. أدت هذه الاستراتيجية المزدوجة إلى تحقيق توازن أفضل في تدفق الهواء، وتقليل استهلاك الطاقة، وتحسين السلامة التشغيلية.

الكلمات المفتاحية: التهوية، منجم تحت الأرض، التبطين، المروحة الثانوية، مقاومة تدفق الهواء، كفاءة الطاقة

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List of Abbreviations and Symbols

Q : Airflow rate (m^3/s)

V : Air velocity (m/s)

S : Cross-sectional area of airway (m^2)

ΔP : Pressure loss (Pa)

R : Resistance of airway (Ns^2/m^8)

η : Fan efficiency (dimensionless)

K : Friction coefficient (Ns^2/m^4)

P : Power (W)

Per: Wetted perimeter (m)

L : Length of the airway (m)

General Introduction :

Underground mining continues to serve as a critical pillar of industrial development, supplying essential raw materials needed for infrastructure, manufacturing, and energy production. However, this type of mining comes with major technical and environmental challenges, particularly when it comes to ensuring the safety, health, and comfort of underground workers. One of the most vital elements in meeting these challenges is the design and management of an effective mine ventilation system.

Proper ventilation in underground environments serves multiple functions. It ensures an adequate supply of oxygen to work zones, removes hazardous gases and dust, and regulates temperature and humidity levels to create acceptable working conditions. Moreover, with rising global concerns about energy consumption and environmental impact, optimizing ventilation has become a matter of both operational safety and energy efficiency.

In deep and extensive mining layouts such as that of the Chaabet El-Hamra mine in Algeria, standard ventilation systems often face difficulties related to unbalanced airflow distribution, excessive resistance in certain branches, and high power consumption. Such inefficiencies may lead to localized heat accumulation, poor air renewal, and unnecessary energy loss, putting both production and worker safety at risk.

To address these issues, this thesis explores a two-stage ventilation optimization approach applied specifically to the Chaabet El-Hamra mine. The first stage involves **passive optimization** through geometric improvements such as lining high-resistance galleries (e.g., YK and KO branches) to reduce wall roughness and improve airflow dynamics. The second stage focuses on **active optimization** using mechanical intervention—namely the installation of a secondary fan in the KO branch—to redistribute pressure and reduce energy demand.

The methodology adopted combines field measurements, analytical modeling, and simulation tools. Pressure loss, airflow resistance, and ventilation power demand are evaluated before and after the proposed interventions. The results highlight the effectiveness of combining passive and active methods to achieve balanced airflow, lower energy costs, and enhanced mine safety.

Through this work, we aim to contribute to the development of practical, data-driven ventilation strategies that can be applied not only at Chaabet El-Hamra but in other underground mining operations facing similar challenges.

Chapter I

Site Description and Mine Presentation

1. Introduction:

Minerals are the pillar of industrial economies since they are a source of raw materials which speed technological and infrastructural progress. Chaabet El-Hamra is one such metallic ore deposit in Algeria, which is a strategic metallic ore deposit with industrial value according to its position, geology potential, and producibility. The exploitation of such deposits not only should be effective in the extraction of minerals but also equipped with sufficient support systems to ensure safety and environmentally friendly standards. Of all these, ventilation within the mines is essential to the preservation of underground air quality, temperature regulation, and the evacuation of poisonous gases. Design and installation of ventilation systems are thus paramount to safeguarding safe and effective working conditions. This chapter will give a detailed overview of the Chaabet El-Hamra mine site, its geographical location, topography, and technical plan of its ventilation system. By so doing, the chapter lays a base for greater technical and operational scrutiny subsequently

2. Site location:

The Chaabet El-Hamra deposit is located approximately 350 km southeast of Algiers and 50 km south of Sétif, in the Chouf-Bouarket region, 5 km from Ain-Azel and 12 km southeast of the Kharzet Youssef mining complex.

Tab.I.1. Perimeter Coordinates

Points	A	B	C	D
X	726 900	728 500	728 500	726 900
Y	3 963 200	3 963 200	3 962 500	3 962 500

- Geographic coordinates: Longitude: 05° 30' 38", East - Latitude: 35 41' 55", North
- The altitude of the deposit varies from 950 to 1,200 meters. [1]

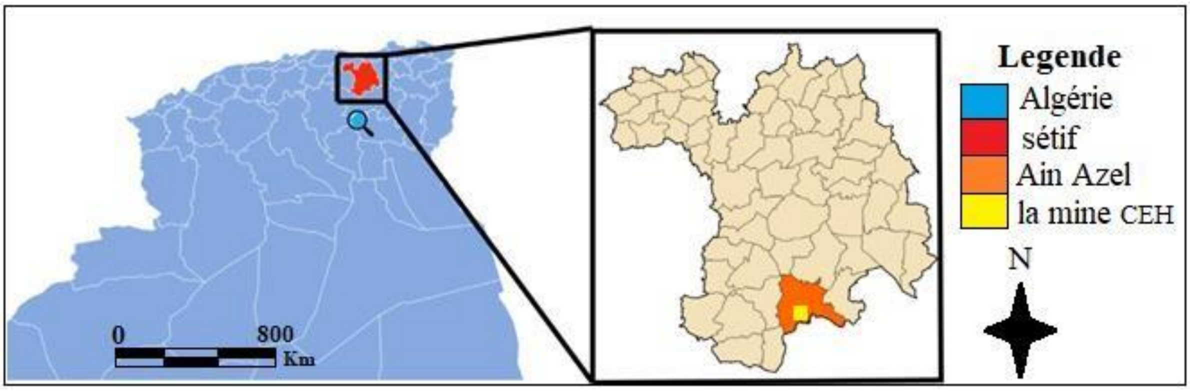


Figure.I.1. Geographic location of the « Ain Azel » commune

3. Mine Ventilation:

Given the morphological characteristics of the Chaabet deposit and the mining method used, which generates large horizontal expanses, ventilation is done mechanically using fans to ensure adequate working conditions.

3.1. Main Ventilation :

The main ventilation for the Chaabat-El-Hamra case is a forced type, reinforced by an exhausting fan type 1300 HDM (fig1.3. A) installed on the surface at the head of the return air shaft, with the following specifications:

- Flow rate : 51 m^3/s
- Pressure drop: 202 mm wg (water gauge) Fresh air passes through the decline towards the active working faces, and the stale air is routed through the ventilation gallery, then evacuated to the surface via the return shaft [2].

3.2.Secondary Ventilation:

A secondary ventilation installation is mandatory for routing fresh air to the work sites, given that these sites are far from the fresh air intake point. The ventilation of each working face is ensured by secondary fans in a combined ventilation system, i.e., pushing fresh air towards the face and exhausting stale air from it. The mine is equipped with 12 secondary fans of types

CVM5, CVM6, 24KVK to ensure ventilation of the work sites (fig1.3. B). [2],

A : Main Exhaust Ventilator [2]

B : Secondary Ventilation Fan

Figure .I.1. Types of Ventilators Used in the Mine

The Chaabet El-Hamra mine is supplied by an electrical network originating from the Ain-Azel power plant, with an incoming voltage of 30 KV. This electrical energy is used for mine lighting, ventilation, and in the processing plant.

4. Conclusion:

This chapter offered a detailed description of the various elements of the Chaâbet El-Hamra mine. Following the geographical location of the site, specific emphasis was put on its ventilation system, a crucial component to ensure safety and efficiency in underground operations. All the information provided helps to better understand internationally the functioning of the mine and forms a good foundation for future technical and operational studies.

Chapter II

State of art

1. Introduction:

Underground mine ventilation is a critical component of the mining industry, essential for ensuring the health and well-being of workers as well as the operational efficiency. This chapter addresses the subjects of ventilation systems, the character of the mine atmosphere, and introduces ventilation network analysis as a basic tool for ventilation plan optimization.

2. Atmospheric air:

The ambient atmospheric air is a fairly homogeneous mixture of nitrogen dioxide, oxygen, arsenic, carbon dioxide, and water vapor. However, the water vapor tensor is subject to large variations. The mining environment and the surrounding soil are increasingly in disequilibrium due to high atmospheric pollutants. [3]

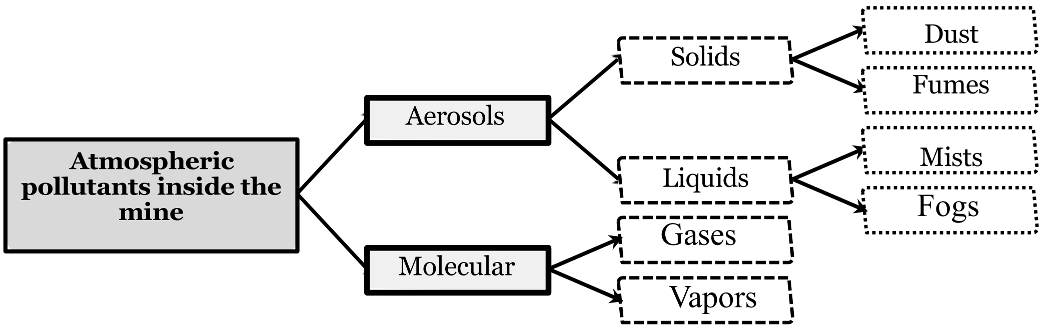


Figure II.1. Atmospheric pollutants in mines [3]

Proper mine ventilation is not limited to ensuring adequate airflow.. It must also take into account: the concentration of toxic gases, temperature, humidity, and other environmental factors that may affect working conditions.

3. Generalities on Mine Ventilation:

Mine ventilation encompasses all processes and systems implemented to ensure air circulation in underground workings. Its primary objective is to maintain a safe and healthy working environment for miners by controlling air quality, temperature, humidity, and by diluting contaminants. These contaminants can include toxic gases (methane, carbon monoxide, carbon dioxide, etc.), fine dusts, and fumes resulting from mining operations (blasting, diesel engine operation) [4], [5].

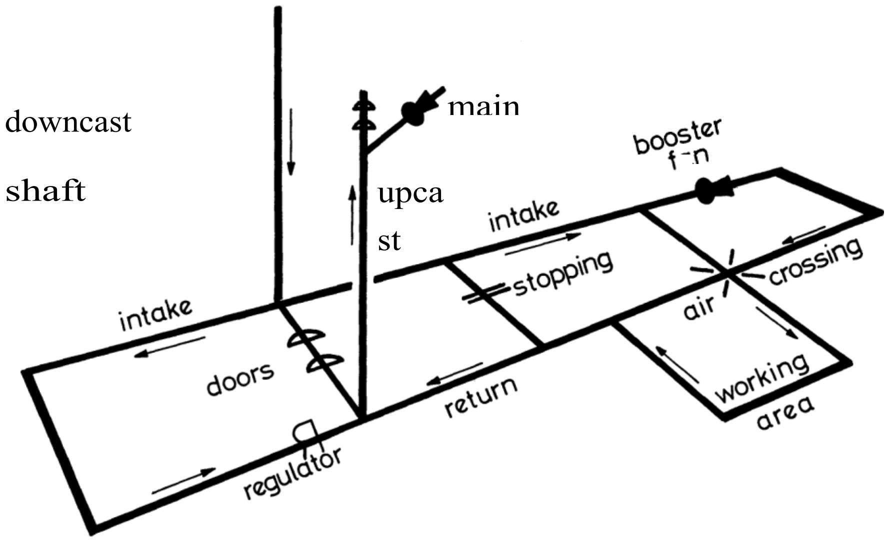


Figure II.2. The ventilation system and its control.[5]

An effective ventilation system must ensure a sufficient supply of fresh air to working areas, evacuate vitiated air and pollutants, and control thermal conditions. The design of such a system is complex and must consider numerous factors, such as the geometry of the galleries, the depth of the mine, heat production by rocks and equipment, and the presence of natural gases [5].

4. Factors Influencing Ventilation:

Several factors influence the effectiveness and design of a mine ventilation system. These factors can be classifed into geometric, physical, and operational categories [4],[5]

Geometric Factors	Physical Factors	Operational Factors
1.Cross-sectional area of roadways 2.Length of roadways 3.Wall roughness 4.Changes in direction and cross-	1.Air density 2.Temperature and humidity 3.Atmospheric pressure	1.Gas and dust production 2.Equipment and machinery 3.Mining methods

5. Air flow regimes:

The airflow in mine roadways can occur in two main regimes: laminar and turbulent. Understanding these regimes is crucial for predicting air behavior and calculating pressure losses in the ventilation network [4].

5.1. Rynolds number :

The flow regime is characterized by the Reynolds number (Re), a dimensionless number that represents the ratio of inertial forces to viscous forces in a fluid [4], [5]. It is defned by the formula:

$$Re = \frac{\rho v L}{\mu}$$

Where: ρ is the fluid density (kg/m^3), v is the average fluid velocity (m/s) and L is System characteristic length or pipe diameter (D) through which the fluid is passing (m). The parameter will often be substituted by the hydraulic diameter.

For non-circular conduit flows, the hydraulic diameter is used to adjust the Reynolds number equation. For mine roadways, since many have non-uniform cross-sections, exact calculation of hydraulic diameter is needed [4].

5.2. Laminar Flow :

The flow is laminar when the Reynolds number is low (typically $Re < 2000$). In laminar flow, in this regime, the fluid travels in parallel layers with minimal mixing between layers. Particles of the fluid move along smooth and regular paths. Pressure losses in laminar flow are primarily due to viscous forces and are proportional to the velocity of flow [4].

In mines, laminar flow is very rarely encountered in main airways due to high velocities and enormous cross-secions. In small-diameter ducts or in extremely low-velocity regions, it may be seen [5].

5.3. Turbulent Flow :

Turbulence is said to occur in flow when the Reynolds number is large (usually $Re > 4000$). In this regime, fluid flow is controlled by random fluctuations and eddies, which lead to intense mixing of fluid layers. Pressure losses in turbulent flow are significantly greater than for laminar flow and vary with the square of the flow velocity [4].

5.4. Transitional Regime :

In the intermediate range between the laminar and turbulent regimes (usually $2000 < Re < 4000$), there is a transition range in which the flow oscillates between the two regimes or exhibits characteristics of both. The nature of the flow in this range is complicated and difficult to ascertain with accuracy [4].

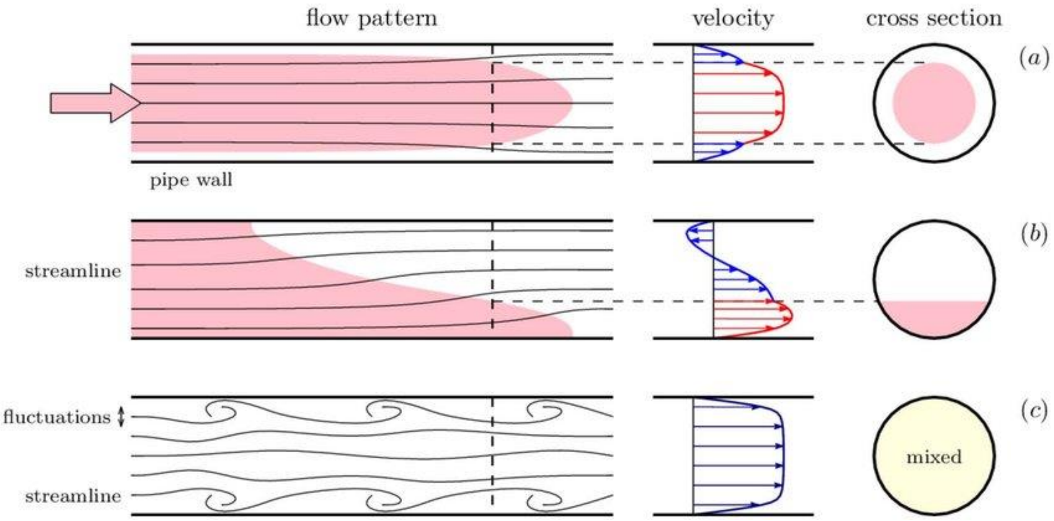


Figure II.3. Velocity Profiles and Flow Behavior in Laminar, Transitional, and Turbulent Regimes.

6. Dimensioning Methods and Ventilation Laws:

Dimensioning a mine ventilation network is a complex process that aims to determine the necessary airflow rates, required pressures, and fan characteristics to ensure adequate ventilation. This process relies on fundamental laws of fluid mechanics and specifc calculation methods for underground airway networks [4], [5].

6.1. Analytical Methods :

Analytical methods involve using laws to form equations that can be solved analytically to give exact solutions [6]:

6.1.1. Fundamental Laws of Airflow in Mines:

Airflow in mine roadways is governed by the principles of conservation of mass, energy, and momentum. Key laws include:

- **Law of Conservation of Mass (Continuity Equation):**

For incompressible flow (which is a reasonable approximation for air in mines at low velocities), the mass flow rate is constant across a given section of a airway. This means that the product of air density, average velocity, and cross-sectional area is constant along a leak-free roadway [4].

$$Q = \text{v}.\text{A}$$

Where:

- Q is the volumetric flow rate (m^3/s)

- v is the average air velocity (m/s)
- A is the cross-sectional area of the roadway (m²)

- **Law of Conservation of Energy (Bernoulli's Equation):**

Bernoulli's equation, adapted for real fluids with losses, relates pressure, velocity, and elevation along a streamline. In ventilation networks, it is used to analyze pressure losses and gains [4].

6.1.2. Pressure Losses:

Pressure losses represent the decrease in air pressure due to flow resistance. They are of two main types:

Frictional Pressure Losses	Shock Losses (or Form Losses):
These are due to the friction of air against the roadway walls. They depend on the roughness of the walls, the length of the roadway, the cross-sectional area, and the air velocity. **Atkinson's law** is commonly used to calculate them [5]. $$\Delta P = R.Q^2$$ Where: • ΔP is the frictional pressure loss (Pa) • R is the roadway resistance (Ns²/m⁸), which depends on the roadway geometry and wall roughness. • Q is the volumetric flow rate (m³/s) • The resistance R is given by: $$R = \frac{KPL}{A^3}$$ Where: • R is the airway resistance (Ns²/m⁸), • k is Atkinson's friction coefficient (Ns²/m⁴), • P is the wetted perimeter of the airway (m), • L is the length of the airway (m), • A is the cross-sectional area of the airway (m²).	These are due to changes in direction (bends), cross-section (expansions, contractions), or the presence of obstacles (doors,regulators). They are proportional to the square of the velocity and are often expressed in terms of equivalent length of straight roadway [4]. $$h_S = K\frac{\rho v^2}{2}$$ Where: • hs is the shock loss (Pa), • K is the shock loss coefficient (dimensionless), which depends on the type of obstruction or geometry change, • ρ is the air density (kg/m³), • v is the average air velocity (m/s).

6.2. Numerical Methods :

Although analytical methods for ventilation network analysis received considerable attention before the development of analog computers in the 1950s, the multiple simultaneous equations they produced could not be easily solved by manual means. Since the mid-1960s, considerable research has been conducted to find more efficient numerical methods for analyzing ventilation networks. [7]

Calculating ventilation networks involves solving complex systems of equations to determine flow rates and pressures in each branch of the network. Commonly used methods include [5]:

- ***Hardy-Cross Method:***

This is an iterative method widely used to solve ventilation networks. It is based on applying Kirchhoff's laws (conservation of flow at junctions and conservation of pressure along closed loops).

7. Structural and Operational Elements of Ventilation Optimization :

Ventilation optimization in underground mining involves not only airflow management but also structural and mechanical interventions that ensure safety, efficiency, and long-term functionality. This section explores two key components: the use of gallery linings to reduce resistance and stabilize excavations, and the deployment of secondary fans to ensure adequate air delivery in complex or expanding mine networks.

7.1. Lining Effects on Gallery Form in Underground Mining :

Lining plays a critical role in maintaining the stability and shape of underground mine galleries. It provides structural support that limits deformation caused by rock convergence and excavation damaged zones, especially in weak or sensitive geological media such as clay formations. The lining also controls the interaction between the rock mass and the support system, which affects long-term gallery stability and deformation behavior.

- Numerical simulations have demonstrated that discontinuous concrete linings, assembled from wedge-block segments, effectively reduce radial convergence and maintain the gallery’s designed shape during and after excavation. These linings accommodate rock movements while preserving structural integrity by distributing stresses and limiting micro-fracturing around the excavation. [10]
- The lining thickness and segment arrangement influence the degree of deformation and strain evolution in the gallery lining. For example, a 40 cm thick lining with segmented rings showed measurable strain patterns consistent with numerical predictions, validating the importance of lining design in gallery stability . [10]

- Lining also limits the excavation damaged zone extent and modifies the rock's mechanical properties near the gallery, which is essential for deep underground excavations . [10]
- Beyond structural support, linings contribute to operational safety and longevity of underground workings by preventing collapse and controlling water or gas ingress. [11]

7.2. Impact of Secondary Fans on Underground Mine Ventilation Systems :

Secondary (auxiliary) fans are indispensable components of underground mine ventilation systems. They provide targeted airflow to remote or developing areas of the mine where the primary ventilation circuit cannot deliver sufficient fresh air.

- Secondary fans improve air quality and safety by diluting hazardous gases, dust, and heat in dead-end headings, crosscuts, and working faces, thereby protecting miners and equipment. [11]
- These fans offer operational flexibility as they can be relocated according to mining progress, ensuring continuous ventilation coverage in evolving mine layouts. [11]
- Energy consumption related to secondary ventilation can be significant, sometimes accounting for a large portion of total mine energy use. Efficient fan selection and control strategies are therefore critical for minimizing operational costs while maintaining safety standards. [11]
- The design and maintenance of secondary ventilation systems must consider duct resistance, fan reliability, and changing mine conditions to ensure consistent airflow and avoid production disruptions. [11]

8. Conclusion :

Underground mine ventilation is a multifaceted discipline that combines principles of fluid mechanics, environmental engineering, and structural design. This chapter reviewed the composition and behavior of atmospheric air, the foundational concepts of airflow in mine networks, and the mathematical methods used for system analysis and dimensioning.

In addition to theoretical approaches, the role of structural elements such as gallery linings and operational tools like secondary fans has been highlighted. These components are essential in reducing aerodynamic resistance, maintaining gallery integrity, and ensuring efficient air delivery across complex or deep mine layouts.

Through this review, it becomes clear that optimizing ventilation requires a holistic strategy one that integrates analytical modeling, engineering interventions, and adaptive ventilation design. These insights form the scientific and technical foundation upon which the proposed optimization methods in this thesis are built.

Chapter III

Proposed Solutions and Conducted Experiments

1. Introduction :

In underground mines, balanced ventilation is crucial for the safety of the workers. Many factors can affect the ventilation system and lead to an imbalanced air distribution in one or more galleries of the mine. These factors must be controlled and checked regularly to avoid poor airflow distribution, ensure good conditions for workers, and avoid risks.

2. Description of the Mine Ventilation Circuit :

The Chaabat El Hamra mine uses artificial ventilation for its main ventilation system because the mine is deep and complex. A 1300 HDM suction ventilator is connected to the return air shafts. It draws air through the mine openings, benches, and tunnels to reach the working areas. The air is then expelled through the shaft where the ventilator is installed [8].

Figure.III.1. illustrate the main ventilation of the Chaabat El Hamra mine

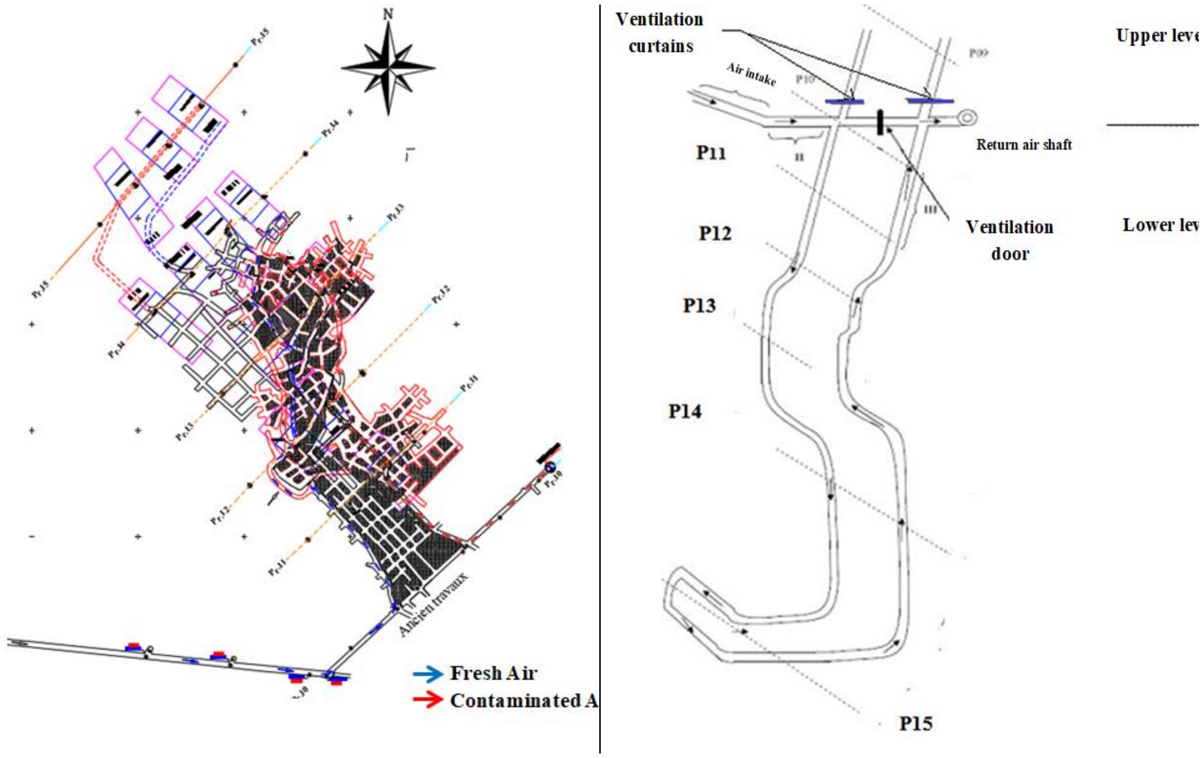


Figure.III.1. Main Ventilation of the Chaabat El Hamra mine [8]

Auxiliary ventilation (Figure III.1), is ensured by 12 secondary fans operating within a combined ventilation system. This means fresh air is pushed toward the working face, while used air is pulled out from it. Fresh air comes from Gallery No. 1 and flows over the working face. The used air is then drawn out and sent back through the same gallery. To prevent fresh

Air from mixing with used air, a partition is placed in the middle of the connecting galleries near the previous blocks [8].

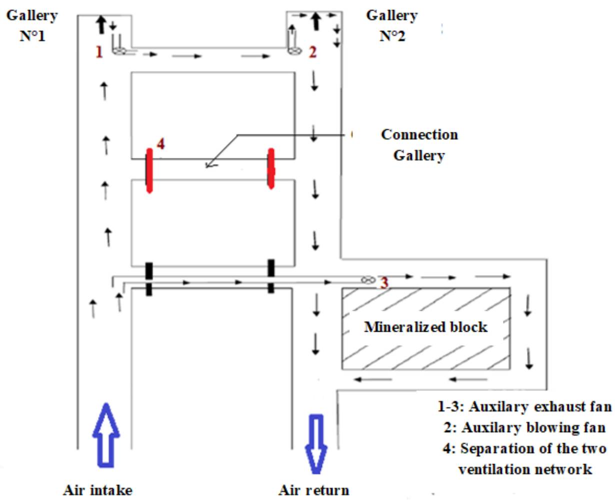


Figure III.2. Auxilary ventilation plan CEH [8]

In some parts of the mine, we noticed heavy air and poor circulation. Breathing was harder, showing that airflow is weak in those zones. This may be due to rough tunnel walls, sharp turns, narrow areas, or badly placed regulators. Trucks, and blasting also add dust and fumes, making the air worse. These issues suggest the system is unbalanced and need to be checked through airflow measurements

3. Evaluation of Air Distribution :

To better understand the ventilation problems, air measurements were taken in different parts of the mine. Two anemometers were used to measure air velocity in the mine branches, allowing results to be cross-checked for better accuracy. Temperature was also measured to assess thermal comfort and detect any abnormal heat buildup in certain areas

A propeller anemometer is a simple tool used to measure wind speed. The propeller turns when air moves through it. The air pushes the blades, making it spin. The number of spins is used to calculate the wind speed in meters per second (m/s).The temperature also can be measured.

The figure III.3, shows the anemometers used to measure air velocity in the branches of CEH Mine

Figure .III. 3Anemometers

The results of the measurement are summarized in the Table III.

Tab. III.1. Field Observations of Airflow Conditions in Mine Galleries

Branches	Air Velocity (m/s)	Temperature (°C)	S (m²)	Airflow Q (m^3/s)
FW	3.3	14.1	11.39	37.587
FZ	4.8	19.1	5.42	26.016
ZX	1.1	16	7.87	8.657
ZK	2.3	21.5	7.36	16.928
XY	2	15.2	6.36	12.72
YK	0.4	21	10.06	4.024
YO	1	16	9.49	9.49
KO	2.3	20	10.15	23.345
WX	0.7	16.7	7.66	5.362
WO	1.4	15.8	10.59	14.826

- The measured airflow in the **FW and FZ** branches is about 37.587 m³/s, 26.016 m³/s respectively indicating a high volume of air passing through.
- **ZX** and **XY**, the airflow is more moderate, about 8.657 m³/s and 12.72m³/s. Air is moving, but at a lower rate.
- **ZK** and **WO** have intermediate values, with 16.928 m³/s and 14.826 m³/s respectively.
- The **YO** branch shows a lower airflow of about 9.5 m³/s, compared to the more ventilated areas.
- **WX** and **YK** show low values, 5.362 m³/s and 4.024 m³/s respectively.
- Finally, **KO** has a relatively high airflow of 23.345 m³/s.

The Figure III.4 shows the distribution of airflows and temperature in the measured galleries.

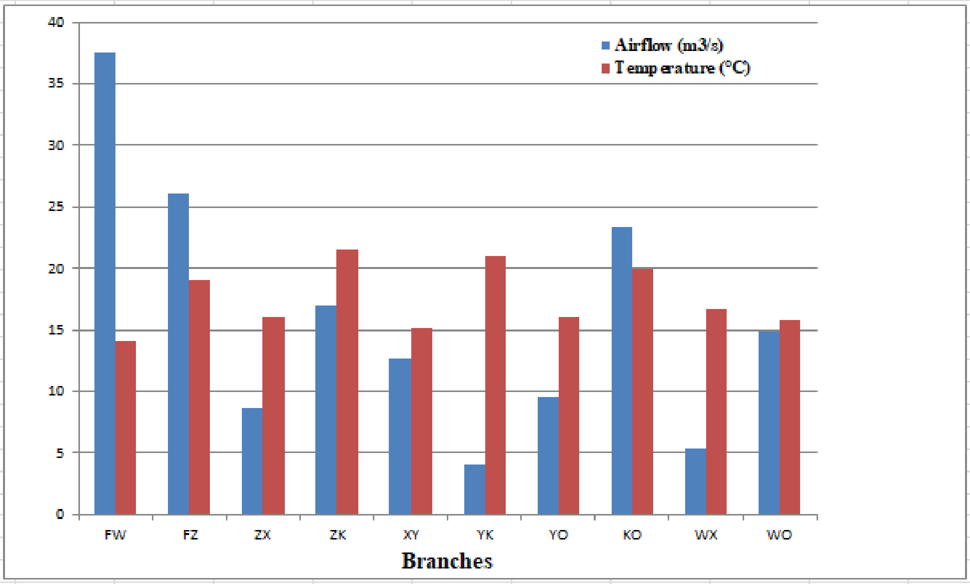


Figure .III.4. Airflow and Temperature Distribution in different Branches

The temperature varies between 14°C and 21.5°C , FZ and ZK show the highest temperatures (19.1°C – 21.5°C) , which can suggest a slower heat removal or lower airflow efficiency. Even though their airflows values are acceptable. FW and WO are cooler , indication better air renewal.

YK shows both high temperature (21°C) and a low airflow (4.024 m^3/s), this confirms the poor ventilation in that area , the air is not moving enough to remove the heat.

However, airflow rate and temperature alone are not enough to identify poorly ventilated areas. Other factors like resistance in the airway (can affect the flow. These resistances cause pressure losses (ΔP), which reduce airflow efficiency and can lead to unbalanced distribution across the network.

To identify the extent of the imbalance in the branches, basic calculations were carried out to evaluate **pressure losses,** airflow adequacy, and how ventilation is distributed between different branches. These technical indicators help confirm the field observations.

- **Calculation of Initial Resistances**

  The resistance in each branch is calculated using the McPherson formulation for fully developed turbulent airflow in irregular ducts [5]:

Where:

$$R = \frac{K.L.Per}{A^3}$$

- K: friction coefficient (kg/m^3),

- L: branch length (m),
- Per: perimeter (m),
- A: cross-sectional area (m^2)

The table below illustrates the resistance values in the mine branches.

Tab. III.2. Geometric and Resistance Characteristics

	L(m)	**K**	**Per (m)**	**S(m^2)**	**R(Ns^2/m^8)**
FW	11	0.013	13.69	11.39	0.00132485
FZ	145	0.012	8.6	5.42	0.09398312
ZX	34	0.015	11.68	7.87	0.0122205
ZK	544	0.009	9.93	7.36	0.1219431
XY	19	0.01	9.72	6.36	0.00717874
YK	64	0.231	12.61	10.06	**0.18311044**
YO	72	0.052	12.3	9.49	0.05388183
KO	341	0.052	12.83	10.15	**0.21756361**
WX	142	0.008	10.56	7.66	0.02669045
WO	245	0.019	12.88	10.59	0.05048329

YK and KO are the branches with the highest resistance values. This resistance is directly related to the **friction factor,** which depends on the condition of the galleries, like rough walls, narrow passages, or bends. These features increase resistance to airflow, making it harder for air to flow through and reducing ventilation efficiency in those areas.

– **Pressure Loss**

Each ventilation branch was analyzed with measured geometries and estimated K values. Airflow rates were imposed based on operational needs and pressure losses were computed by:

$$\Delta P = R.Q^2 \quad \text{(Pa)}$$

Where:

- ΔP: pressure loss (Pa)
- R: resistance of the airway (Ns^2/m^8)
- Q : Airflow (m^3/s)

The table III.3 summarizes the results of pressure losses for different branches:

Tab. III.3. Pressure losses

	R(Ns²/m⁸)	Q(m^3/s)	ΔP (Pa)
FW	0.00132485	37.587	0.52994196
FZ	0.09398312	26.016	84.5848044
ZX	0.0122205	8.657	1.22204957
ZK	0.1219431	16.928	48.7772381
XY	0.00717874	12.72	1.6152176
YK	0.18311044	4.024	4.57776092
YO	0.05388183	9.49	5.38818271
KO	0.21756361	23.345	**135.977255**
WX	0.02669045	5.362	0.66726132
WO	0.05048329	14.826	11.3587407

The results show that the KO branch loses more pressure than any other. This means it takes, more energy, for air to move through it. When too much energy is spent on one branch, less is left for others. That's what's happening with YK, where the airflow is weak and the temperature is higher, a clear sign that air isn't moving well in that part of the mine.

Figure III.5 represents the distribution of the pressure loss in all branches.

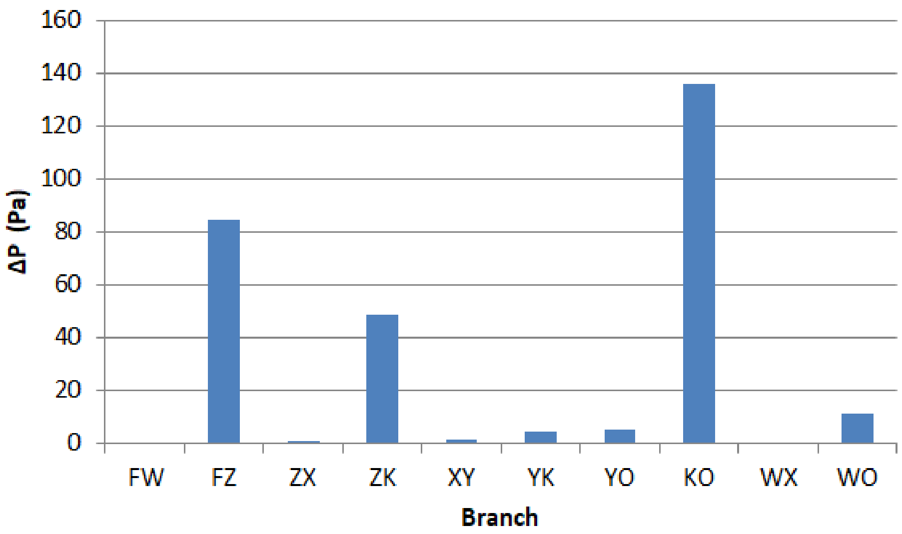
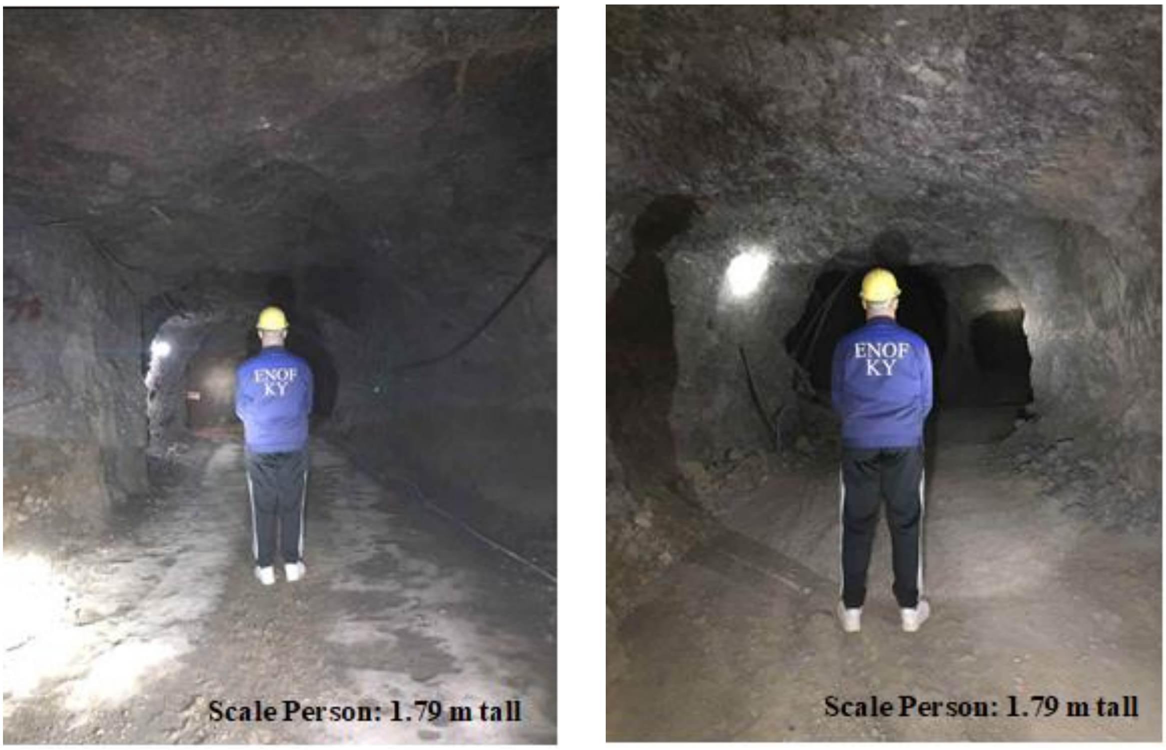


Figure. III.5. Pressure Loss distribution

This may be caused by rough walls, bends, or blockages. KO and YK clearly need attention to improve airflow and reduce energy waste , Figure III.4 illustrates the profile of KO and YK gallery.



A. Cross-Section Profile of KO Branch B. Cross-Section Profile of YK Branch

Figure. III.6. Profile Views of Underground Galleries: YK and KO Branches

On site, it was observed that both branches have not conditions to create proper air circulation. In the KO branch, part of the gallery has collapsed due to extraction activities, creating a large cavity. This cavity has reduced the airflow in that area. In addition, there are several sharp turns in this part of the mine, which act as obstacles to smooth airflow. The roughness of the tunnel walls also increases resistance, making air movement even more difficult. These factors must be taken into consideration.

4.Conclusion:

The KO branch needs a lot of pressure to move air because of high resistance and this takes pressure away from other areas, like YK, which then get less air and have poor ventilation. This makes the system unbalanced. Fixing KO branch is important to help the air move better across the whole mine.

Chapter IV

Evaluation of Proposed Solutions, Analysis, and Discussion

1.Intruduction :

This chapter explains enhancing the airflow situation of the mine network by using two levels of optimization. One is a passive optimization which consists of coating the rough surface of the branches YK and KO in order to minimize the aerodynamic resistance. This solution optimizes the system without introducing any mechanical device. The second phase, an active optimization, deals with the KO branch by introducing an auxiliary fan for load decrease in the primary system, less energy consumption, and enhanced global airflow stability. The results are quantified in terms of resistance changes, pressure drops, and ventilation power demand.

2. Passive Optimization Approach « Impact of Lining on Airflow Resistance in YK and KO » :

KO and YK segments constitute two of the most critical components of the mine ventilation system. The auxiliary supply is supplied by YK branch (64 meters), with KO (341 meters) being a primary return. Since they originally developed with minimal geometric control, both had irregular cross-sections contributing to the bulk of the loss and resistance.

As discussed in Chapter III , the lining treatment applied to both branches resulted in a reduction of resistance and pressure drop. In this section, we analyze these gains technically and evaluate their practical impact on airflow performance.

To better assess the ventilation performance of branches YK and KO, the original geometrical parameters were first analysed. The table below presents the key characteristics of both branches prior to any optimisation.

Tab.IV.1. Geometric Characteristics of YK and KO Branches Before Optimization

Branch	Length (m)	K	Perimeter (m)	Cross-sectional Area S (m²)
YK	64	0.231	12.61	10.06
KO	341	0.052	12.83	10.15

These baseline values reflect the irregular shapes and relatively limited sections resulting from uncontrolled excavation. Such configurations tend to generate higher airflow resistance and reduced ventilation efficiency

Geometric optimisation was done in order to surmount these problems. The process involved creating smooth, uniform cross-sections optimized for efficient airflow.

A modelling technique was used to simulate the new geometry. With these results, a lining was created and erected along both YK and KO.

This lining:

- Increases the effective cross-sectional area,
- Reduces shape irregularities,
- Improves velocity distribution in the flow.

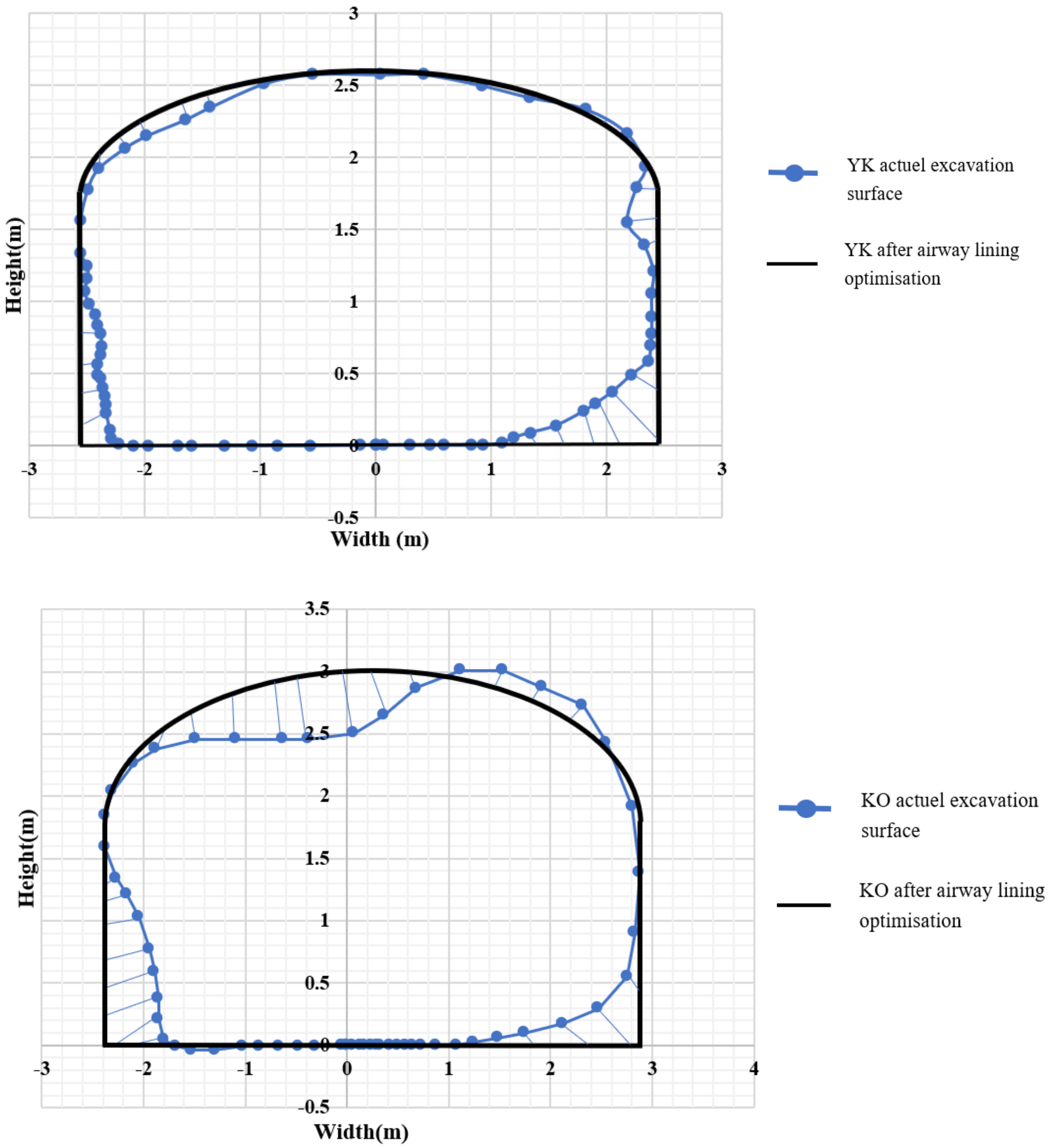


Figure.IV.1. Geometric optimisation using airway lining

The linings implemented in YK and KO branches have produced the effects quantifiable on the geometrical parameters that determine the ventilation performance. Table IV.2.is a comparison overview of the most significant parameters before and after optimisation : length (L), friction factor (K), hydraulic perimeter (Per), and cross-sectional area (S).

Tab. IV.2. Comparison of Geometric Characteristics of YK and KO Branches Before and After Lining

Branch	L (m)	K	Per (m)	S (m²)
YK	64	0.231	12.61	10.06
KO	341	0.052	12.83	10.15
YK (new)	64	0.231	15.07	11.71
KO (new)	341	0.052	14.94	12.12

Lining increased the cross-sectional area in either case by approximately 16.4% for YK and 19.4% for KO and added to the hydraulic perimeter because of smoother and more even contours. It is to be noted that the friction factor K remained unaffected because the inner surface roughness of the lining was assumed to be the same as that of the encircling walls.

This geometric increase has a direct effect on the resistance to the airflow. Since the resistance is inversely proportional to the cube of the area ($R \propto \frac{K.L.Per}{S^3}$), the increase in cross-sectional area results in the decrease in resistance on both sides.

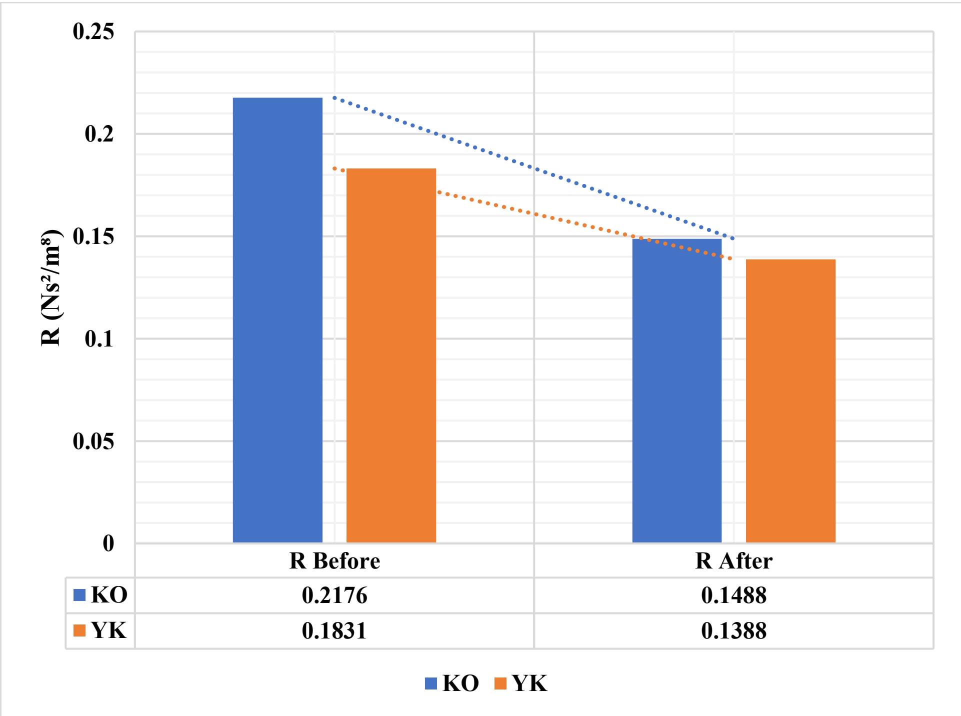


Figure.IV.2. Change in Resistance Before and After Lining

The chat in Figure IV.2 confirms this effect:

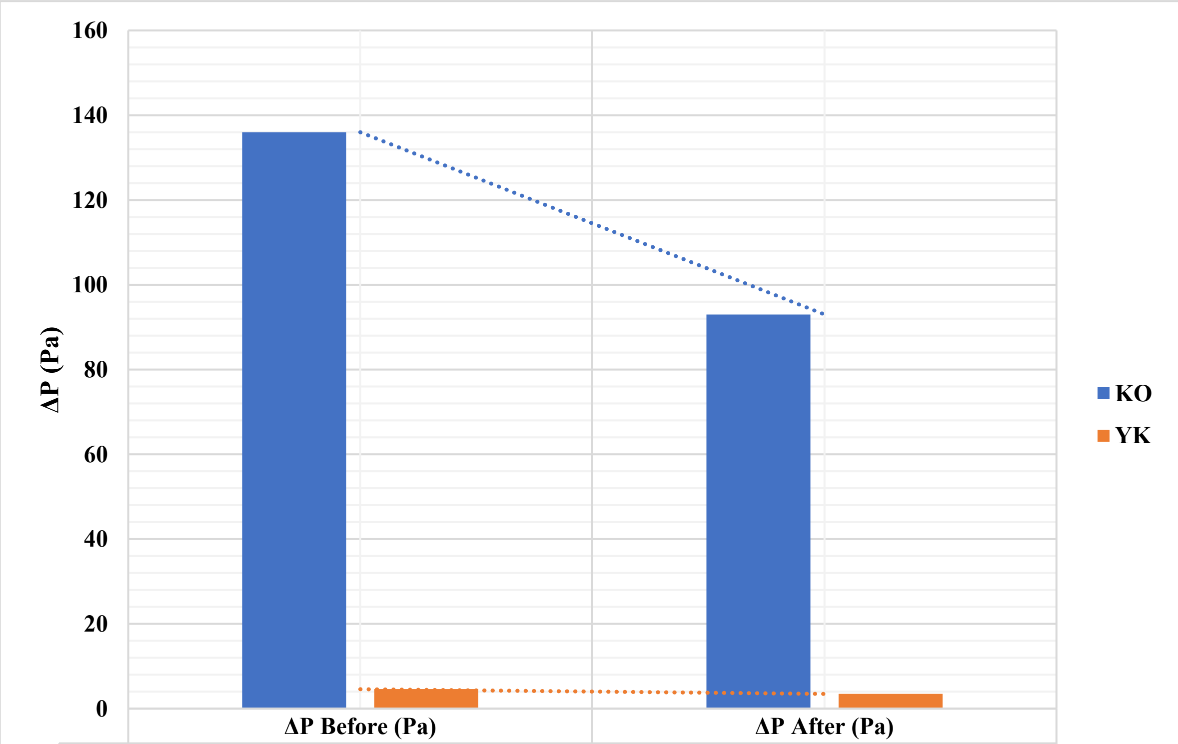
- In YK, the resistance decreased from 0.1831 to 0.1388 Ns²/m⁸.
- In KO, resistance decreased from 0.2176 to 0.1488 Ns²/m⁸.

These measurements validate the efficiency of the geometric optimisation by lining, especially in airflow loss minimisation. However, as will be explained in detail, the resulting pressure drop is still high for the KO branch from its greater length and load of flow thus indicating a requirement for an ancillary intervention.

- **Impact on Pressure Losses :**

The geometric optimisation of YK and KO branches led to measurable resistance drop, as uncovered in Chapter III. This continues to embrace the fluctuations of pressure drops occasioned thereby, which constitute the actual aerodynamic effect of the lining treatment.

As can be observed from the figure below, in both branches there occurs a drop of ΔP after optimisation. In branch YK, it occurs quite modest due to its length and low airflow. In branch KO, however, the drop is much larger: from 135.98 Pa to 93.00 Pa — 32% drop. This is a proof of the lining's function to limit energy losses.



	ΔP Before (Pa)	ΔP After (Pa)
KO	135.98	93
YK	4.58	3.47

Figure .IV.3. Pressure drop Before and After Optimization

Though this reduction has been maximized, KO still experiences the maximum pressure drop in the network. Its large flowrate and longer length still make it large losses-losses even after geometrical correction. This implies that a second optimisation must be performed and that it must be specially designed for this sensitive segment.

- **Impact of Lining on Resistance and Airflow Optimization:**

The lining of KO and YK branches was applied to smooth out rough surfaces and increase the cross-sectional area of the airways. This intervention targets two major sources of aerodynamic resistance:

a. Wall Roughness: The irregular, fractured rock surfaces previously caused turbulent airflow and frictional losses.

b. Constricted Cross-Sections: Limited area and sharp bends intensified local resistance.

The implemented lining reduced these effects by:

- Expanding the effective area: KO from 10.15 to 12.12 m^2, YK from 10.06 to 11.71 m^2.
- Reducing aerodynamic resistance: KO from 0.2176 to 0.1488 Ns^2/m^8 (↓ 31.6%), YK from 0.1831 to 0.1388 Ns^2/m^8 (↓ 24.2%).

These changes led to improved airflow behavior (less turbulence, more laminar profiles) and directly decreased the required ventilation pressure.

Figure IV.2 and IV.3 clearly show this performance gain:

- KO's pressure loss dropped from 135.98 Pa to 93.00 Pa after lining.
- This pressure reduction not only lowers energy consumption but also improves airflow uniformity throughout the mine.

This confirms that geometric optimization via lining is a practical, low-cost method to reduce resistance and enhance system efficiency.

3. Active Optimization « Integration of a Secondary Fan in KO » :

Following the geometric optimization of branches YK and KO, the airway resistance R was significantly reduced. However, due to the high rate of airflow in KO, pressure drop ΔP remained relatively high even upon lining. This residual resistance is shown in Figure .IV.3, where pressure drop for KO remains about 93 Pa even after optimization.

This level of pressure corresponds to high power load from the main ventilation system. To offset this issue and spread the load more evenly, an active optimization measure was undertaken by adding a secondary fan at branch KO specifically. This measure is not reliant on varying geometry but on offering mechanical support to reduce pressure load on the main fan.The secondary fan power design and sizing are obtained from the following equation [9]:

$$P = \frac{\Delta P . Q}{\mu}$$

where:

- P is the fan power (W),
- ΔP is the pressure difference the fan must overcome (Pa),
- Q is the volumetric airflow rate (m^3/s),
- η is the fan efficiency (dimensionless),

For the purpose of calculation in this work, a fan efficiency (η) of 70% is assumed, which is the standard for ventilation fans employed in mining activity. Under this assumption, the following calculation led to the finding of the power required by the proposed secondary fan to deliver the airflow through branch KO:

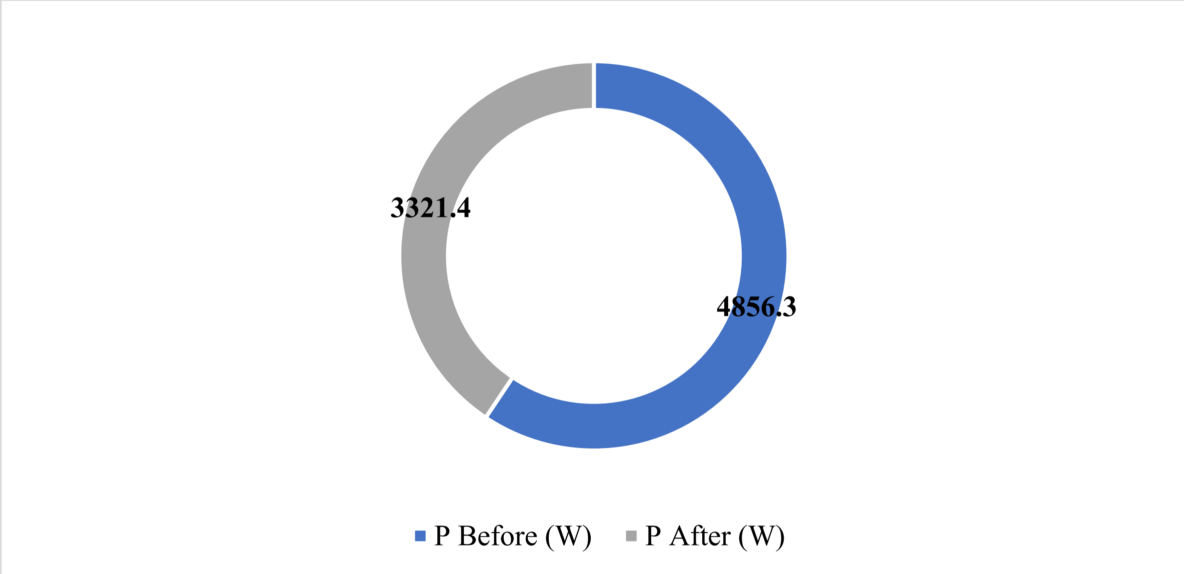
Given:

- ΔP = 93 Pa
- Q = 25 m^3/s
- η = 70% (0.7)
- Applying the equation:

$$P = \frac{93 * 25}{0.7} = 3321.4 \, Watt$$

This result means that a fan of approximately 3.32 kW rating would suffice to neutralize the local pressure loss through branch KO while achieving the required airflow. It is an energy measure to overcome resistance through the branch geometry and friction.

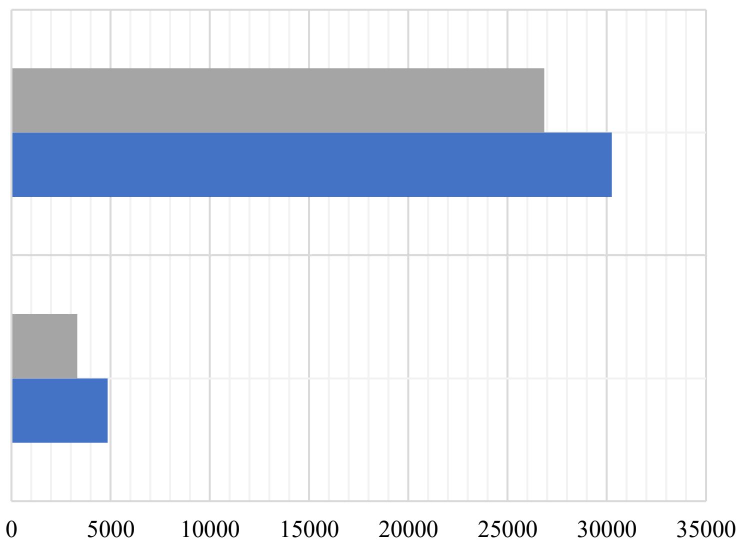
This solution is part of what is called active optimization, as it involves the addition of a mechanical device to aid the airflow, and not merely geometric improvement. The effect of this addition is illustrated in Figure.IV.3., by the reduction in power required just for the KO branch.



.**Figure.IV.4.** KO branch power before and after secondary fan installation.

As shown, the fan power demand in KO decreased from 4856.3 W to 3321.4 W after the installation of the secondary fan, a clear local energy saving of over 30%. But the benefit is not restricted to KO alone.

A broader view of the ventilation network is shown in Figure.IV.4., comparing the local as well as global power demands before and after the installation.



	KO power(w)	Total systeme power (w)
after secondary fan	3321.4	26849.68
before secondary fan	4856.3	30258.77

Figure.IV.5. Comparison of KO branch and total system power before and after secondary fan installation.

-This graph confirms that when the KO power is reduced directly, the system power is reduced considerably as well from 30,258.8 W to 26,849.7 W demonstrating the overall gain of the intervention.

-Redistribution of the pressure support allows the core system to perform better, reduces overall energy input, and facilitates more desirable conditions for airflow stability and system controllability.

-These findings verify the merits of complementing passive optimization (geometrical optimization) with active mechanisms (mechanical support), especially for long and high-resistance return limbs like KO.

4.Alignment Between Objectives and Results:

The main objectives of this thesis were:

I. Enhance the efficiency of the Chaabet El Hamra mine ventilation system,

II. Reduce energy consumption

III. Improve airflow distribution, particularly in high-resistance branches such as KO and YK.

The results presented demonstrate a clear alignment with these goals:

- The passive optimization through airway lining led to a 21% and 31.6% reduction in resistance for YK and KO branches respectively.

- This geometrical modification also resulted in a 32% drop in pressure loss for KO, indicating improved energy efficiency.

- Despite this, KO still exhibited elevated pressure demands. The introduction of a secondary fan (active optimization) further reduced local energy consumption by over 30%, and the total system power decreased from 30.2 kW to 26.8 kW.

- These quantitative outcomes validate the effectiveness of the proposed two-stage optimization strategy and support the thesis title and objectives.

In summary, the strategies applied directly addressed the initial problem of inefficient airflow and excessive energy use in the network, confirming the success of both passive and active interventions.

5.Conclusion :

Through this chapter, we explored two complementary ways of improving airflow conditions in the mine: reshaping geometry and supporting the network with mechanical aid. By lining the walls of the YK and KO branches, the airflow faced less resistance, and pressure losses were visibly reduced. Still, despite this improvement, the KO branch continued to demand a significant amount of power because of its length and high flow. That’s why a secondary fan was introduced in this area — a small change that made a big difference. The fan helped ease the load on the main system, cutting down KO’s power needs by over 30% and reducing the total system energy demand by around 3.4 kW. Overall, combining both passive and active measures proved to be an effective way to make the ventilation system more balanced and efficient.

General Conclusion:

This thesis has presented a comprehensive investigation into the optimization of the underground mine ventilation system at the Chaabet El-Hamra site, with a specific focus on reducing energy losses, improving airflow distribution, and enhancing the operational safety of the ventilation network.

The initial diagnosis of the ventilation system revealed two critical issues: high resistance and pressure loss in certain key branches (KO and YK), and an imbalanced distribution of airflow that compromised the efficiency of the main ventilation fan. Through quantitative analysis of field data, airflow measurements, and pressure loss calculations, the magnitude of the inefficiencies was identified, setting the stage for the development of a corrective strategy.

To resolve these issues, a two-level optimization framework was proposed and implemented:

1. **Passive Optimization**: By geometrically improving the cross-sections of KO and YK branches using lining, the airflow resistance was significantly reduced. The lining smoothed out irregular wall surfaces, increased the effective cross-sectional area, and improved flow behavior. This alone led to a 21–31% reduction in resistance and a 32% drop in pressure loss in KO, demonstrating the value of targeted structural improvements in reducing aerodynamic losses.

2. **Active Optimization**: Despite the success of passive measures, KO remained a high-demand branch due to its length and high airflow. An auxiliary fan was therefore installed to provide localized mechanical support. This intervention decreased the local power requirement by over 30% and reduced the total system energy consumption by approximately 3.4 kW. The load on the main fan was eased, leading to a more stable and efficient ventilation system.

The results confirm that a combined passive-active approach is highly effective for improving underground ventilation performance. Beyond the technical outcomes, this approach also has economic and environmental benefits, such as lower electricity bills, extended equipment lifespan, and reduced carbon footprint.

Looking ahead, future work could build on these findings by integrating **real-time airflow monitoring**, **smart control algorithms**, and **computational fluid dynamics (CFD)** simulations to create adaptive ventilation systems. These systems would not only respond dynamically to operational changes but also allow predictive maintenance and energy optimization on a continuous basis.

In conclusion, this research demonstrates that mine ventilation can be significantly improved through data-informed structural and mechanical interventions, ultimately contributing to safer, more efficient, and more sustainable underground mining operations

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