



Thermoenvironmental Simulation in Underground Works Using Mechanical Ventilation Using Three Turbulence Closure Models in CFD

Baltazar Vera, J. C., Vizguerra Morales, P., De Jesús Rodríguez Rodríguez, C., Valtierra Olivares, J. E., López Mejía, R. I., Salazar Pedroza, H. G., Ontiveros Ibarra, R., Solís Rodríguez, R., Zamorategui Molina, A., Vázquez Rodríguez, G. y Abraham Juárez, M. del R. (2026). Thermoenvironmental Simulation in Underground Works Using Mechanical Ventilation Using Three Turbulence Closure Models in CFD [*Postprint*]. CIENCIA *ergo-sum*, 33. <https://doi.org/10.30878/ces.v32n0a58>

Sección: Ciencias Exactas y Aplicadas

Universidad Autónoma del Estado de México, México

Esta obra está bajo una Licencia Creative Commons Atribución-NoComercial-SinDerivar 4.0 Internacional.



Esta versión del artículo es una “versión final del autor” que fue aceptada por un proceso de **evaluación por pares ciegos**. Este documento diferirá en formato respecto a la “versión del editor”, la cual se someterá a un proceso de corrección de estilo y de diseño editorial. De ninguna forma se modificará el contenido. Todas las ideas que se presentan son responsabilidad del autor.

Thermoenvironmental Simulation in Underground Works Using Mechanical Ventilation Using Three Turbulence Closure Models in CFD

Simulación termoambiental en obra subterránea mediante ventilación mecánica mediante tres modelos de cierre de turbulencia en CFD

Juan Carlos Baltazar Vera, Universidad de Guanajuato, México

Correo electrónico: jc.baltazarvera@ugto.mx

ORCID: <https://orcid.org/0000-0001-5747-0052>

Pablo Vizguerra Morales, Universidad de Guanajuato, México.

Correo electrónico: p.vizguerramoraes@ugto.mx

ORCID: <https://orcid.org/0000-0002-4610-9648>

Carolina de Jesús Rodríguez Rodríguez, Universidad de Guanajuato, México.

Correo electrónico: carolina.rodriguez@ugto.mx

ORCID: <https://orcid.org/0000-0001-7482-4860>

Joel Everardo Valtierra Olivares, Universidad de Guanajuato, México.

Correo electrónico: valtierra.je@ugto.mx

ORCID: <https://orcid.org/0009-0001-2787-9911>

Rosa Isela López Mejía, Universidad de Guanajuato, México.

Correo electrónico: rosa26@live.com.mx

ORCID: <https://orcid.org/0009-0006-9571-2810>

Héctor Gabriel Salazar Pedroza, Universidad de Guanajuato, México.

Correo electrónico: hg.salazar@ugto.mx

ORCID: <https://orcid.org/0009-0000-0253-4215>

Roberto Ontiveros Ibarra, Universidad de Guanajuato, México.

Correo electrónico: rontiver@ugto.mx

ORCID: <https://orcid.org/0009-0007-5183-8013>

Ricardo Solís Rodríguez, Universidad de Guanajuato, México.

Correo electrónico: solis.r@ugto.mx

ORCID: <https://orcid.org/0000-0001-7208-6454>

Adrian Zamorategui Molina, Universidad de Guanajuato, México.

Correo electrónico: zamorategui@ugto.mx

ORCID: <https://orcid.org/0000-0002-1038-6635>

Guadalupe Vázquez Rodríguez, Universidad de Guanajuato, México.

Correo electrónico: vazquez.g@ugto.mx

ORCID: <https://orcid.org/0000-0002-3560-0909>

Ma. Del Rosario Abraham Juárez, Universidad de Guanajuato, México.

Correo electrónico: mabraham@ugto.mx

ORCID: <https://orcid.org/0000-0002-4630-7900>

Recepción: 18 de septiembre de 2024

Aprobación: 2 de julio de 2025

RESUMEN

Se realizó la simulación de las condiciones termo-ambientales de una obra subterránea con y sin sistema de ventilación con la finalidad de dilucidar si existe diferencias significativas entre los modelos utilizados. Los resultados muestran que la temperatura y humedad relativa en obra sin ventilación van de 304 °K a 307 °K y 82.9 % a 85 % respectivamente; para los casos con ventilación se obtienen resultados de temperatura y humedad relativa que van de 296°K a 303°K y 57.5% a 80% respectivamente, así mismo se realizó un análisis estadístico que indicó que no existe diferencia

significativa entre los resultados obtenidos siendo indicativo de la homogeneidad de estos modelos para simular el fenómeno de interés.

PALABRAS CLAVE: sistema de ventilación, mina subterránea, modelo de turbulencia, estudio comparativo.

ABSTRACT

A simulation of the thermo-environmental conditions of an underground work with and without a ventilation system was carried out in order to determine whether there are significant differences between the models used. The results show that the temperature and relative humidity in the work without ventilation range from 304 °K to 307 °K and 82.9% to 85% respectively; for the cases with ventilation, temperature and relative humidity results are obtained ranging from 296°K to 303°K and 57.5% to 80% respectively. A statistical analysis was also carried out which indicated that there is no significant difference between the results obtained, which is indicative of the homogeneity of these models to simulate the phenomenon of interest.

KEYWORDS: ventilation system, underground mine, models of turbulence, comparative study.

INTRODUCCIÓN

The human being is considerably sensitive to changes in temperature and humidity in the environment (Yana et al., 2017:2), this is because thermal environmental conditions are uncomfortable for workers in conditions above 30 ° C and a relative humidity above 80% (Meiling et al., 2017:768). These conditions generate situations of high stress in the human being which can lead to mental and physical wear (Mullins and White, 2019:2; Ropo et al., 2019:2-4).

In underground mines, the main function of ventilation is to provide enough air for human consumption, as well as to dilute and subsequently extract toxic and harmful gases to humans, this through a constant flow of air circulating through underground mining works developed for this activity (Wey et al., 2011:1371-1373). The implementation of mechanical ventilation is due to the deficiency of the natural ventilation circuit, so the use of extractors or injectors is implemented to force the ventilation circuit, reducing the amount of harmful gases produced by the different activities that are carried out inside the mine and improving its thermo-environmental conditions, in this sense an adequate ventilation system is essential to regulate the climate, and ensure an adequate operating work environment (Wey et al., 2009:355-358; Quiceno and Molina, 2011:73-74). Currently the technology in relation to

ventilation systems has been evolving through the improvement of both injection and extraction fans (Quevedo, 2013:27-70). Ventilation systems there are two aspects that must be considered to achieve good ventilation, (1) air losses and (2) supply and control of the amount of air (Ontiveros et al., 2006:174-178). To determine the amount of air that must be fed to a ventilation system, in Mexico the requirements indicated in the Official Mexican Standard NOM-121-STPS-1996 are used (Normas Oficiales Mexicanas STPS, 1996:1-34).

When an underground mine is in operation, two cases of ventilation should be considered: Ventilation after blasting and Ventilation during work in the mine. The first case corresponds to the ventilation that is carried out after carrying out a blasting in which toxic gases remaining from the explosion must be extracted and supply the adequate air to provide an adequate working environment for the personnel that later worked in the extraction of the mineral. The second case corresponds to the ventilation that must be made when the personnel is inside the mine in extraccion jobs, in this case the main gases to be extracted are the emission gases from the diesel equipment used for this task. An important aspect in terms of safety for the underground mine worker refers to the thermo-environmental conditions (temperature and humidity), according to this the Official Mexican Standard NOM-015-STPS-2001, which indicates that the maximum temperature that the work area must have must be between 10 °C and 37 °C. and the humidity percentage should be from 20% to 90%, this for the safety of the workers and not putting their lives at risk (Normas Oficiales Mexicanas STPS, 2001:1-16).

Computational fluid dynamics is a type of computational analysis to simulate the movement of fluids and, on occasions, other associated phenomena: heat transfer, chemical reactions, entrainment of solids, etc. This method has been used by various engineering professionals to solve theoretical and practical problems in the investigation of phenomena not yet fully understood (Rodríguez, 2010:27-40). This discipline has become very important among current engineering methods thanks to softwares, which since the last decade have been essential for solving problems by executing the required calculations and simulating the interaction of liquids and gases with surfaces defined by boundary conditions of each problem (Tennekes and Lumley, 1994:1).

Currently developing models that simulate the effect produced by various ventilation systems

are widely attractive tool (López , 2018: 5-20; Launder and Spalding, 1972:1-10; Torano et al., 2011: 201-210); In this work, a CFD simulation is developed using three turbulence closure models applied to a mono-extraction ventilation system in an underground mine in front work, elucidating the effect on temperature and relative humidity. In this sense, in a previous work, the effect of combustion gases on the system was analyzed (López, 2018).

1. MATERIAL AND METHODS

1. 1. Approach of the mathematical models for the simulation corresponding to the monoextractive ventilation system in underground mine during work in front

In this paper we report the simulation results corresponding to temperature and percentage of relative humidity for a monoextractive ventilation system in underground mine during work in front using three models of turbulence closure making a comparison between these. The simulation was carried out using software Computational Fluid Dynamics (CFD) Fluent™ of ANSYS which allows to simulate process parameters such as: The distribution of air flow velocity, temperatures in various areas of the mine site among others (Gelves and Benavides, 2012: 1192-1202; Anicode and Madenci, 2021:1-5; López et al., 2015: 88-95). A computer with 8 GB RAM and an AMD A 8 processor was used.

1. 2. Turbulence closure models

To carry out the study, the models were used: Standard (Wilcox, 1998: 1-522; Fluent Inc, 2006:1-44; Zeng et al., 2019: 167-184); k-kl-omega (ANSYS, 2009: 1; Wang et al., 2022:5-10; Lorini et al., 2021: 1-9) and Reynolds Stress (Sarkar and Lakshmanan, 1991: 743; Parekh et al., 2018:231-245).

Standard model.

This model is within the class of turbulence models and is one of the main tools in the calculation of mass and energy transfer phenomena for engineering, it is very useful for flow simulation, this is due to its robustness, economy, reasonable accuracy. The governing equations of this model are:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + G_{\varepsilon k} (G_k + C_{3\tau} G_b) - C_{3\tau} \rho \frac{\varepsilon^2}{k} + S_\tau \quad (2)$$

Where turbulent kinetic energy is k and its reason for dissipation ε ; G_k represents the generation of kinetic turbulence due to the average velocity gradients, G_b is the generation of turbulent kinetic energy due to buoyant forces, Y_M represents the contribution of fluctuating dilation in compressible turbulence to the dissipation rate Global, $C_{1\varepsilon}$, $C_{2\varepsilon}$ y $C_{3\varepsilon}$ are constant, σ_k y σ_ε are the turbulent Prandtl numbers for k y ε respectively, S_k and S_ε are source terms.

k-kl-omega model.

The k-kl-omega model is considered a type of Eddy viscosity, which includes transport parameters for turbulent kinetic energy (k_T), laminar kinetic energy (k_L) and the turbulent reverse time scale (ω), R and R_{NAT} represent bypass and natural transition, respectively, D_t represent the anisotropic dissipation term for k_T , Pk_T and Pk_L are the production of turbulent and laminar kinetic energy by mean strain. This method is used mainly for problems in which the fluid passes from laminar to turbulent regime at some point within the control volume (Keith and Colkjat, 2008:1-14) the equations that govern this model are:

$$\frac{Dk_T}{Dt} = Pk_T + R + R_{NAT} - \omega k_T - D_T + \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\alpha T}{\alpha k} \right) \frac{\partial k_T}{\partial x_j} \right] \quad (3)$$

$$\frac{Dk_L}{Dt} = Pk_L + R + R_{NAT} - D_T + \frac{\partial}{\partial x_j} \left(\nu \frac{\partial k_L}{\partial x_j} \right) \quad (4)$$

Reynolds Stress model.

The Reynolds Stress model can be used to solve problems related to the following types of flow:

- a) Flows with sudden changes in the average deformation rate.
- b) Flow with a strong aerodynamic curvature.

Reynolds Stress models have shown superior performance compared to viscosity models. These models are characterized by a greater degree of universality (it is a high degree of

complexity in the resulting mathematical system); the equations that govern this model are:

Reynolds Stress Transport Equation

$$\frac{DR_{ij}}{Dt} = D_{ij} + P_{ij} + \Pi_{ij} - \Omega_{ij} - \varepsilon_{ij} \quad (5)$$

Where DR_{ij} is rate of change of R_{ij} , P_{ij} represents the production term, Π_{ij} corresponds to pressure strain correlation, Ω_{ij} is rotational term and ε_{ij} is the term of dissipation. The elements of this equation are described below:

$$D_{ij} = \text{div} \left(\frac{v_t}{\sigma_k} \nabla R_{ij} \right) \quad (6)$$

The modelling of diffusion term (D_{ij}) assumes that the rate of transport of Reynolds stresses by diffusion is proportional to the gradients of Reynolds stresses. This is an application of the concept of the gradient diffusion hypothesis to modeling the effect of spatial redistribution of the Reynolds stresses due to the fluctuating velocity field; where:

$$v_t = C_\mu \frac{k^2}{\varepsilon}, \sigma_k = 1.0, C_\mu = 0.9 ; \varepsilon \text{ represents dissipation rate of turbulent kinetic energy.}$$

$$P_{ij} = \left(R_{im} \frac{\partial u_j}{\partial x_m} + R_{jm} \frac{\partial u_i}{\partial x_m} \right)_{ij} \quad (7)$$

Physically, the Production term represents the action of the mean velocity gradients working against the Reynolds stresses. This accounts for the transfer of kinetic energy from the mean flow to the fluctuating velocity field. It is responsible for sustaining the turbulence in the flow through this transfer of energy from the large scale mean motions to the small-scale fluctuating motions.

$$\frac{\Pi_{ij}}{k} = C_2 S_{ij} + C_3 (b_{ik} S_{jk} + b_{jk} S_{ik} - \frac{2}{3} b_{mn} S_{mn} \delta_{ij}) + C_4 (b_{ik} W_{jk} + b_{jk} W_{ik}) \quad (8)$$

Where b_{ij} is the Reynolds stress anisotropy tensor; S_{ij} is the rate of strain term for the mean velocity field; W_{ij} is the rate of rotation term for the mean velocity field. C_2, C_3, C_4 are the coefficients of the rapid pressure strain correlation model (Versteeg and Malalasekera, 2013: 20-50).

$$\Omega_{ij} = -2\omega_k(R_{jm}e_{ikm} + R_{im}e_{jkm}) \quad (9)$$

Where ω_k is the rotation vector; $e_{ijk}=1$ if i,j,k are in cyclic order and are different, $e_{ijk}=-1$ if i,j,k are in anti-cyclic order and are different and $e_{ijk}=0$ in case any two indices are same.

$$\varepsilon_{ij} = \frac{2}{3}\varepsilon\delta_{ij} \quad (10)$$

Where $\delta_{ij}=1$ when $i=j$ and 0 when $i \neq j$ (Bernard and Wallace, 2002: 324).

The greater number of transport equations leads to reduced numerical robustness, which requires a greater calculation effort. In this sense, the Generalized forms of the effective viscosity / Prandtl number was used as a heat transfer model:

$$Pr_t = \frac{(\gamma_t\mu_t + \gamma_{TU}\mu_{TU})}{(k_m/cp)_t} \quad (11)$$

Where, μ denotes the viscosity; Pr , the Prandtl number; γ , the intermittency factor varying from 0 to 1; k_m , the thermal conductivity and cp , the specific heat; the subscripts 't' and 'TU' is for evaluating under the turbulent and freestream turbulence conditions, respectively.

General Boussinesq Equation.

To analyze the buoyancy effect, the Boussinesq general equation was used, which is as follows:

$$\rho \left(\frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla p + \nabla \cdot (\nabla \mu + (\nabla u)^T) - \frac{2}{3}\mu(\nabla \cdot u)I + \rho g \quad (12)$$

For constant density:

$$\rho_0 \left(\frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla p + \mu \nabla^2 u + \rho g \quad (13)$$

$$\rho_0 \left(\frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla p + \mu \nabla^2 u + \rho g + (\rho_0 + \Delta\rho)g \quad (14)$$

For the ideal gas:

$$\beta = 1/T_0 \quad (15)$$

$$(\rho - \rho_0)g = -\rho_0\beta(T - T_0)g \quad (16)$$

$$\rho_0 \left(\frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla p + \mu \nabla^2 u + \rho_0 g - \rho_0 (T - T_0)/T_0 g \quad (17)$$

1.3 Calculation of requirements and design parameters of the ventilation system.

CFD simulation analysis of a ventilation system was carried out using an extractor and a burner that supplies air contaminated with monoxide and carbon dioxide inside the underground mine with dimensions of 7m X 7m and a length of 150 m this to be able to control the design, as well as the different factors that intervene in the ventilation circuit (temperature, pressure, speed, etc.). Based on what is established by the Official Mexican Norm NOM-121-STPS-1996, which establishes that the ventilation requirement for personnel working inside the mine is 1.5 m³/min per person and having a team of 8 people working we have that the necessary flow per number of people is 12 m³/min. For the calculation of air flow, the NOM-121-STPS-1996 indicates that the adequate amount is 2.13 m³/min per HP, in this case a scoop and a charge truck with a power between them of 687.95 HP were considered, therefore an air flow of 1465.33 m³/min is required. An adjustment is made in the amount of air required by personnel considering the height of the mine (2012 meters above sea level), leaving the flow at 16.8 m³/min, adding this value to the air requirement by equipment, there is a requirement of 1482.13 m³/min. For the calculation of the final flow the formula will be used.

$$Qf = Qt \left(1 - \frac{F}{100} \right)^{-\left(\frac{L}{100} \right)} \quad (18)$$

Where Qt = Air requirement for the number of personnel and diesel combustion equipment, F = Leakage factor, L = Equivalent length of mine. For this case study L = 217.97m and F = 1 therefore Qf = 25.2 m³/s. The pressure loss of an auxiliary ventilation circuit can be divided into friction losses, singular losses and dynamic pressure losses, the friction pressure loss is calculated as follows:

$$P = \frac{KCLQf^2}{A^3} \quad (19)$$

Where: P = Pressure drop, K = Friction factor of the pipe, C = Perimeter of the duct, A = Area of the duct. For this case K = 2x10⁻⁹, C = 3.14m and A = 0.785m. Therefore P = 6.7 x10⁵ Pa (Quevedo, 2013:27-70). The dynamic pressure loss is calculated by the expression:

$$\Delta P_{din} = \frac{\rho U^2}{2g} \quad (20)$$

Where: ΔP_{din} = Air pressure drop, ρ = Air density, U = Air velocity in the duct, g = gravity. For this case study, $\rho = 1.22 \text{ Kg/m}^3$ and $U = 31.79 \text{ m/s}$, a value of $\Delta P_{din} = 62.84 \text{ Pa}$ is obtained (Quevedo, 2013:27-70). The pressure drop due to singular losses is calculated as follows:

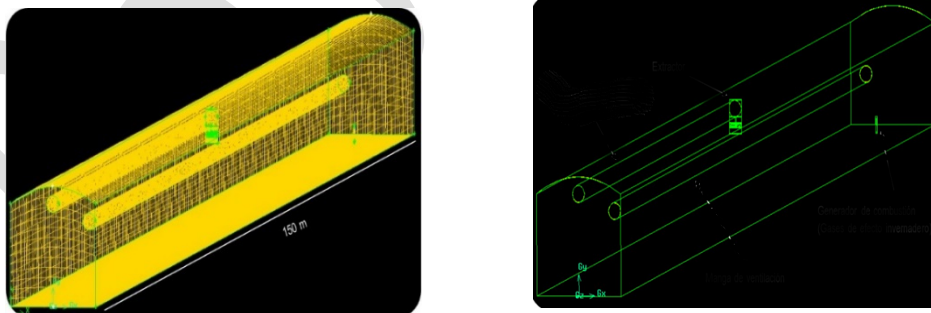
$$\Delta P_{sin} = \varepsilon \Delta P_{din} \quad (21)$$

Where: ε = loss coefficient of the element, therefore $\Delta P_{sin} = 1.07 \times 10^4 \text{ Pa}$ (Quevedo, 2013:27-70). Finally, the total pressure of the system must overcome all losses, so the final pressure (P_f) is equal to the sum of all the pressure drops calculated having $P_f = 7 \times 10^5 \text{ Pa}$.

1. 4 Generation of the geometric element and mesh for the simulation process.

For the elaboration of the mesh and its components, hexahedral mesh units with a grid size of 0.05 m and a spacing of 0.001 were used using the Gambit 2.4.6 program (Figure 1a and 1b), which have been used in the cases in which the models used in this case study have been worked with (Aghaei *et al.*, 2008: 657-665; Safaeil *et al.*, 2011: 4826-4838; Slack *et al.*, 2000:1098-1104).

Figure 1
(a) Mine work mesh (b) Scheme of mine work

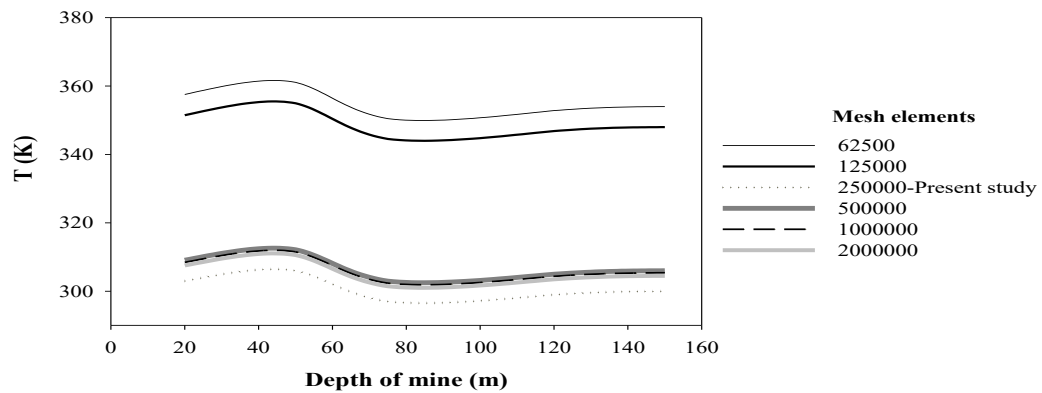


Source: own elaboration

As recommended by some authors, the mesh quality test was performed by increasing the number of cells by a factor of 2, testing a total of 6 cases (Buwa *et al.*, 2006: 2815-2822; Ameur. 2016: 572-580; Ituna *et al.*, 2017:1063-1078) for each of the models. Figure 2 shows the mesh test for the standard model; Initially, when going from a mesh of 62,500 to 125,000 cells, the temperature presented a variation of approximately 18%. Later, when increasing

the number of cells from 125,000 to 250,000, the variation was 16%; Likewise, when increasing the number of cells to 500,000, the variation was approximately 2%; consequently, increasing the number of cells to 1,000,000 showed a difference of around 1.6%; Finally, for the case in which the number of cells was increased to 2,000,000, a difference of 1.5% was obtained.

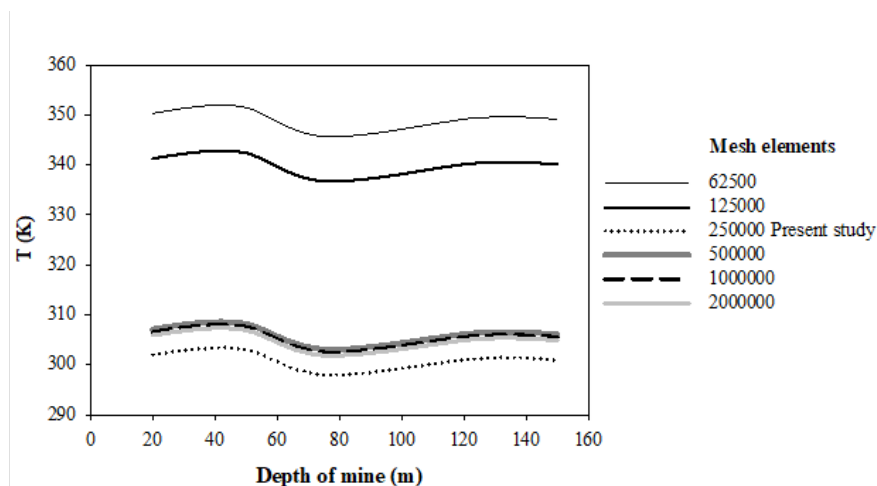
Figure 2
Mesh independence analysis for the standard model



Source: own elaboration

Following the same methodology as in the previous case, the mesh test using the k-kl-omega model (Figure 3) shows that when going from 62,500 to 125,000 cells the temperature presents a variation of 16%, when increasing to 250,000 cells the variation was 13 %; In this sense, when increasing to 500,000 cells there is a difference of 1.7%, likewise when reaching 1,000,000 the variation is 1.5%, finally, having 2,000,000 cells, the difference was 1.3%.

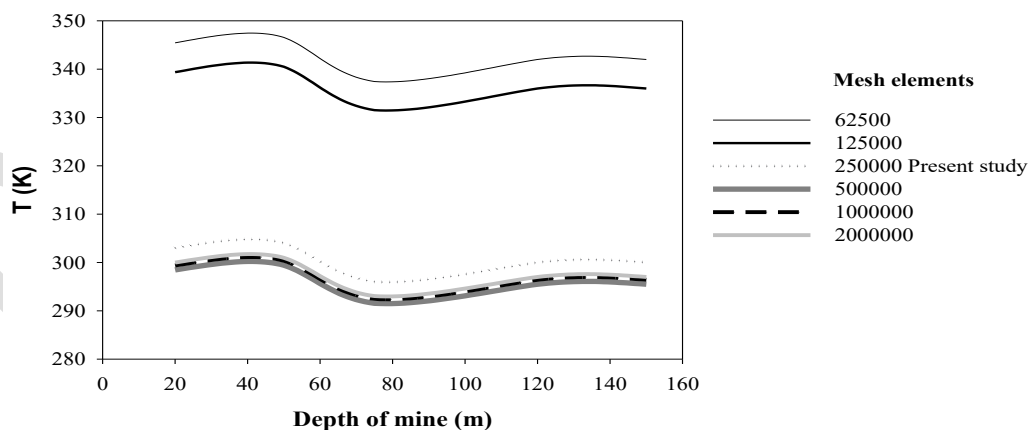
Figure 3
Mesh independence analysis for the k-kl-omega



Source: own elaboration

Regarding the Reynolds Stress model, the mesh test (Figure 4) indicates that when going from 62,500 to 125,000 cells the temperature presents a variation of 14%, when increasing to 250,000 cells the variation was 12%; Likewise, when increasing to 500,000 cells there is a difference of 1.5%, in this sense when reaching 1,000,000 the variation is 1.2%, finally, having 2,000,000 cells the difference was 1.3%.

Figure 4
Mesh independence analysis for the Reynolds Stress model



Source: own elaboration

These results indicate that for the three models analyzed from 250,000 cells, the difference of the results when varying them is minimal, which allows making the decision to use the mesh with 250,000 cells to reduce the computation time required. Mesh Check is shown in Table 1a; likewise, Table 1b shows Mesh characteristics of the geometric model having a minimum orthogonal quality of 1.58934×10^{-1} , a maximum ortho skew of 7.15666×10^{-1} and

a maximum aspect ratio of 16.4171 (Kwon and Ames. 1995: 10-20).

Postprint

Table 1a
Mesh check and mesh size

Domain Extents	Max (m)	Min (m)
x-coordinate	-3.500000	3.500000
y-coordinate	$-4.592274 \times 10^{-18}$	6.995084
z-coordinate	-1.500000×10^{-2}	0.000000
Volume statistics	Max (m ³)	Min (m ³)
	1.427818×10^{-1}	2.190201×10^{-8}
Total volume (m³)	7.143654×10^3	
Face area statistics	Max (m ²)	Min (m ²)
	2.914632×10^{-1}	1.208070×10^{-5}
Level	0	
Cells	249543	
Faces	589545	
Nodes	110986	
Partitions	5	
Cell zones	6	
Face zones	23	

Source: own elaboration

Table 1b
Mesh characteristics of the geometric model

Item	Size
Nodes	224985
Elements	250000
Orthogonality	
Minimum	0.3722
Maximum	0.9996
Skewness	
Minimum	0.0016
Maximum	0.7915

Source: own elaboration

Tables 2 and 3 show the boundary conditions and combustion mixture properties respectively according to the presented case study.

Table 2
Boundary conditions

Boundary Condition	Type of condition	Parameter value	Temperature
Fresh air	Velocity inlet	16.82 m/s	298 K
Air burner	Velocity inlet	0.5 m/s	300 K
Indoor gases	Inside	Interior	-
Diesel	Velocity inlet	80 m/s	333 K
Extractor outlet	Pressure outlet	20000 Pa	320 K
Mine entrance	Outlet pressure	0	298 K
Right wall	Inlet flow rate	0.51m/s	322 K
Left wall	Wall	stationary wall	320 K
Ceiling	Wall	stationary wall	325 K
Floor	Wall	stationary wall	330 K
Mine front	Wall	stationary wall	340 K
Fresh air duct	Wall	stationary wall	335 K
Exhaust gas duct	Wall	stationary wall	340 K

Source: own elaboration

Table 3. Combustion mixture properties

Property	Values
Density	Incompressible Ideal Gas
Cp(J/KgK)	1000
Thermal conductivity (W/m-K)	0.0454
Viscosity (Kg/m-s)	1.72×10^{-5}
Mass diffusivity (m ² /s)	2.88×10^{-5}
Properties of air	
Density (Kg/m ³)	1.22
Cp(J/Kg K)	1006.46
Thermal conductivity (W/m-K)	0.0242
Viscosity (Kg/m-s)	1.79×10^{-5}
Molecular weight (Kg/Kgmol)	28.96
Standard state enthalpy (J/Kgmol)	0
Reference temperature (K)	298
Properties of the sterile material	

Density (Kg/m ³)	2100
Cp(J/Kg K)	871
Thermal conductivity (W/m-K)	202

Source: own elaboration

For the simulation, a transient state is considered using decoupled equations in relation to the segregated pressure in a three-dimensional geometry. The models described above were used, using the standard wall functions with a simulation time of 500 seconds. The simulation process was carried out iteratively until the convergence criterion was met, which corresponds to a difference less than or equal to 0.001 and for the energy parameter less than 1×10^{-6} (Table 4).

Table 4
Convergence criteria

Equations	Absolute criterio
Continuity	0.001
x-velocity	0.001
y-velocity	0.001
z-velocity	0.001
Energy	1.00×10^{-6}
K	0.001
Epsilon	0.001
C ₁₀ H ₂₂	0.001
O ₂	0.001
CO ₂	0.001
H ₂ O	0.001

Source: own elaboration

2. RESULTS

2. 1. Simulation of the thermo-environmental conditions of the underground mine work without ventilation system

The results of the simulation corresponding to the thermo-environmental conditions of the underground mine work without implementation of the ventilation system are presented below. Figure 5 shows the temperature profile corresponding to this case study, in which it can be seen that at a position between 20m and 50m with respect to the entrance of the work the temperature increases linearly between $304^{\circ} \text{K} \leq T \leq 309^{\circ} \text{K}$, then the increase decreases between the 50m and 75m positions, standing around $309^{\circ} \text{K} \leq T \leq 310^{\circ} \text{K}$, a new linear

increment of $310^{\circ}\text{K} \leq T \leq 313^{\circ}\text{K}$ occurs between the positions 75m and 120m and finally at the position of 150m maintaining a temperature of 313°K . The temperature contour corresponding to this case study (Figure 6), presents a homogeneous distribution through the underground work, in this sense the temperature presents an increase that goes from the entrance of the work to the front; likewise, the contour coincides with the temperature profile. As it can be observed, the temperature exceeds 303°K , so according to NOM-015-STPS-2001, 75% recovery time is required for every 25% of working time for each hour in these conditions, which affects severely the worker's health as well as the productivity of the mining process.

Figure 5
Underground mine work temperature profile without ventilation system

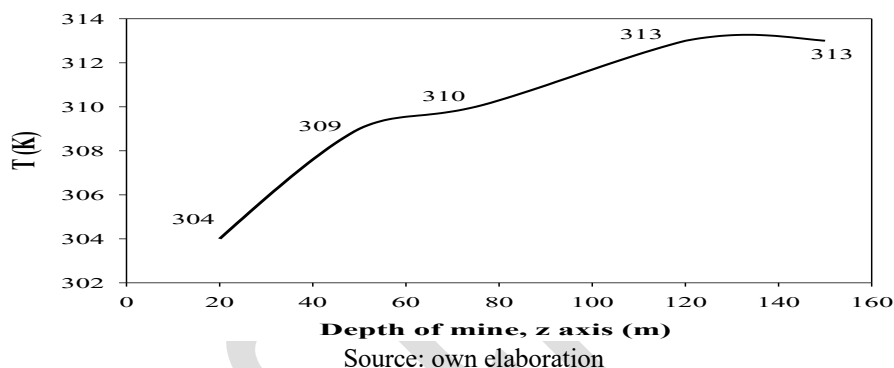


Figure 6
Temperature contour of underground mine work without ventilation system

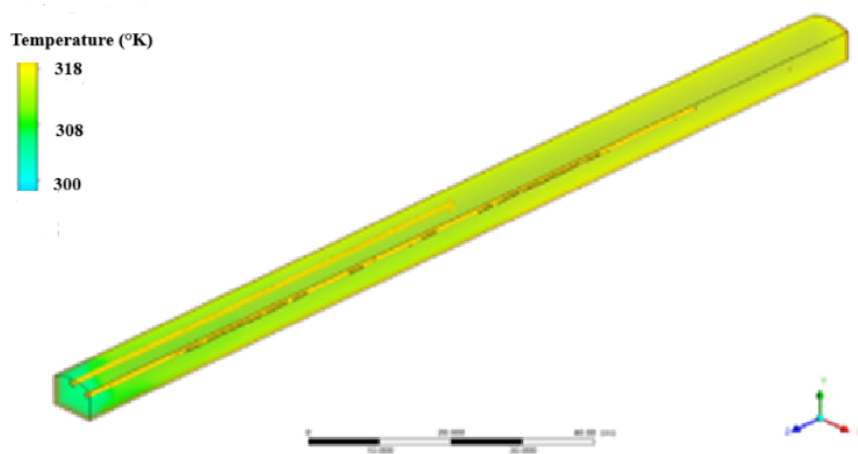


Figure 7 shows the humidity relative profile corresponding to this case study, in which it can be seen that at a position between 20 m and 50 m with respect to the entrance of the work, the humidity relative increases linearly between $82.9 \leq \% \text{ Humidity} \leq 84.5$, subsequently the increase decreases considerably between the 50 m and 75 m positions, standing around $84.5 \leq \% \text{ Humidity} \leq 84.7$, a new linear increment of $84.7 \leq \% \text{ Humidity} \leq 85.0$ is given between the positions 75 m and 120 m and finally at the position of 150m maintain a 85% humidity. The humidity relative contour corresponding to this case study (Figure 8) shows a homogeneity around 83% and 85% which coincides with the humidity relative profile that registers the highest humidity relative at the front of the mine. These humidity relative values in combination with the reported temperatures generate risk conditions and work stress for the worker, which is a risk factor for their health and an important parameter in the reduction of efficiency in mining production. The results show that the equations involved in the mathematical model used behave in a way consistent with the physical phenomenon that it can be inferred that this simulation is appropriate for this case study.

Figure 7
Profile of humidity relative of underground mine moisture without ventilation system

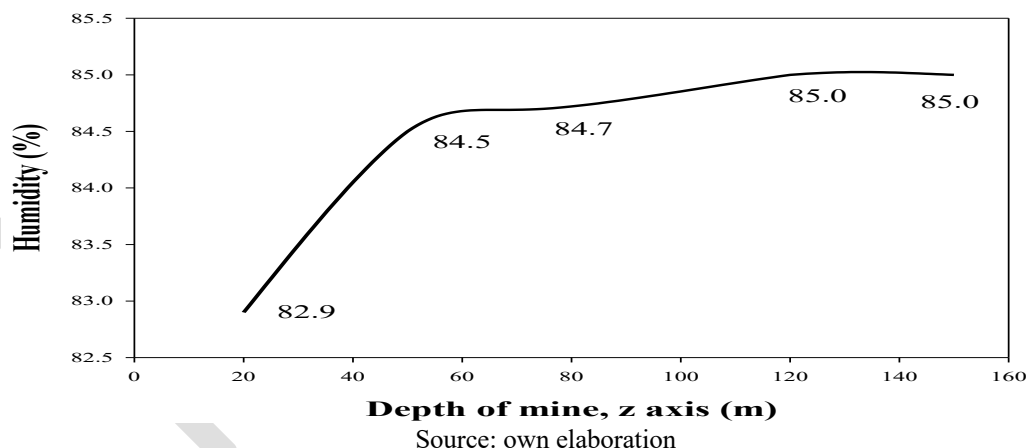
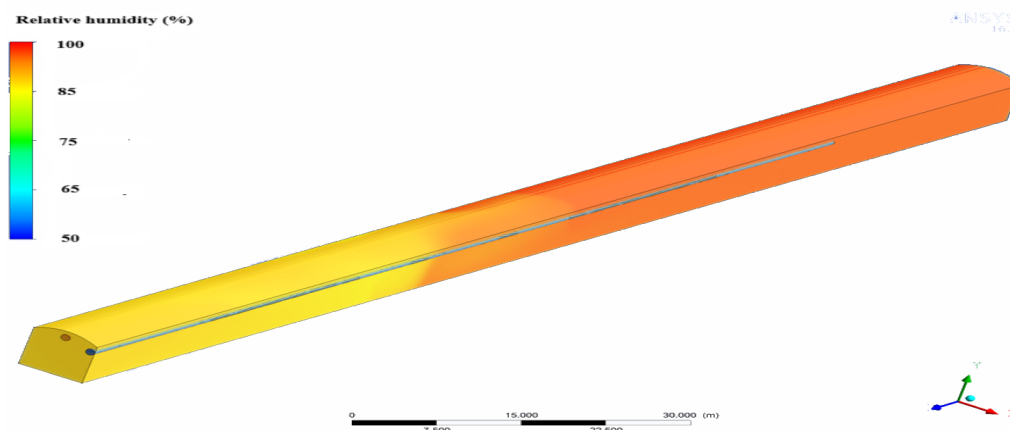


Figure 8
Contour of humidity relative of underground mine without ventilation system

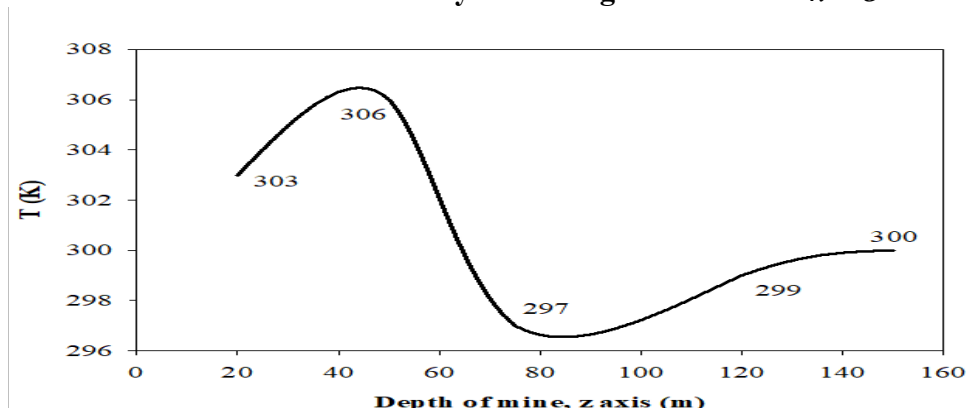


Source: own elaboration

2. 2. Simulation of the thermo-environmental conditions of the underground mine work with a monoextractive ventilation system using the standard model

Results of the simulation corresponding to the thermo-environmental conditions of the underground mine work with the implementation of the extractive mono ventilation system using the standard $k - \varepsilon$ model are presented. Figure 9 shows the temperature profile corresponding to this case study, in which it can be seen that at a position between 20m and 150m with respect to the entrance of the work, the temperature increases linearly between $303^{\circ}\text{K} \leq T \leq 306^{\circ}\text{K}$, subsequently a decrease is recorded between the 50 m and 75m positions, standing around $306^{\circ}\text{K} \leq T \leq 297^{\circ}\text{K}$, a new linear increment of $297^{\circ}\text{K} \leq T \leq 299^{\circ}\text{K}$ is given between the positions 75 m and 120 m and finally at the position of 150m, reaching a temperature of 300°K . As can be seen, between the exhaust fan and the air injector the temperature drops to a range of 297°K to 300°K , which according to NOM-015-STPS-2001 at the mine front can work maintaining a ratio of 50% work and 50% recovery per hour, indicating that thermo-environmental conditions improved with respect to almost no ventilation, thus generating more suitable conditions for the worker and the production process.

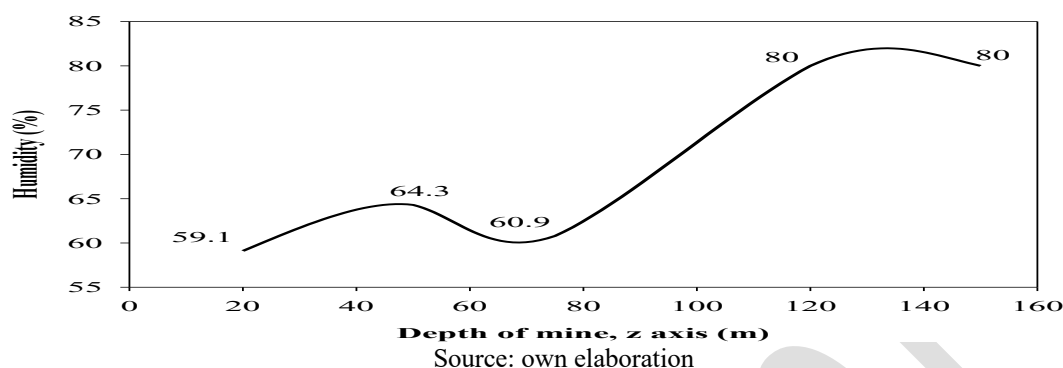
Figure 9
Temperature profile of underground mine work with the implementation of the extractive mono ventilation system using the standard $k - \varepsilon$ model



Source: own elaboration

Figure 10 shows the humidity relative profile corresponding to this case study, in which it can be seen that at a position between 20 m and 50 m with respect to the entrance of the work, the humidity relative increases linearly between $59.1 \leq \% \text{ Humidity} \leq 64.3$; subsequently there is a decrease between positions 50 m and 75 m, standing around $64.3 \leq \% \text{ Humidity} \leq 60.9$, a new linear increment of $60.9 \leq \% \text{ Humidity} \leq 80.0$ is given between the positions 75 m and 120 m and finally at the position of 150 m maintain a humidity% of 80. According to the results obtained from the simulation using the standard model, the relative humidity conditions between the extractor and the air injector range between 61 and 80%, which represents a decrease compared to the system without ventilation, improving thermo-environmental conditions for worker health and increased production efficiency. According to the results obtained from the simulation using the standard $k - \varepsilon$ model which is consistent with the mass and energy transfer phenomenon and therefore it can be elucidated that said model is adequate to represent this case of study.

Figure 10
Profile of humidity relative vs depth of mine with the implementation of the extractive mono ventilation system using the standard $k - \varepsilon$ model



2. 3. Simulation of the thermo-environmental conditions of the underground mine work with a monoextractive ventilation system using the k-kl-omega model

Next, results of the simulation corresponding to the thermo-environmental conditions of the underground mine work with the implementation of the mono extractive ventilation system using the k-kl-omega model are presented. Figure 11 shows the temperature profile corresponding to this case study, in which it can be observed that at a position between 20 m and 50 m with respect to the entrance of the work, the temperature increases linearly between $302^{\circ}\text{K} \leq T \leq 303^{\circ}\text{K}$; subsequently, a decrease is recorded between the 50 m and 75 m positions, standing at around $303^{\circ}\text{K} \leq T \leq 298^{\circ}\text{K}$, a new linear increase of $298^{\circ}\text{K} \leq T \leq 301^{\circ}\text{K}$ occurs between the 75 m and 120 m positions, finally at the 150 m position the temperature is maintained at 301°K . In accordance with the provisions of NOM-015-STPS-2001, for the conditions recorded by this mathematical model, 50% rest and 50% work must be met for each hour; As in the previous model, the results show that the ventilation system improves the thermoenvironmental conditions of the underground work, reporting a variation in temperature from the 301°K air injector to the 298°K exhaust fan.

Figure 11
Temperature profile of the underground mine work with the implementation of the mono extractive ventilation system using the k-kl-omega model

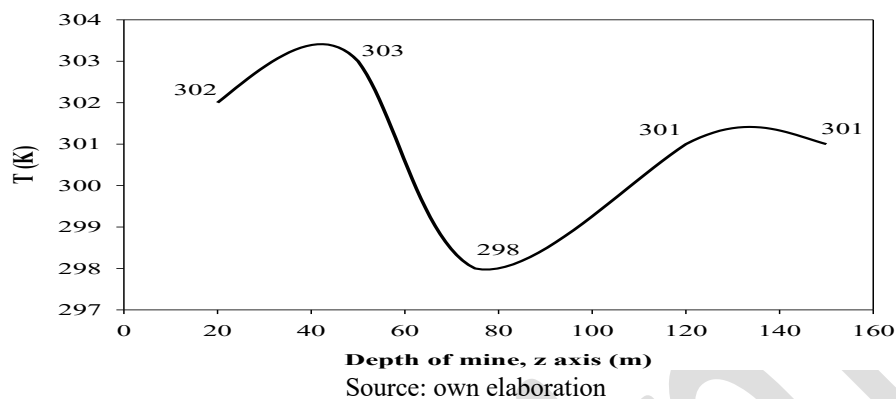
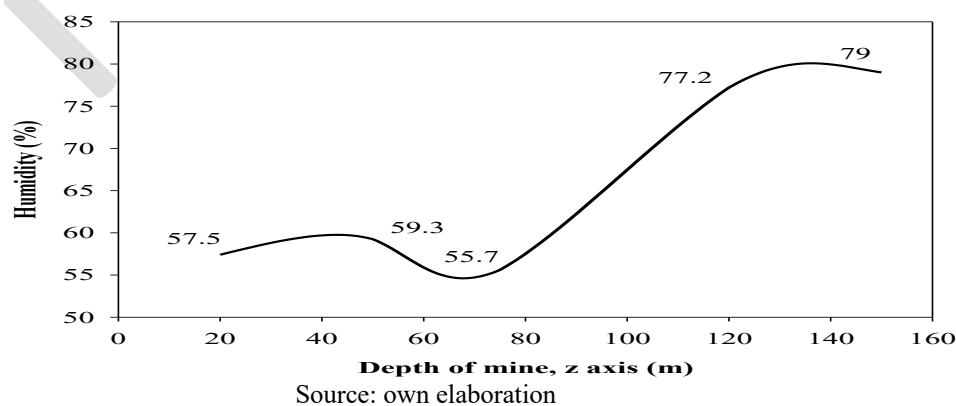


Figure 12 shows humidity relative profile corresponding to this case study, in which it can be seen that at a position between 20m and 50m with respect to the entrance of the work, the humidity relative increases linearly between $57.5 \leq \% \text{Humidity} \leq 59.3$; subsequently there is a decrease between the positions 50m and 75m, standing at around $59.3 \leq \% \text{Humidity} \leq 55.7$, a new linear increase of $55.7 \leq \% \text{Humidity} \leq 77.2$ is given between the positions 75m and 120m and finally at the position of 150m maintain a % humidity of 79. According to the results obtained from the simulation using the k-kl-omega model can be seen that thermo-environmental conditions improve in the position where the extraction system is located, which is consistent with the mass and energy transfer phenomenon and coincides with the model described in the previous case, so it can be explained that This model is adequate to represent this case study.

Figure 12
Profile of humidity relative vs depth of mine with the implementation of the extractive mining system using k-kl-omega model



2. 4. Simulation of the thermo-environmental conditions of the underground mine work with a monoextractive ventilation system using the Reynolds Stress model

Next, results of the simulation corresponding to the thermo-environmental conditions of the underground mine work are presented with the implementation of the mono extractive ventilation system using the Reynolds Stress model. Figure 13 shows the temperature profile corresponding to this case study, in which it can be observed that at a position between 20m and 50m with respect to the entrance of the work, the temperature increases linearly between $303^{\circ}\text{K} \leq T \leq 304^{\circ}\text{K}$; subsequently, a decrease is recorded between the 50m and 75m positions, standing at around $304^{\circ}\text{K} \leq T \leq 296^{\circ}\text{K}$, a new linear increase of $296^{\circ}\text{K} \leq T \leq 300^{\circ}\text{K}$ occurs between the 75m and 120m positions and finally at the position of 150 m the temperature is maintained at 300°K . In accordance with the provisions of NOM-015-STPS-2001, for the conditions recorded by this mathematical model, 50% rest and 50% work must be met for each hour; Like the two previous models, the results show that the ventilation system provides improvements in terms of the thermos-environmental conditions of the underground work, recording a variation in temperature from the 300°K air injector to the 296°K exhaust fan.

Figure 13
Temperature profile of underground mine work with the implementation of the mono extractive ventilation system using the Reynolds Stress model

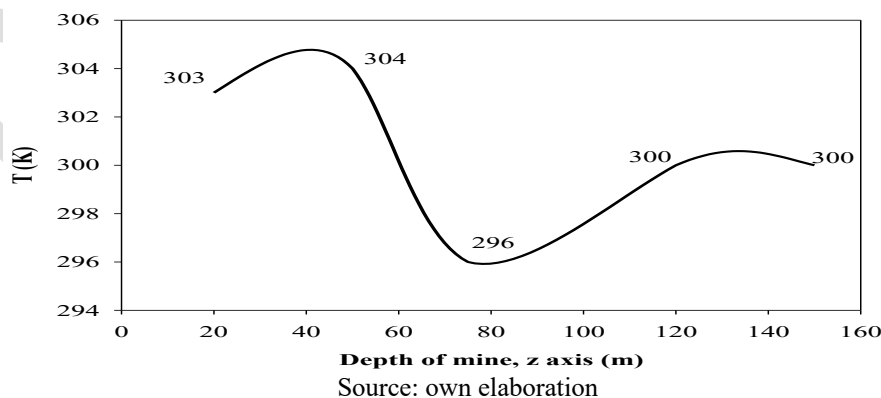
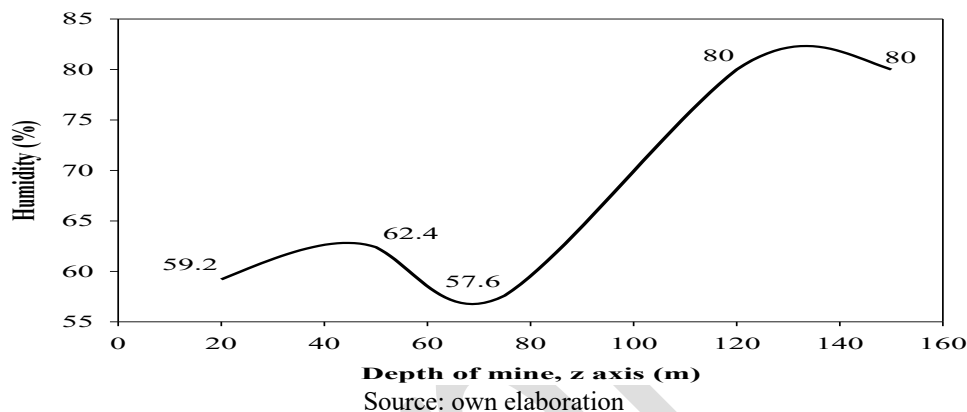


Figure 14 shows the humidity relative profile corresponding to this case study, in which it can be observed that at a position between 20m and 50m with respect to the entrance of the work, the humidity relative increases linearly between $52.9 \leq \% \text{ Humidity} \leq 62.4$; subsequently there is a decrease between positions 50m and 75m, standing at around $62.4 \leq \%$

Humidity ≤ 57.6 , a new linear increase of $57.6 \leq \text{Humidity} \leq 80$ is between positions 75m and 120m and finally at the position of 150m, maintain a humidity relative of 89. According to the results obtained from the simulation using the Reynolds Stress model as in the previous models, the results are consistent with both the conditions of this system.

Figure 14
Profile of humidity relative of underground mine with the implementation of the mono extractive ventilation system using the Reynolds Stress model

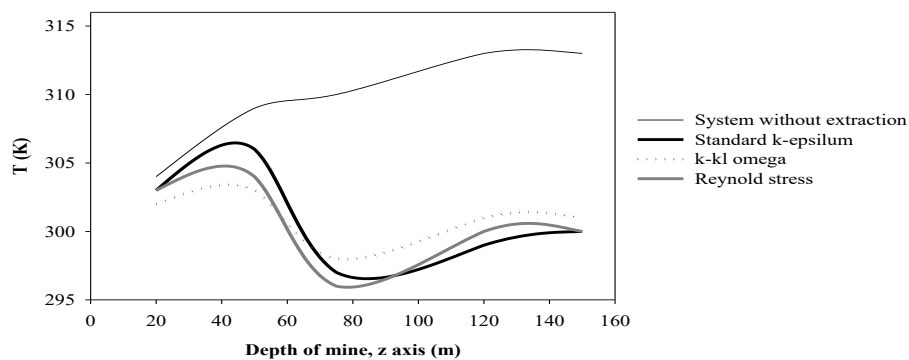


2.5. Comparative analysis of the three models of turbulence closure used in the simulation of the temperature for underground mine work with a monoextractive ventilation system

Figure 15 shows the comparison of temperature with the implementation of a ventilation circuit in the development work of the underground mine of the three models used in the simulation vs the model without the extraction. In the figure it can be seen that at the distance of 20 m there is a temperature decrease in 1°K , 1°K , 2°K for the Reynolds Stress, standard $k - \varepsilon$ and k-kl-omega models, respectively with respect to the model without extraction; at a distance of 75 m (position of the extractor) the temperature decreases 14°K , 13°K , 12°K for the models Reynolds Stress, Standard $k - \varepsilon$ and k-kl-omega respectively; 150m where the maximum temperature is, which tends to decrease 13°K , 13°K and 12°K for the models Reynolds Stress, Standard $k - \varepsilon$ and k-kl-omega respectively, with respect to the model that registered the maximum temperature without the implementation of a ventilation circuit. The results obtained show that the Reynolds Stress model records the lowest temperature in the case study implementing the ventilation circuit. According to the results shown in terms of temperature, the three models show similar values, which is indicative that the three models

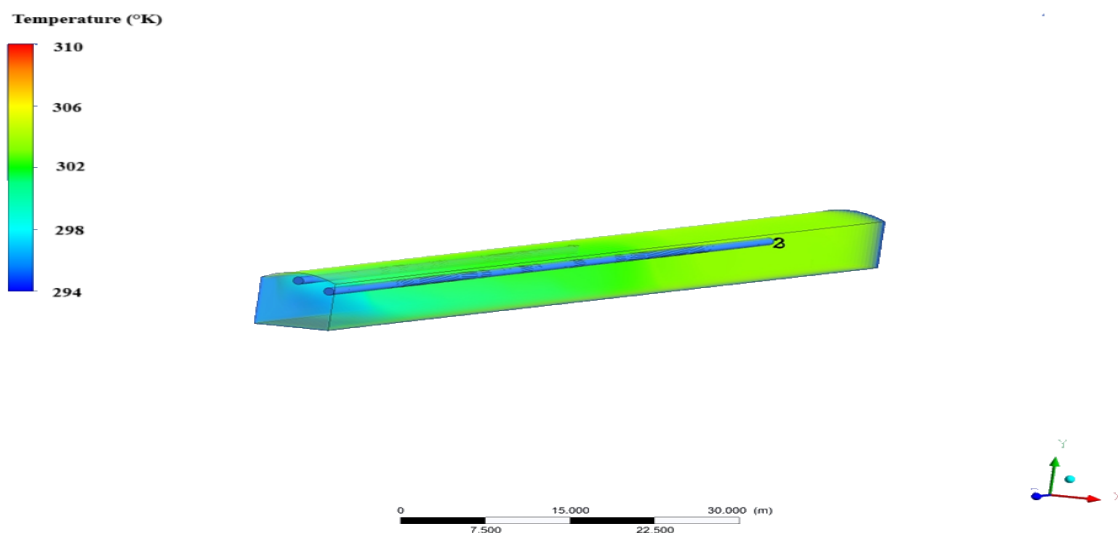
are viable to describe the studied phenomenon. This can be verified by observing the temperature contour (Figure 16), which presents a homogeneous temperature distribution increasing towards the mine front, which is coincident in the three cases and represents a characteristic of real underground works; In terms of computability, the standard model represents the shortest time, making it the fastest option for generating results.

Figure 15. Comparative profiles of underground mine work temperature with the implementation of the mono extractive ventilation system employing three models of turbulence closure



Source: own elaboration

Figure 16. Contour of temperature of underground mine work with the implementation of the extractive mono ventilation system



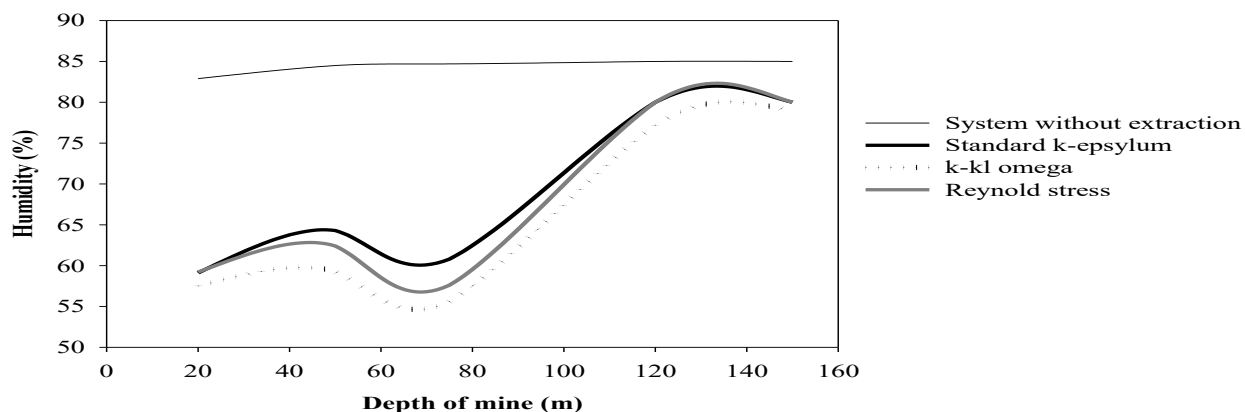
Source: own elaboration

2.6. Comparative analysis of the three models of turbulence closure used in the simulation of humidity relative in the underground mine work with a monoextractive ventilation system

Figure 17 shows the comparison of the humidity relative obtained in the three models used in the simulation with the application of a ventilation circuit vs the model that registered the highest humidity relative without extraction. In the figure it is observed that at a distance of 20m the humidity relative decreases 24%, 24%, 25% for the models standard $k-\varepsilon$, Reynolds Stress and k-kl-omega, respectively with respect to the model without extraction; corresponding to the distance of 75m (position of the extractor) the humidity relative is reduced to 61%, 58%, 56% in the models standard $k-\varepsilon$, Reynolds Stress and k-kl-omega, respectively; in relation to the 150m distance where the highest humidity relative is recorded, this parameter tends to decrease 5%, 5%, 6% for the models standar $k-\varepsilon$, Reynolds Stress and k-kl-omega, respectively, compared to the model that registered the maximum humidity relative without the implementation of a ventilation circuit. The data obtained indicate that by applying the k-kl-omega for the ventilation circuit, the results obtained are the lowest humidity relative because the extraction is adequate for fresh air to ventilate the development work of the underground mine. As in the previous case in terms of relative humidity, the three models present congruent results, which makes it possible to elucidate that the three models are apt to define the proposed case study. The above can be verified by observing the temperature contour (see figure 18). Similarly, figure 19 shows the flow velocity vector contour in which a fluid movement characteristic of these ventilation systems can be observed, in which the highest velocity is between the air injection zone and the working front.

Figure 17

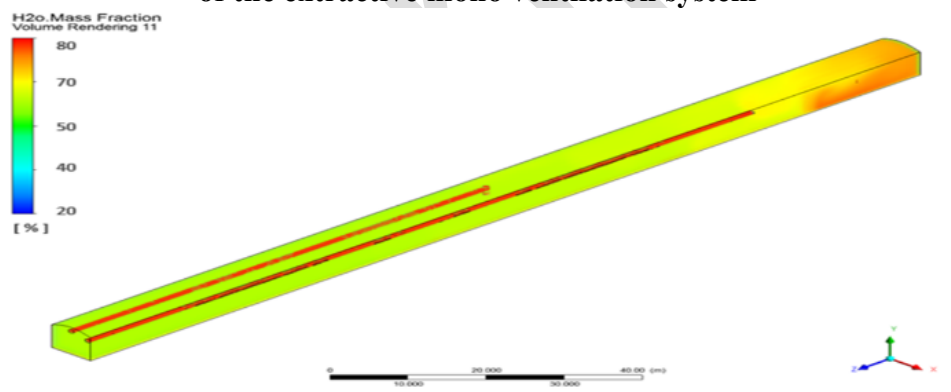
Comparative profiles of relative humidity of underground mine work with the implementation of the mono extractive ventilation system employing three models of turbulence closure



Source: own elaboration

Figure 18

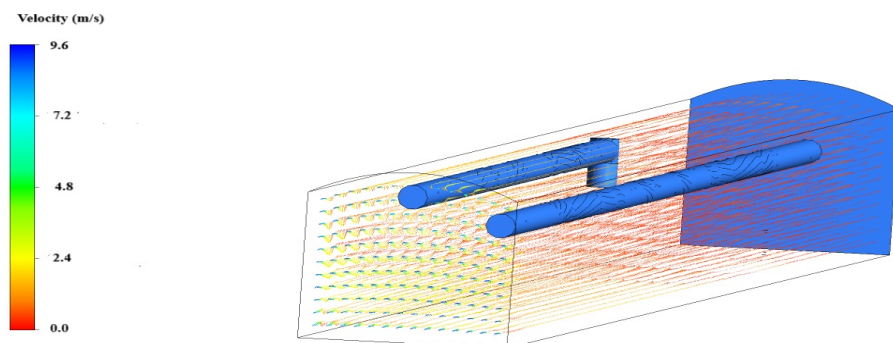
Humidity relative contour in underground mine construction with the implementation of the extractive mono ventilation system



Source: own elaboration

Figure 19

Flow velocity vector contour in the underground work with the implementation of the mono-extraction ventilation system



Source: own elaboration

2.7. Statistical analysis of the models used to simulate temperature and relative humidity

Below is the statistical analysis corresponding to the case studies analyzed (Tables 5 and 6) for temperature and relative humidity respectively, using the analysis of variance method and Fisher's LSD with 95% confidence. The results of this study indicate that for both parameters there are no significant differences between the results obtained by the three models used for the simulation. In this sense, it can be inferred that the three models behave in a similar way and therefore the model that requires the least computational work can be selected.

Table 5
Analysis of variance and Fisher's LSD method with 95% confidence for temperature

Variance Analysis					
Fountain	GL	SC Adjust.	MC Adjust.	Value F	Value p
Factor	2	0.533	0.2677	0.03	0.97
Error	12	103.200	8.6		
Total	14	103.733			
Fisher's LSD method with 95% confidence					
Factor	N	Half	Group		
Standard	5	301.00	A		

Omega	5	301.00	A
Reynolds Stress	5	300.60	A

Source: own elaboration

Table 6. Analysis of variance and Fisher's LSD method with 95% confidence for humidity

Variance Analysis					
Fountain	GL	SC Adjust.	MC Adjust.	Value F	Value p
Factor	2	25.31	12.65	0.10	0.901
Error	12	1449.78	120.81		
Total	14	1475.08			
Fisher's LSD method with 95% confidence					
Factor	N	Half	Group		
Standard	5	68.86	A		
Omega	5	67.84	A		
Reynolds Stress	5	65.74	A		

Source: own elaboration

PROSPECTIVE

This work shows that the comparative study of three transfer models to simulate the thermal-environmental conditions in an underground work provides data that are consistent with this type of works; in this sense, it can be elucidated that the models used behave in a similar way for this type of phenomena, allowing prospecting for future analysis and validation through experimental data. This is relevant since it allows proposing a methodology to generate predictive studies of the thermal-environmental conditions that can be generated in specific underground works. This will help in decision-making by the designers and operators of these works since currently, to determine this type of conditions, there are software programs that provide data from complete sections (inputs, outputs, etc.) and in order to know the data at different points, it is necessary to sample manually with measuring equipment, which requires time and can cause inconveniences in the operation and development of the work.

CONCLUSIONS

The comparative study of three models of turbulence closure shows that the results when simulating this phenomenon is similar in the three models.; according to the above, the models that presents the most suitable extraction conditions is the Reynolds Stress for the temperature whit 296 °K and Omega model, reporting relative humidity value of 55.7%; however, the three models reported values close, which makes it possible to elucidate that in case of requiring a diagnosis using less time and computing capacity, the Standard model is adequate. In terms of temperature and relative humidity distribution, the contours show that these parameters present a logical behavior to the described phenomenon, which suggests that these tools can be used to generate diagnoses of specific sections that need to be analyzed in ventilation circuits. The results show that the ventilation system with the simulated models, the thermo-environmental conditions improve, which would allow to double the working time in the underground work in accordance with NOM-015-STPS-2001. This case study presents a novel application regarding the use of turbulence closure models by means of CFD, the foregoing is due to the dimensions of the simulated system, the mesh independence study demonstrated, and the similarity of the results obtained in the different models, which opens a promising perspective for the use of these models in the analysis of ventilation systems in underground mines and their subsequent validation with experimental and specific case studies.

ACKNOWLEDGMENTS

The authors of this work would like to thank the academic peers who served as reviewers for this work, as well as the University of Guanajuato for their support.

REFERENCES

- Aghaei R., Tousi A and Tourani A. (2008). Comparison of turbulence methods in CFD analysis of compressible flows in radial turbomachines Aircraft Engineering and Aerospace Technology: An International Journal, 80, 657–665.
<https://www.emerald.com/insight/content/doi/10.1108/00022660810911608/full/html>
- Ameur, H. (2016). 3D hydrodynamics involving multiple eccentric impellers in unbaffled cylindrical tank. Chinese Journal of Chemical Engineering. 24, 572-580.
<https://doi.org/10.1016/j.cjche.2015.12.010>

Anicode, S. and Madenci, E. (2021). Three-dimensional moisture diffusion simulation with time dependent saturated concentration in ANSYS through native thermal and spring elements. *Microelectronics Reliability*, 123, 1-5.

<https://doi.org/10.1016/j.microrel.2021.114167>

ANSYS, Release 12.0 ©. (2009). Inc. Transport Equations for the k - kl - ω Model, 1, 1.

<https://www.afs.enea.it/project/neptunius/docs/fluent/html/th/node71.htm>

Bernard, P. and Wallace, J. (2002). *Turbulent Flow: Analysis, Measurement & Prediction*.

John Wiley & Sons. 1, 324. <https://www.cambridge.org/core/journals/journal-of-fluid-mechanics/article/abs/turbulent-flow-analysis-measurement-and-prediction-by-p-s-bernard-j-m-wallace-wiley-2002-1999-497-pp-isbn-0-471-33219-4-10000-or-6995-or-1112/32139CA43B3DB5167C2D5134CC870CC1>

Buwa, V., Dewan, A., Nassar, A.F., Durst, F. (2006). Fluid dynamics and mixing of singlephase flow in a stirred vessel with a grid disc impeller: Experimental and numerical investigations. *Chemical Engineering Science*. 61, 2815-2822.

<https://doi.org/10.1016/j.ces.2005.10.066>

Fluent Inc. (2006). *FLUENT 6.3 Getting Started Guide*. Reaction Design Inc. PathScale Corporation, 1, 1-44. <https://romeo.univ-reims.fr/documents/fluent/fluentGettingStarted.pdf>

Gelves R. and Benavides A. (2012). Predicción del comportamiento hidrodinámico en el escalado de un reactor de tanque agitado para procesos aerobios, mediante CFD, *Journal of power sources*, 162, 1192 - 1202. <https://revistas.uta.cl/pdf/1907/art05.pdf>

Ituna, J.F., Belman, J.M., Elizalde, F., García, O. (2017). Numerical investigation of CO₂ behavior in the internal heat exchanger under variable boundary conditions of the transcritical refrigeration system. *Applied Thermal Engineering*. 115, 1063-1078.

<https://doi.org/10.1016/j.applthermaleng.2017.01.042>

Keith, D., Colkhat, D. (2008). A Three-Equation Eddy-Viscosity Model for Reynolds-Average Navier-Stokes Simulations of Transitional Flow. *Journal of Fluids Engineering*. 130, 12:1-14. <https://doi.org/10.1115/1.2979230>

Kwon, O. and Ames, F. (1995). Advanced k-epsilon Modeling of Heat Transfer. Allison Engine Company. 4679, 10-20. <https://ntrs.nasa.gov/citations/19950025002>

Launder B.E., and Spalding D.B. (1972). Lectures in Mathematical Models of Turbulence. Academic Press, 1, 1-10. <https://lib.ugent.be/en/catalog/rug01:000004139>

López, A., Nicholls, W., Stickland, M., Dempster, W. (2015). CFD study of Jet Impingement Test erosion using Ansys Fluent® and OpenFOAM®. Computer Physics Communications. 197, 88-95. <https://doi.org/10.1016/j.cpc.2015.07.016>

López, R.I. (2018). Estudio comparativo de tres modelos de transferencia de masa y energía mediante simulación en CFD para un sistema de ventilación mono extractivo en una obra de desarrollo de mina subterránea, Universidad de Guanajuato, 1, 5- 112. <http://repositorio.ugto.mx/handle/20.500.12059/7786>

Lorini, M., Bassi, F., Colombo, A., Ghidoni, A., Noventa, G. (2021). Discontinuous Galerkin solution of the RANS and $kL-k-log(\omega)$ equations for natural and bypass transition. Computers and Fluids. 214, 1-9. <https://doi.org/10.1016/j.compfluid.2020.104767>

Meiling, H., Nianping, L., Yingdong, H., De, H., and Kuan W. (2017). Influences of Temperature and Humidity on Perceived Air Quality with Radiant Panel Workstation. Procedia Engineering, 205, 765–772. <https://doi.org/10.1016/j.proeng.2017.10.008>

Mullins, J. and White, C. (2019). Temperature and mental health: Evidence from the spectrum of mental health outcomes. Journal of Health Economics, 68, 1-22. <https://doi.org/10.1016/j.jhealeco.2019.102240>

Normas Oficiales Mexicanas STPS. (1996). “Norma Oficial Mexicana NOM-121-STPS-1996, Seguridad e Higiene para los trabajos que se realizan en Minas “. Estados Unidos Mexicanos. https://www.dof.gob.mx/nota_detalle.php?codigo=704747&fecha=19/02/2003#gsc.tab=0

Normas Oficiales Mexicanas STPS. (2001). “NORMA Oficial Mexicana NOM-015-STPS-2001, Condiciones térmicas elevadas o abatidas-Condicioness de seguridad e higiene”.

Estados Unidos Mexicanos.

https://dof.gob.mx/nota_detalle.php?codigo=728016&fecha=14/06/2002#gsc.tab=0

Ontiveros, R., García, E.J., Ugalde., Gerardo. (2006). Estudio de Ingeniería de Minas para la Planeación y Desarrollo del Tunel Vial Proyectado en el Centro Histórico de la Ciudad de Guanajuato, México, Universidad de Guanajuato, 1, 174-214.

Parekh, J., Rzehak, R. (2028). Euler–Euler multiphase CFD-simulation with full Reynolds stress model and anisotropic bubble-induced turbulence. International Journal of Multiphase Flow. 99, 231-245. <https://doi.org/10.1016/j.ijmultiphaseflow.2017.10.012>

Quevedo C,M. (2013). Sistema de ventilación de diez kilómetros del túnel de conducción de la Central Hidroeléctrica Huanza, Universidad Nacional Mayor de San Marcos, 1, 27-70. https://cybertesis.unmsm.edu.pe/bitstream/handle/20.500.12672/12738/Quevedo_Chaname_Carlos_Manuel_2013.pdf?sequence=1

Quiceno C. and Molina Martín. (2011). Characterization of Ventilation Systems In Underground Mines. Ciencias de la Tierra, 1, 73-74. <http://www.scielo.org.co/pdf/bcdt/n29/n29a06.pdf>

Rodríguez, D. (2010). Diseño del sistema de control para la ventilación de una mina subterránea usando un controlador AC800m. Universidad Nacional de Ingeniería Facultad de Ingeniería Mecánica.1, 27-40. <https://repositorio.uni.edu.pe/handle/20.500.14076/860>

Ropo, I., Perez, S., Mukalazi, A., Yewande, O. and Nel W. (2019). Implications of climate variability and change on urbanand human health: Areview. Cities, 91, 213-223. <https://doi.org/10.1016/j.cities.2019.01.009>

Safaeil, M., Goshayeshi, H., Razavi, B. and Goodarzi. (2011). Numerical investigation of laminar and turbulent mixed convection in a shallow water-filled enclosure by various turbulence methods. Scientific Research and Essays, 6, 22: 4826-4838. https://academicjournals.org/article/article1380729478_Safaei%20et%20al.pdf

Sarkar, S and Lakshmanan, B. (1991). Application of a Reynolds-Stress Turbulence Model to the Compressible Shear Layer. IAA JOURNAL, 29, 5: 743.

<https://arc.aiaa.org/doi/10.2514/3.10649>

Slack, M., Prasad R., Bakker, A and Boysan, F. (2000). Advances in Cyclone Modelling Using Unstructured Grids, Trans I ChemE, 78, 1098-1104.

<https://doi.org/10.1205/026387600528373>

Tennekes, H. and Lumley, J. (1994). First course in turbulence. The MIT press, Cambridge, MA, USA.1. <https://vdocument.in/tennekes-lumley.html?page=1>

Torano J., Torno, S., Menéndez, M and Gent M. (2011). Auxiliary ventilation in mining roadways driven with road headers: Validated CFD modelling of dust behavior. Tunneling and Underground Space Technology, 26, 201-210.

<https://doi.org/10.1016/j.tust.2010.07.005>

Versteeg, H. and Malalasekera, W. (2013). An Introduction to Computational Fluid Dynamics. Pearson Prentice Hall. 2, 96:20-50.

http://ftp.demec.ufpr.br/disciplinas/TM701/Versteeg_Malalasekera_2ed.pdf

Wang S., Fu X., Deng X. (2022). Higher-order aerodynamic numerical simulations in compressible RANS framework with inverse- ω scale variable. Aerospace Science and Technology, 131 A, 5-10. <https://doi.org/10.1016/j.ast.2022.107971>

Wey, F., Fangping, Z., Huiqing, L. (2011). The use of 3D simulation system in mine ventilation management, Procedia Engineering, 26, 1370-1379.

<https://doi.org/10.1016/j.proeng.2011.11.2313>

Wey, L. (2009). Topology theory of mine ventilation network, Procedia Earth and Planetary Science, 1, 354-360. <https://doi.org/10.1016/j.proeps.2009.09.056>

Wilcox, D. (1998). Turbulence Modeling for CFD. DCW Industries, Inc., La Canadá, California, 1, 1-522.

Yana, H., Liu, Q., Zhao, W., Pang, C., Dong, M., Zhang, H., Gao, J., Wang, H., Hu, B., Yang, L. and Wang., Lu. (2017). The coupled effect of temperature, humidity, and air

movement on human thermal response in hot–humid and hot–arid climates in summer in China. *Building and Environment*, 177, 1-15.

<https://doi.org/10.1016/j.buildenv.2020.106898>

Zeng, X., Wang, Y., Maccall, B. (2019). A k–e Turbulence Model for the Stable Atmosphere. *Journal of the Atmospheric Sciences*. 77, 167-184.

<https://doi.org/10.1175/JAS-D-19-0085.1>

CC BY-NC-ND

Postprint