TUNNEL TRANSIENT HEAT TRANSFER

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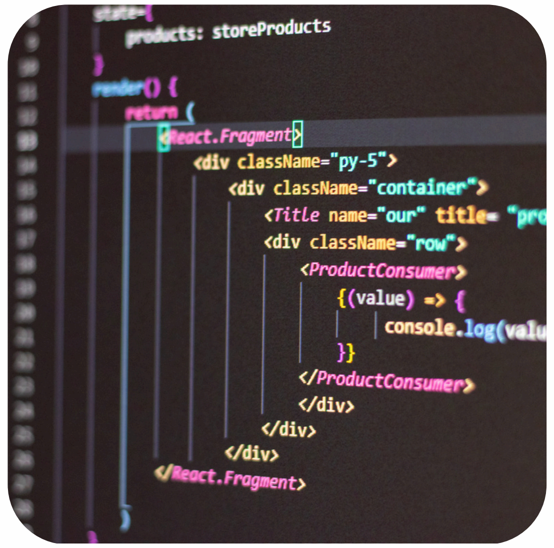


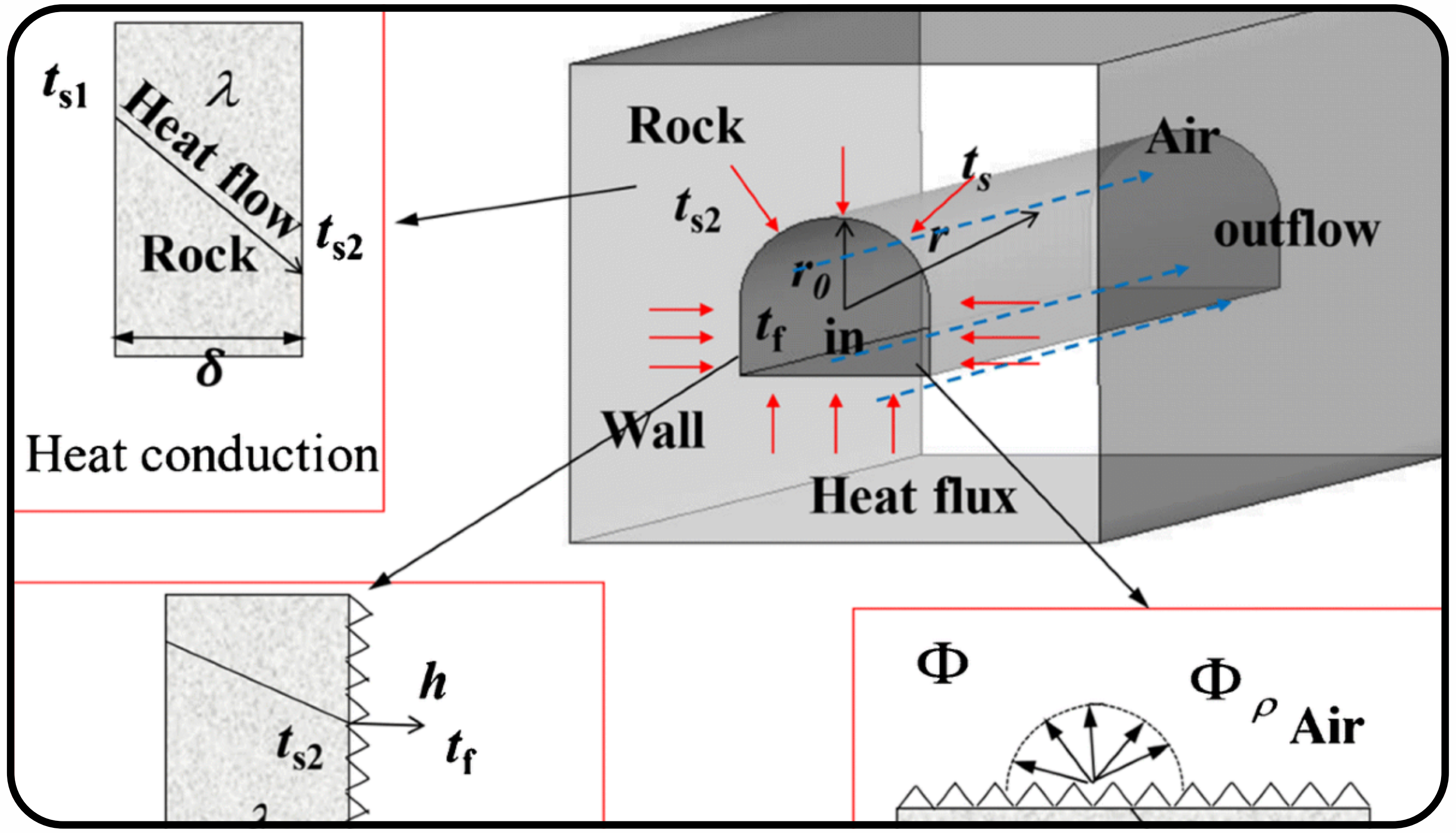
MINE VENTILATION

- Safety
- Comfort
- Efficiency
- Energy Planning

Mine ventilation supplies fresh air to remove heat, hazardous gases, and dust from underground workings. It ensures a safe environment, prevents heat stress for workers, and is essential for productive operations, especially as mining goes deeper and temperatures rise.

Proper simulation allows mining engineers to optimize tunnel layouts and develop efficient ventilation strategies tailored to the unique heat transfer characteristics of the rock mass.

PROBLEM STATEMENT



In underground mining, understanding how the temperature of the surrounding rock mass evolves around a mine tunnel is crucial for safe, comfortable, and efficient mine operations. When cold air is pumped into a newly excavated tunnel, it gradually cools the hot rock near the tunnel wall. The temperature decreases with distance from the wall—and this process happens over hours, days, or even weeks.

Tasks:

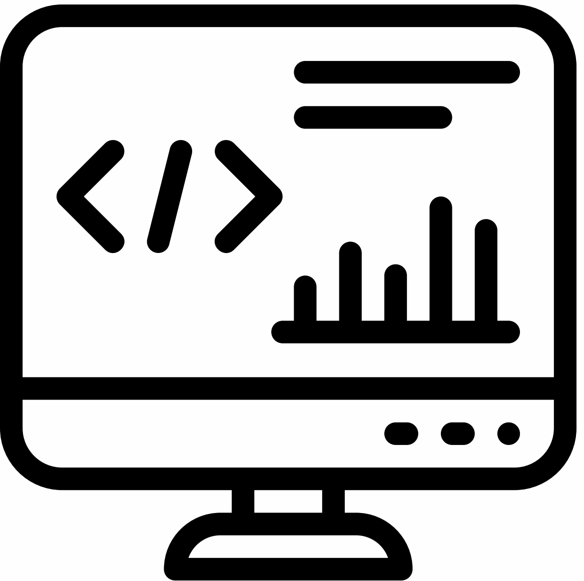
- Solving the transient (time-dependent) radial heat conduction in the rock surrounding a mine tunnel.
- Visualizing how the temperature profile changes both in space and time.
- Solving the transient radial heat convection (velocity change) in the rock surrounding a mine tunnel.

CODE

[Code Link]

Mathematical Formulae :

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)$$



Parameters :

Density, Specific Heat, Thermal Conductivity, VRT, Air Temp(Tunnel wall), Outer Rock Temp., Tunnel Inner Radius, Outer Radial Distance from Tunnel Wall, Total Simulation Time, Number of Radial Mesh pts, Number of Time Steps, Radial (spatial) Increment, Time Increment/step, Thermal Diffusivity of Rock, List of Air Velocities, Kinematic Viscosity of air, Air Thermal Conductivity, Tunnel Diameter.

Parameter	Description	Value/Unit
rho	Rock density	2500 kg/m³
cp	Rock specific heat	880 J/kg/K
k	Rock thermal conductivity	2.5 W/m/K
h	Tunnel wall heat transfer coefficient	15 W/m²/K
T_air	Tunnel air temperature	15.0 °C
T0	Initial rock temperature	30.0 °C
T_outer	Far field rock temperature	30.0 °C
r1	Tunnel inner (wall) radius	2.0 m
r2	Outer simulated radius	10.0 m
t_sim_min	Total simulation time	2880 min (2 days)
nr	Number of radial mesh points	100 parts
nt	Number of time steps	400 parts
dr	Radial step size	0.0808 m
dt	Time step	432 s
alpha	Thermal diffusivity (k/(rho*cp))	~1.136e-6 m²/s
air_velocities	Simulated air velocities	m/s
nu	Air kinematic viscosity (convection calc)	1.5e-5 m²/s
k_air	Air conductivity (convection calc)	0.026 W/m/K
D	Tunnel diameter (convection calc)	4.0 m

CODE LOGIC

Conduction :

$$T_{i+1} = T_i + \Delta r T_i' + \frac{(\Delta r)^2}{2} T_i'' + \frac{(\Delta r)^3}{6} T_i''' + \dots$$

$$T_{i-1} = T_i - \Delta r T_i' + \frac{(\Delta r)^2}{2} T_i'' - \frac{(\Delta r)^3}{6} T_i''' + \dots$$

First Derivative :

$$T_{i+1} - T_{i-1} = 2\Delta r T_i' + \frac{2(\Delta r)^3}{6} T_i''' + \dots$$

$$\frac{T_{i+1} - T_{i-1}}{2\Delta r} = T_i' + \frac{(\Delta r)^2}{6} T_i''' + \dots \rightarrow \left.\frac{\partial T}{\partial r}\right|_i \approx \frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r}$$

Second Derivative :

$$T_{i+1} + T_{i-1} = 2T_i + (\Delta r)^2 T_i'' + \frac{(\Delta r)^4}{12} T_i^{(4)} + \dots$$

$$T_i'' = \frac{T_{i+1} - 2T_i + T_{i-1}}{(\Delta r)^2} - \frac{(\Delta r)^2}{12} T_i^{(4)} + \dots \rightarrow \left.\frac{\partial^2 T}{\partial r^2}\right|_i \approx \frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta r)^2}$$

Time Discretization : $\left.\frac{\partial T}{\partial t}\right|_{t=t^n} \approx \frac{T_i^{n+1} - T_i^n}{\Delta t}$

Heat Equation : $\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)$

$$\frac{T_i^{n+1} - T_i^n}{\Delta t} = \alpha \left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta r)^2} + \frac{1}{r_i} \cdot \frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r} \right)$$

Mathematical Formulae : $\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)$

```python
for step in range(nt):
    T_new = T.copy()
    wall_flux = h * (T_new[0] - T_air) / (rho * cp)
    T_new[0] -= wall_flux * dt

    for i in range(1, nr-1):
        d2T_dr2 = (T[i+1] - 2*T[i] + T[i-1]) / dr**2
        dT_dr = (T[i+1] - T[i-1]) / (2*dr)
        radial_term = (1/r[i]) * dT_dr
        T_new[i] = T[i] + alpha * dt * (d2T_dr2 + radial_term)

    T_new[-1] = T_outer
    T = T_new

    if (step % (nt // 5) == 0) or (step == nt - 1):
        T_store.append(T.copy())
        time_store.append(step * dt / 60)
```

CODE LOGIC

Convection :

Heat Equation : $\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)$

$$\frac{T_i^{n+1} - T_i^n}{\Delta t} = \alpha \left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta r)^2} + \frac{1}{r_i} \cdot \frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r} \right)$$

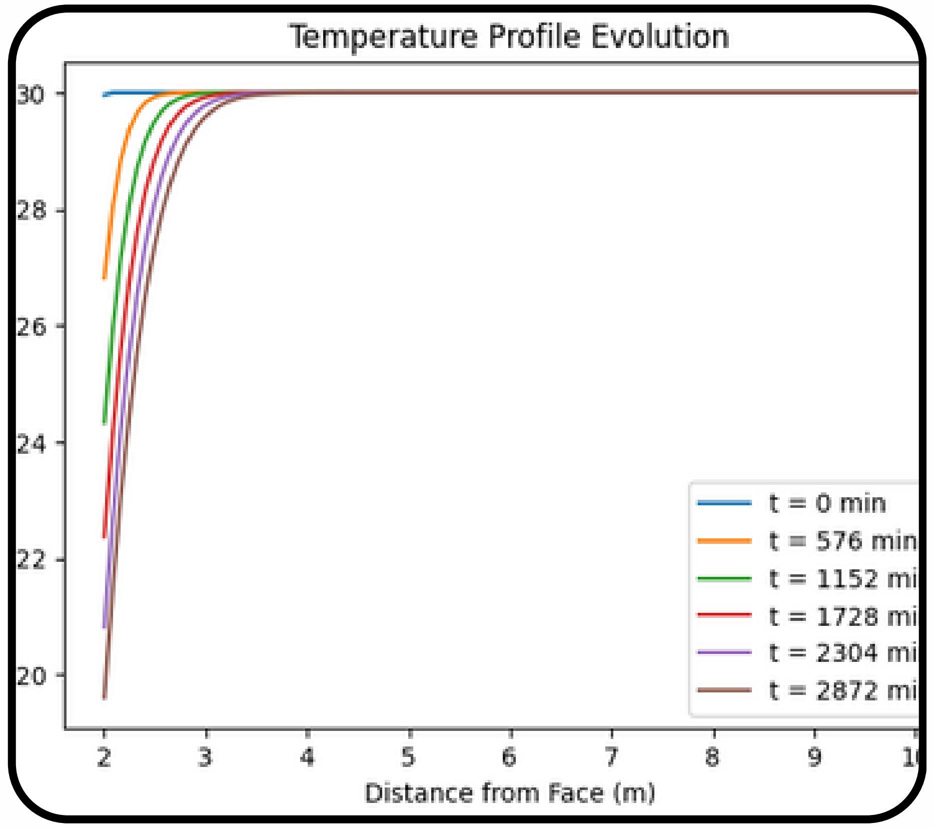
Mathematical Formulae : $Nu = \frac{0.35 \times Re}{1 + 1.592 \left(\frac{15.217 \times Re^{0.2} - 1}{Re^{0.125}} \right)}$

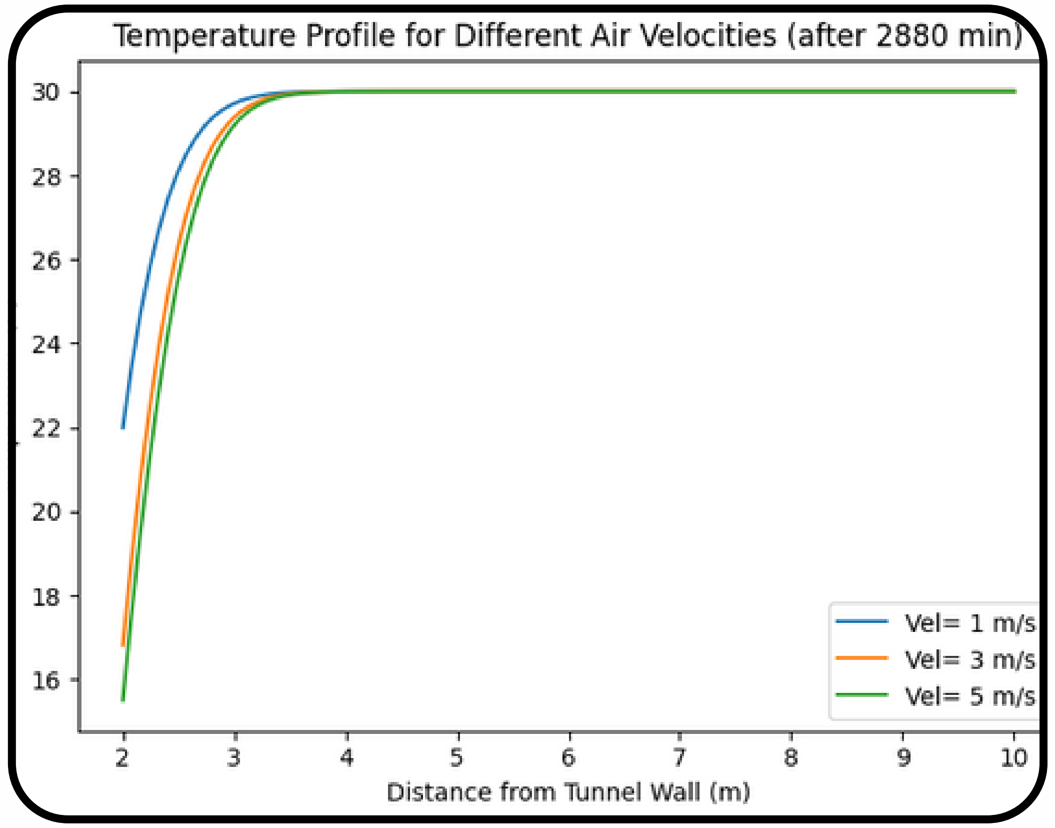
```python
# Nusselt number formula
def h_nusselt_sheet(T_wall, air_vel, D=4):
    kv = 1.5e-5  # Kinematic viscosity of air (m^2/s)
    Re = air_vel * D / kv
    term1 = 0.35 * Re
    term2 = 1.592 * ((15.217 * Re**0.2 - 1) / (Re ** 0.125))
    Nu = term1 / (1 + term2)
    k_air = 0.026  # Air thermal conductivity (W/m/K)
    h = Nu * k_air / D
    return h
```

```python
for v in air_velocities:
    T = np.linspace(T0, T_outer, nr)
    for step in range(nt):
        T_new = T.copy()
        h = h_nusselt_sheet(T_new[0], v)
        wall_flux = h * (T_new[0] - T_air) / (rho * cp)
        T_new[0] -= wall_flux * dt
        for i in range(1, nr-1):
            d2T_dr2 = (T[i+1] - 2*T[i] + T[i-1]) / dr**2
            dT_dr = (T[i+1] - T[i-1]) / (2*dr)
            radial_term = (1/r[i]) * dT_dr
            T_new[i] = T[i] + alpha * dt * (d2T_dr2 + radial_term)
        T_new[-1] = T_outer
        T = T_new
    final_profiles.append(T)
```

Mine Ventilation

The World Runs on Logic





CODE RESULT

Temperature Profile - Conduction

Forms a smooth gradient from the tunnel wall to the outer region as heat slowly diffuses from the hotter rock towards the cooler tunnel air by direct molecular contact or vibration within the solid material.

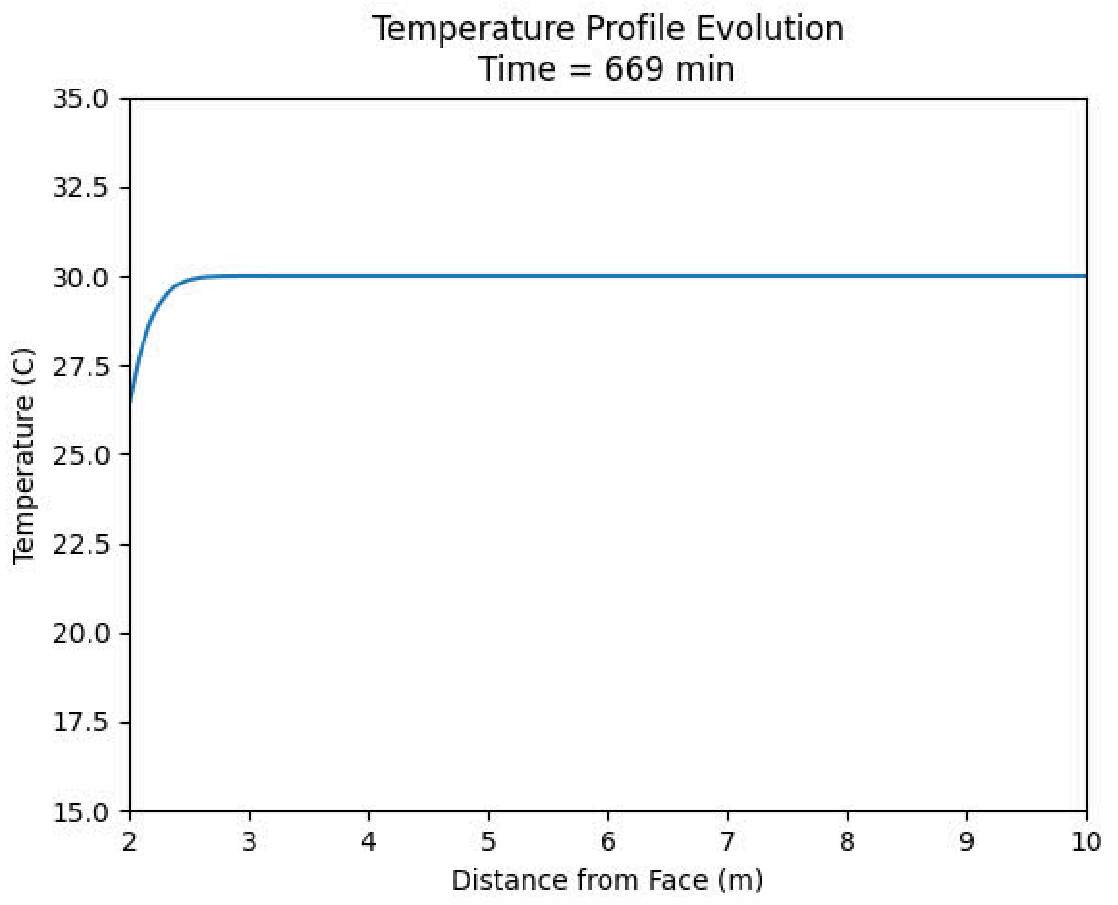
Temperature Profile - Convection

Changes more rapidly because heat is carried away faster by moving air, making the wall temperature drop quickly and steepening the temperature gradient between the wall and the outer rock.

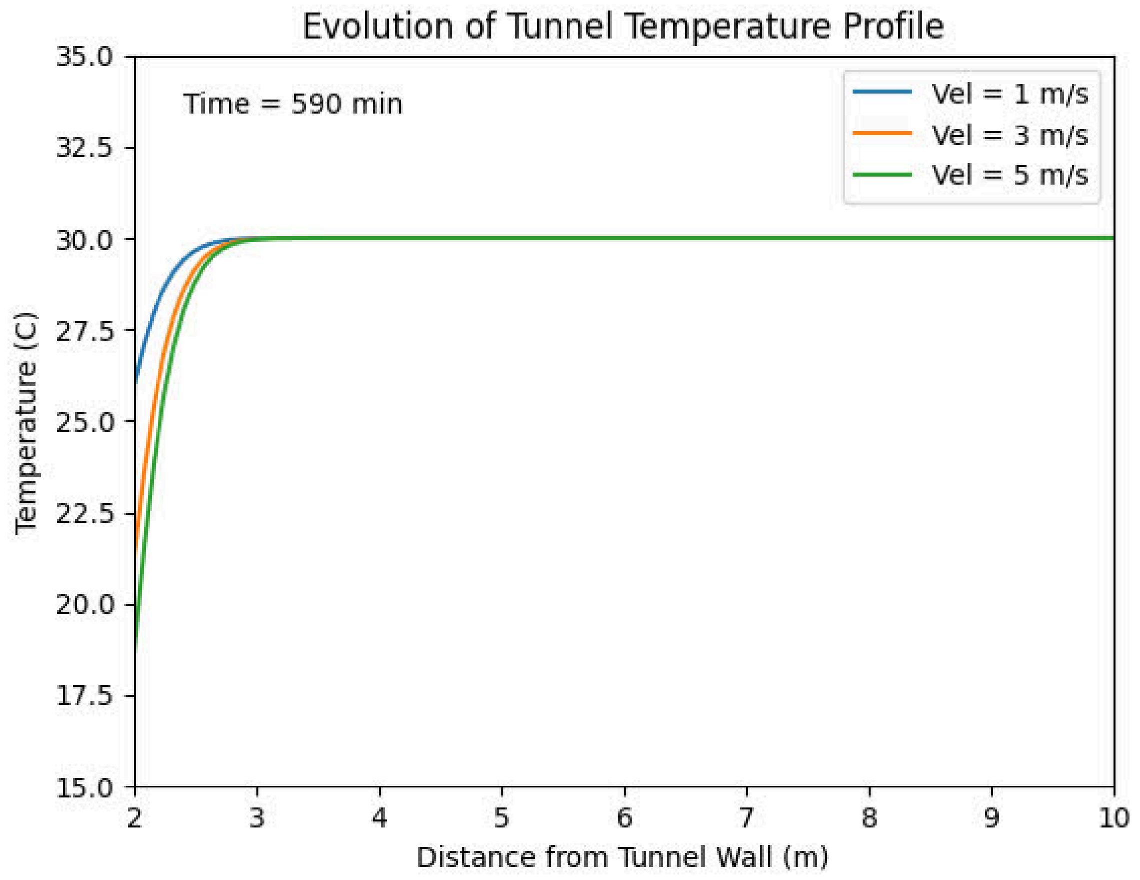
Mine Ventilation

Intro | Problem Statement | Code | Conclusion

Conduction :



Convection :



VISUALIZATION

KEY LEARNINGS

Complex, but can be Simulated with Python

Numerical modelling :

Finite difference method lets us predict the rate and depth of tunnel rock cooling under different ventilation conditions.

Ventilation Speed :

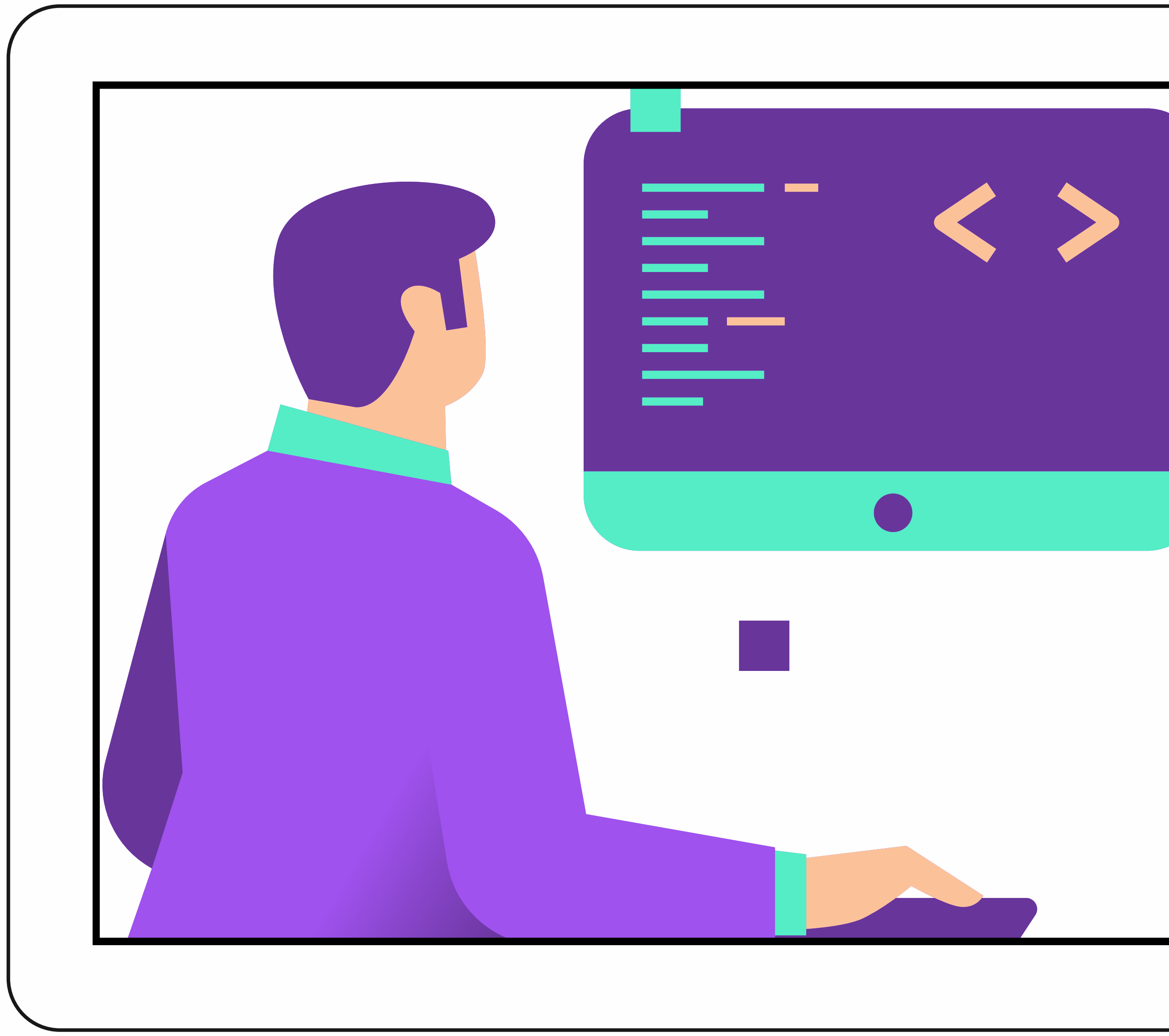
Tunnel airflow velocity is a powerful controlling factor for mine cooling rate: higher velocity dramatically accelerates wall and near-field cooling.

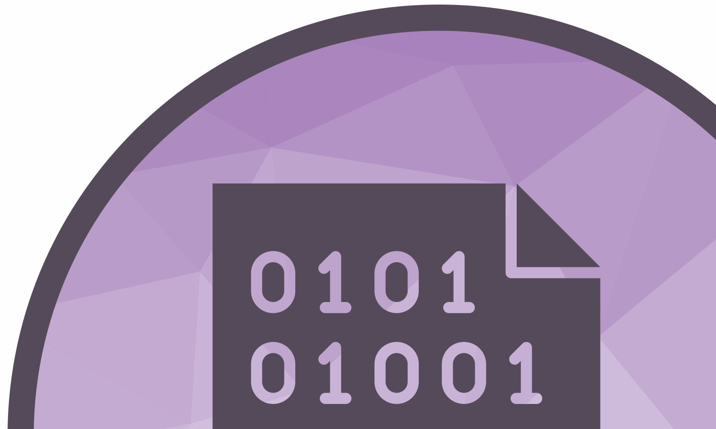
Boundary Conditions :

Dirichlet for perfect air-rock contact, convective for realistic airflow has a large impact on simulation accuracy and project outcomes.

Code Structuring :

Step-by-step debugging and visualizing time-dependent profiles are crucial for both understanding & communicating results.





CHALLENGES & CONSIDERATION

Improvements You Can Make

Numerical Stability
Choose time and space steps carefully to avoid unstable solutions.

Parameter Uncertainty
Real-rock properties and conditions vary, which affects model reliability.

Geometric Complexity
Real tunnels may not be perfect circles, requiring complex 2D or 3D codes.

Boundary Realism
Actual air-rock contact may offer resistance; real boundaries might not be fixed.

THANK YOU

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