
3 Simulation model

3.1 Preamble

The energy saving strategies developed in the previous chapter form part of an integrated system that varies continuously. Any combination of these strategies, implemented on a single system, can be predicted through real time simulation using actual data obtained from the mine as input and boundary values. For this purpose, an integrated dynamic component based simulation package called EfluxS, developed by Enoveer, was used.

The simulation model balances energy and mass over 60 second time intervals and permits hourly boundary inputs for each of the 8 760 hours of the year.

The following components are included in the simulation model:

- Air boundaries for hourly climate data inputs.
- Water boundaries for water temperature inputs.
- Dams to model thermal capacitance.
- Direct contact heat exchangers to model BACs, pre-cooling towers and condenser cooling towers.
- Water cooled chillers to model refrigeration machines.
- PI controllers to integrate basic control.
- Flow converges and diverges to configure flow networks.
- Pumps to model pump energy.
- Fans to model fan energy.

The equations used in the model are shown in the Sections 3.2 to 3.5. These equations are not discussed in detail but merely shown as reference to the equations used by the simulation software ⁽¹³⁾.

3.2 Direct contact heat exchangers

Equation 1 to *Equation 6* were used to model the BACs, pre-cooling towers and condenser cooling towers:

$$h_{a,o} = \frac{(1-r)}{(\tau-r)} h_{a,i} + \frac{(\tau-1)}{(\tau-r)} \varphi T_{w,i} \quad \text{Equation 1}$$

$$T_{w,o} = \frac{\left[\frac{(\tau-1)r}{(\tau-r)} h_{a,i} \right]}{\varphi} + \frac{(1-r)\tau}{(\tau-r)} T_{w,i} \quad \text{Equation 2}$$

$$r = \frac{C_a}{C_w} \quad \text{Equation 3}$$

$$\tau = \exp \left[-UA \left(\frac{1}{C_w} - \frac{1}{C_a} \right) \right] \quad \text{Equation 4}$$

$$C_a = m_a \quad \text{Equation 5}$$

$$C_w = \frac{c_{p_w} m_w}{\varphi} \quad \text{Equation 6}$$

Where:

$h_{a,i}$	<i>Inlet air enthalpy [kJ/kg]</i>
$h_{a,o}$	<i>Outlet air enthalpy [kJ/kg]</i>
$T_{w,i}$	<i>Inlet water temperature [°C]</i>
$T_{w,o}$	<i>Outlet water temperature [°C]</i>
m_a	<i>Air mass flow rate [kg/s]</i>
m_w	<i>Water mass flow rate [kg/s]</i>
c_{p_w}	<i>Water specific heat [J/kg.°C]</i>
φ	<i>Saturation enthalpy/water temperature ratio [J/kg.°C]</i>
UA	<i>Heat transfer coefficient [W/°C]</i>

3.3 Water cooled chillers

Equation 7 was used to calculate the refrigeration plant cooling capacity:

$$\dot{Q} = \dot{Q}_{ref} \left[(T_{evap} - T_{evap}^{ref})(0.03) + 1 \right] \left[(T_{cond}^{ref} - T_{cond})(0.03) + 1 \right] \quad \text{Equation 7}$$

Where:

\dot{Q}	<i>Cooling capacity [W]</i>
\dot{Q}_{ref}	<i>Full load cooling capacity at design conditions [W]</i>
T_{evap}	<i>Average evaporator temperature [°C]</i>
T_{evap}^{ref}	<i>Average evaporator temperature at design conditions [°C]</i>
T_{cond}	<i>Average condenser temperature [°C]</i>
T_{cond}^{ref}	<i>Average condenser temperature at design conditions [°C]</i>

Equation 8 was used to calculate the refrigeration plant COP:

$$COP = COP_{ref} [(T_{evap} - T_{evap}^{ref})(0.03) + 1] [(T_{cond}^{ref} - T_{cond})(0.03) + 1] [-0.781PL^2 + 1.25PL + 0.5313]$$

Equation 8

Where:

COP	<i>Coefficient of Performance [-]</i>
COP_{ref}	<i>Coefficient of Performance at design conditions [-]</i>
T_{evap}	<i>Average evaporator temperature [°C]</i>
T_{evap}^{ref}	<i>Average evaporator temperature at design conditions [°C]</i>
T_{cond}	<i>Average condenser temperature [°C]</i>
T_{cond}^{ref}	<i>Average condenser temperature at design conditions [°C]</i>
PL	<i>Partial cooling load fraction [-]</i>

Equation 9 was used to calculate the refrigeration plant power:

$$P_{wr} = \frac{\dot{Q}}{COP}$$

Equation 9

Where:

\dot{Q}	<i>Cooling capacity [W]</i>
COP	<i>Coefficient of performance [-]</i>

3.4 Pumps and fans

Equation 10 was used to calculate variable pump and fan pressure difference:

$$\Delta P = \frac{m_{pmp}^2}{\rho A} \quad \text{Equation 10}$$

Where:

ΔP	Pump pressure difference [Pa]
m_{pmp}	Pump mass flow [kg/s]
ρ	Water density [kg/m ³]
A	Flow admittance (m ⁴)

Equation 11 was used to calculate pump and fan electrical power:

$$P_{wr} = \frac{\Delta P \cdot m_{pmp}}{\rho \eta_{mot,pmp}} \quad \text{Equation 11}$$

Where:

P_{wr}	Power [W]
ΔP	Pump pressure difference [Pa]
m_{pmp}	Pump mass flow [kg/s]
ρ	Water density [kg/m ³]
$\eta_{mot,pmp}$	Pump and motor efficiency [-]

3.5 PI controllers

Equation 12 was used to model the PI controllers:

$$O = eK_p + e_{int}K_{in} \quad \text{Equation 12}$$

Where:

O	Controller output [-]
e	Control error [-]
e_{int}	Integrated control error over time [-]

K_p *Proportional gain constant [-]*

K_{in} *Integral gain constant [-]*

3.6 Conclusion

This simulation model is a convenient and accurate method for predicting the integrated effect of any combination of the energy saving strategies, as the addition of one strategy influences the system as a whole. The function to input dynamic boundaries such as the hourly weather conditions for the entire year is important for simulating a continually varying system such as a mine refrigeration system. It is essential to verify the solution obtained to either first principle calculations or measured data. It is not feasible to verify a large combination of strategies by first principle calculations; hence measured data should rather be used.