



THERMAL-FLUID MODELLING OF THE TRANSIENT BEHAVIOUR OF A CAPACITY-CONTROLLED UNDERGROUND REFRIGERATION UNIT

The modular and mobile Air-Cooling Unit (ACU) was developed to perform spot cooling in remote underground locations for where traditional cooling approaches proved less effective. Flownex was used to study the transient response of the ACU to fluctuating feedwater and air supply.

HVAC

CHALLENGE:

The transient response of the ACU chiller to fluctuating feedwater and air supply was not well known.

BENEFITS:

Simulation made it possible to obtain valuable response data without risking damage to a real ACU, saving money, time, and effort.

SOLUTION:

Flownex was selected due to its transient simulation capability, which allows the system response to be captured while fundamentally accounting for thermal and hydraulic inertial terms. The developed model helped identify:

- Operational limits for cooling feedwater supply.
- The obtainable cooling duty when feedwater availability is limited.
- System response to fluctuating feedwater and air supply.

DEEP MINING OPERATIONS



INTRODUCTION

South African mining operations are continuously expanding deeper underground to reach the available ore bodies, resulting in an increased demand for cooling. The traditional cooling approach, which uses a vast chilled water network supplied from a surface fridge plant, becomes less effective for deep mining operations, especially in remote underground locations.

Localized or spot cooling in remote areas has become a necessity to comply with mining regulations. The modular and mobile ACU (patent 2007/04679) was specifically developed to achieve more effective spot cooling. The ACU extracts heat from the air and rejects it to service water via a vapour compression cycle. The ACU is dependent on a constant feedwater flowrate to stay operational. Unfortunately, the water supply fluctuates and results in the ACU tripping on over pressure as a safety mechanism.

To improve operations and reduce downtime, infinite capacity control has been implemented on the compressor to handle fluctuating water flow. The effect of the infinite capacity control strategy on the thermal-fluid dynamics of the refrigeration cycle under varying environmental conditions is not well known. This study investigated the refrigeration cycle's response when subjected to fluctuating feedwater or air supplies.

SYSTEM DESCRIPTION

The ACU, shown in Figure 1 below, extracts heat from the air and rejects it into service water via a vapour compression cycle with a nominal cooling capacity of 290 kW.

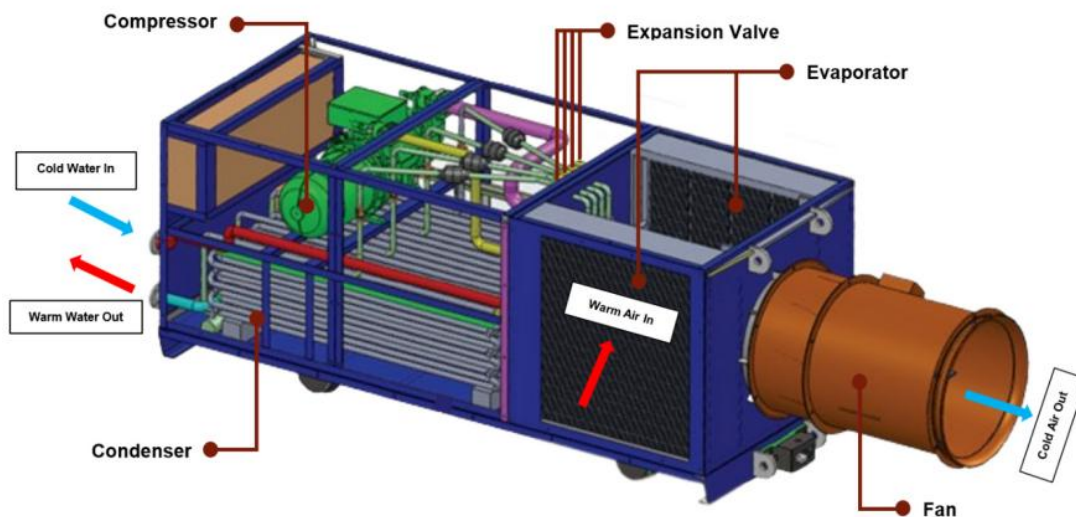


Figure 1: The ACU

OBJECTIVE OF SIMULATION

The study aimed to identify the operational limits for cooling feedwater supply, determine the obtainable cooling duty when feedwater availability is limited, and accurately capture the system's response to fluctuating feedwater and air supply, including the behaviour of the compressor's infinite capacity control.

FLOWNEX MODEL

A detailed thermal-fluid model of the ACU was developed using Flownex. Each of the main cycle components were individually modelled, and their accuracy verified using third-party software. These components were then integrated into a cycle model, the accuracy of which was validated against data recorded underground during operations in the mine. The Flownex model of the ACU is depicted in Figure 2 below.

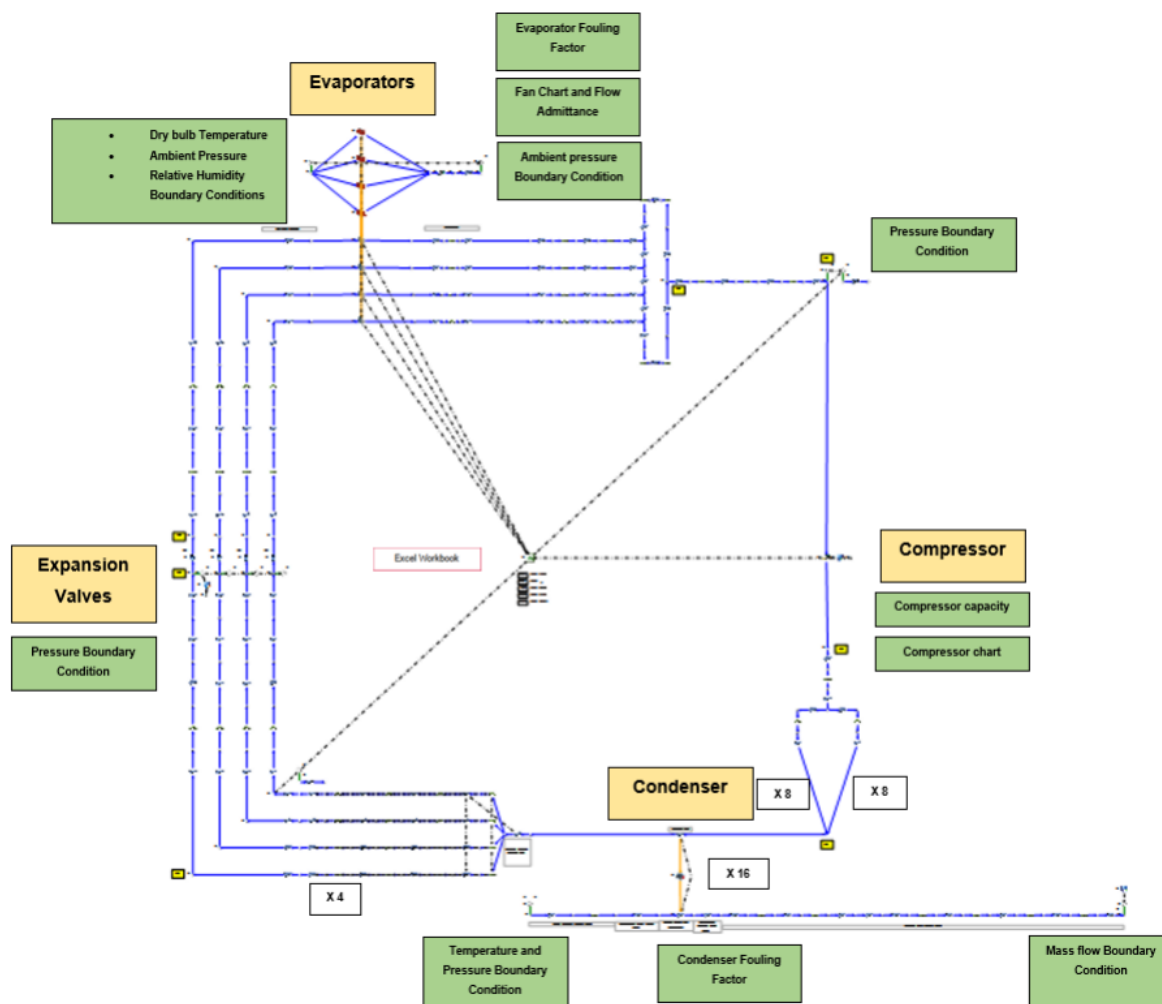


Figure 2: Flownex model of the ACU

Compressor Model

The compressor model relies on performance charts to calculate the pressure rise, mass flowrate and efficiency of the compressor at different capacity levels. These charts were generated using manufacturer data. Table 1 shows the average and maximum errors obtained when comparing the Flownex compressor model results to the performance data provided by the manufacturer.

Table 1: Compressor Model Verification Results

	Compressor Electrical Power	Refrigerant Mass Flowrate
Avg Error (%)	1.23	1.68
Max Error (%)	7.17	6.59

The error was calculated over 196 points using realistic boundary conditions representative of expected operation.

Condenser Model

The Dittus-Boelter correlation is used to calculate the convection heat transfer coefficient for both fluid streams. The tube in tube condenser was modelled as two discretized pipes that exchange heat through a conductive pipe wall. The model relies on the Darcy Weissbach correlation to calculate the primary pressure drop, where a Lockhart-Martinelli two-phase friction correction factor is used during two-phase flow conditions. Table 2 shows the average and maximum errors obtained when comparing the Flownex condenser model results with that of a fundamentally developed EES (Engineering Equation Solver) model.

Table 2: Condenser Model Verification Results

Regime		Refrigerant Temperature Change	Water Temperature Change	Water Pressure-Drop	Refrigerant Pressure-Drop	Heat Transfer
SH	Avg Error (%)	1.21	0.81	0.13	1.86	0.84
	Max Error (%)	1.89	1.56	0.27	3.29	1.54
TP	Avg Error (%)	2.29	2.39	0.07	8.96	2.38
	Max Error (%)	6.08	10.28	0.11	15.12	10.22
SC	Avg Error (%)	0.17	0.16	0.09	0.07	0.14
	Max Error (%)	0.26	0.70	0.11	0.36	0.18
SH, TP, and SC	Avg Error (%)	0.65	2.70	2.06	4.18	2.76
	Max Error (%)	2.21	5.75	3.90	11.97	5.75

Since the refrigerant undergoes phase change in the condenser, the model's accuracy was tested separately in the superheated (SH), two-phase (TP), and subcooled (SC) regions. This was done using a short 1m tube section with boundary conditions that ensured the refrigerant remained in the desired state. Additional testing was performed across the full length of the heat exchanger tubing, where the refrigerant transitioned from superheated too subcooled (the row marked **SH, TP, and SC** in Table 2). The error for each regime was calculated over 25 points using realistic boundary conditions representative of expected operation.

Expansion Valve Model

The thermostatic expansion valve model restricts the flow causing rapid expansion of the refrigerant. Since the model is based on first principles and straightforward to verify analytically, verification results are omitted for brevity.

Evaporator Model

The fin tube evaporator model uses the same heat transfer and pressure drop correlations as the condenser model on the tube side where the refrigerant flows. A friction factor correlation for the

pressure drop on the fin side where air flows was derived from manufacturer data. In addition, the fin side relies on a Colburn J-factor to calculate the heat transfer coefficient between the air and the finned tubes. Table 3 shows the average and maximum errors obtained when comparing the Flownex evaporator model results to the performance data provided by the manufacturer.

Table 3: Evaporator Model Verification Results

	Heat Transfer	Air Temperature Change	Air Pressure-Drop	Refrigerant Pressure-Drop
Avg Error (%)	4.42	3.26	1.99	2.30
Max Error (%)	9.07	7.52	8.50	8.49

The error was calculated over 29 points using realistic boundary conditions representative of expected operation.

Integrated Model Validation

Table 4 shows the average and maximum errors obtained when comparing the Flownex ACU model results to logged operational data for an ACU.

Table 4: Integrated ACU Model Validation Results

Dataset		Condenser Heat Transfer	Compressor Electrical Power	Air Temperature Change	Water Temperature Change
1	Avg Error (%)	0.55	0.45	0.55	0.87
	Max Error (%)	1.04	0.94	1.15	1.37
2	Avg Error (%)	0.50	0.90	1.00	0.46
	Max Error (%)	1.32	1.89	1.27	1.19
3	Avg Error (%)	1.22	1.53	0.56	1.32
	Max Error (%)	1.84	2.71	0.91	1.95
4	Avg Error (%)	0.41	5.51	0.81	0.42
	Max Error (%)	1.06	6.59	1.32	0.93
5	Avg Error (%)	1.52	1.28	0.47	1.77
	Max Error (%)	2.01	3.07	1.07	2.25
6	Avg Error (%)	2.94	1.00	3.58	3.16
	Max Error (%)	3.96	3.35	4.22	4.19

The error for each dataset was calculated over 12 points, with each dataset representing one hour of ACU operation. From the available logged data, the 6 datasets were selected to capture the widest range of ACU operating conditions. From the results in Table 4, it can be concluded that the integrated ACU model accurately captures ACU performance over the operating range investigated.

SYSTEM CONTROL

After validating the model for steady-state operation, the next step was adding system control to make it possible to capture system response when environmental variables like feedwater or air supply changes. The system regulates itself by adjusting the compressor capacity and changing the opening of the expansion valves.

Compressor Control

The operating capacity remains constant when the compressor discharge pressure is within the control range (19 to 23 bar). Capacity control increases if the discharge pressure falls below 19 bar and decreases if it rises above 23 bar, where these limits are referred to as the lower and upper break points respectively, with adjustments made until the pressure returns to the set range. Furthermore, if the compressor discharge pressure exceeds 26 bar or the compressor suction pressure falls below 2 bar, high pressure and low-pressure switches trip the compressor to prevent damage. These pressures are referred to as the upper and lower trip limits.

Expansion Valve Control

Expansion valves respond to changes in the superheat, where the opening is adjusted automatically according to the compression of an internal spring (adjusted for the setpoint) and the expansion of gas in a sensing bulb connected to piping at the compressor suction side. When generated SH is less than the setpoint, the valve opening closes to reduce refrigerant mass flowrate. Given that the order of magnitude for heat flux from the air remains consistent, the lower refrigerant flowrate will undergo more superheating. Likewise increasing the valve opening would lead to reduced SH if the temperature was higher than the setpoint value.

Modelling Control in Flownex

The dynamic behaviour of both the compressor and expansion valves was modelled using Quick Script components. Quick Script components are highly versatile and most commonly used to implement custom correlations for flow and heat transfer. In this case, they were used as custom controllers to mimic the response of the compressor and expansion valves.

CASE STUDIES

Case studies were set up to determine the transient response of the ACU chiller to fluctuating feedwater and air supply. Baseline boundary conditions for all the case studies were as follows:

- Feedwater temperature is 21 °C
- Feedwater flowrate is 9 kg/s
- Ambient air temperature is 37.4 °C
- Ambient relative humidity is 80 %

Case 1: Feedwater supply gradually turned off

Case purpose: To investigate the system response to diminishing feedwater supply. This scenario is likely to occur at night when drilling occurs. Drilling demands significant volumes of water, putting pressure on supply. Thus, as the night progresses the ACU feedwater supply decreases.

Procedure: The ACU operates at the baseline condition when feedwater supply decreases by 1 kg/s every 300 s.

Time step size: 500 ms.

Simulation duration: 45 min.

The following four figures will be used to structure the discussion and illustrate the key impact of reduced feedwater supply on the thermal-fluid cycle.

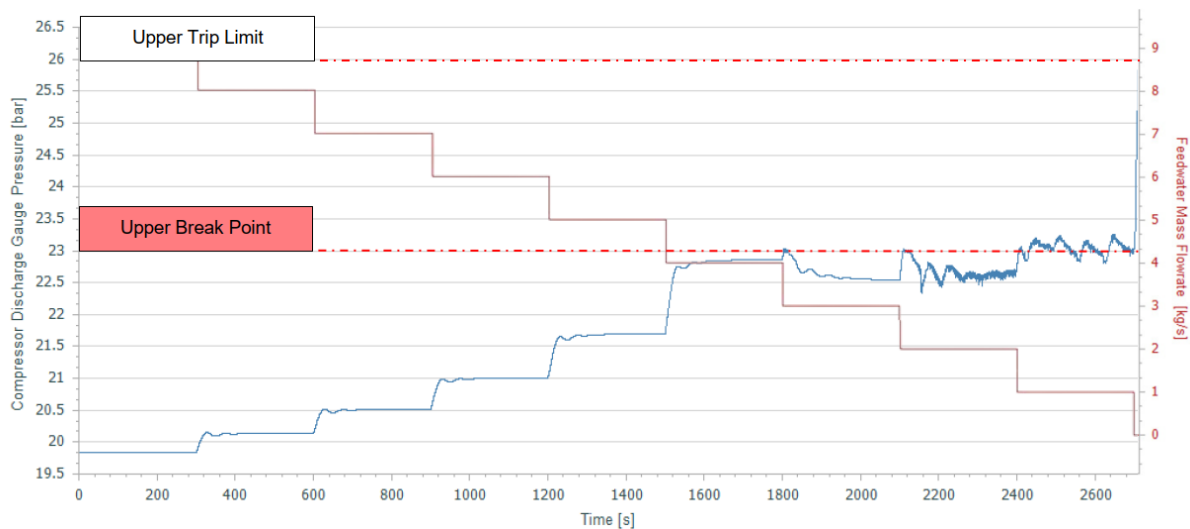


Figure 3: Variation in compressor discharge gauge pressure over time

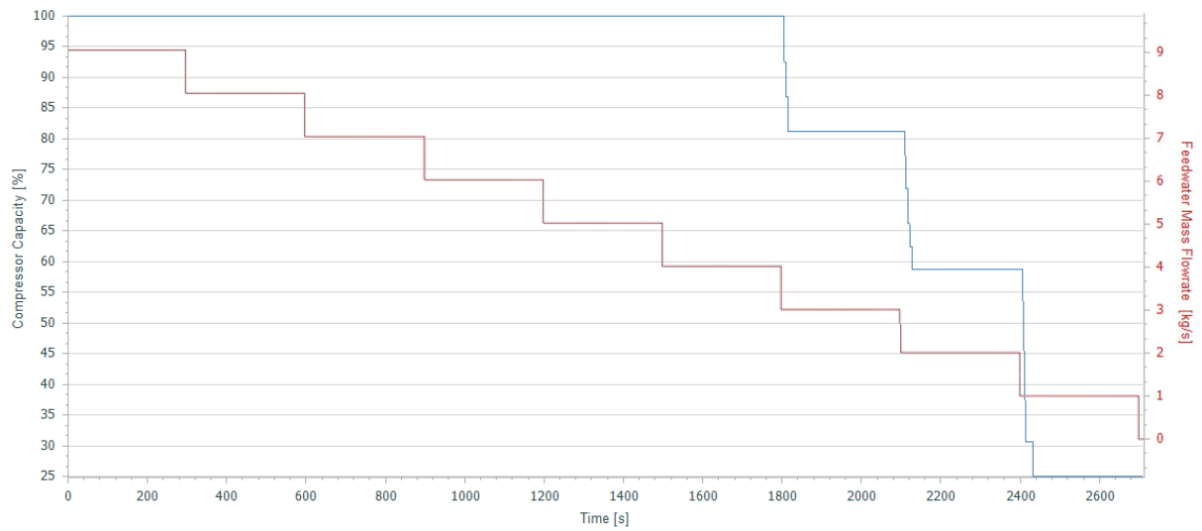


Figure 4: Variation in compressor capacity over time

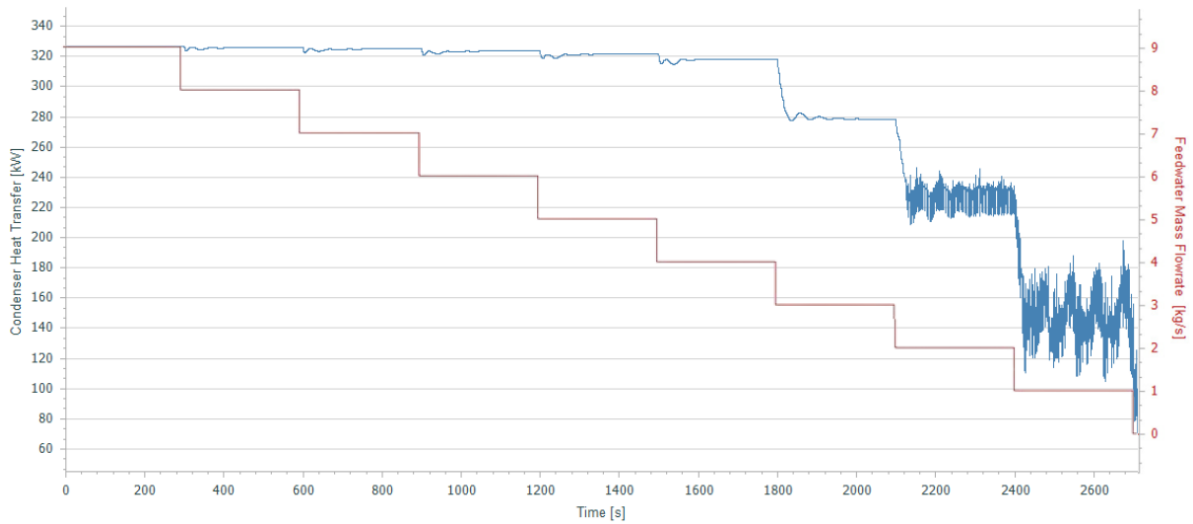


Figure 5: Variation in condenser heat transfer over time

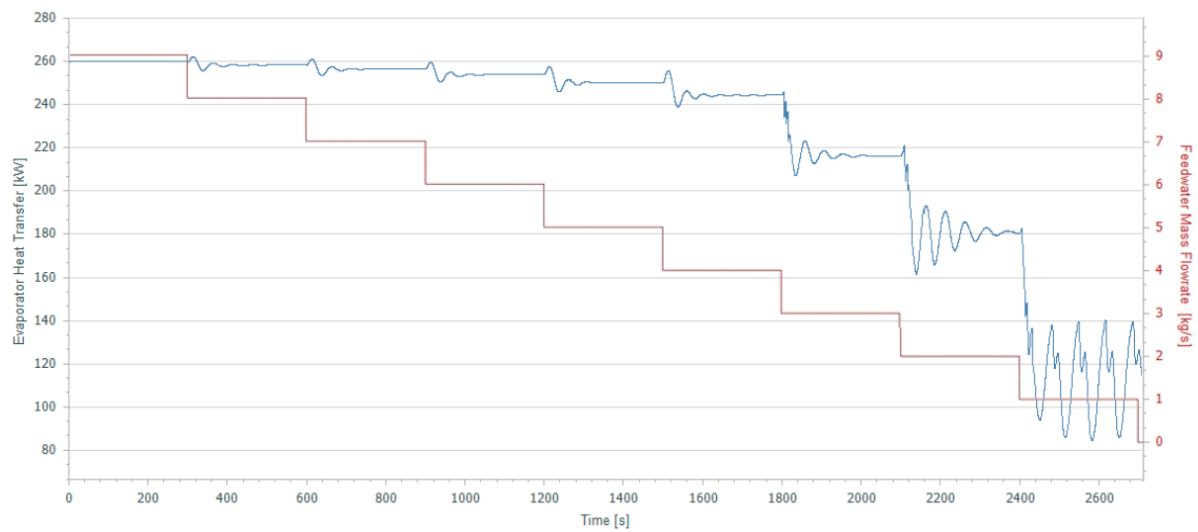


Figure 6: Variation in evaporator heat transfer over time

Between 0 and 2700s, the ACU model regulated itself in response to the decreasing feedwater supply by reducing compressor capacity to stay within pressure limits. When the feedwater dropped below 4 kg/s, the compressor discharge pressure exceeded the 23 bar upper break point, and when it fell below 1 kg/s, the 26 bar upper trip limit was breached, ending the simulation. To manage the rising pressure, the compressor capacity decreased to 81.2% at 3 kg/s, 58.8% at 2 kg/s, and 25% at 1 kg/s. This demonstrated how the infinite capacity control maximised achievable cooling while adapting to severe water cutbacks.

Case 2: Feedwater fluctuations

Case purpose: To investigate the system response to fluctuating feedwater supply. This scenario is likely to occur when feedwater supply valves are adjusted to redistribute flow in the mine.

Procedure: The ACU operates at the baseline condition with a feedwater supply of 4.5 kg/s for 300 s. This flowrate is then gradually decreased to 2.25 kg/s, which is maintained for 300 s, after which this transitions to 9 kg/s for another 300 s interval. The feedwater flowrate transitions occur gradually rather than instantaneously, as a point of realism.

Time step size: 500 ms.

Simulation duration: 16 min.

The following four figures will be used to structure the discussion and illustrate the key impact of fluctuating feedwater supply on the thermal-fluid cycle.

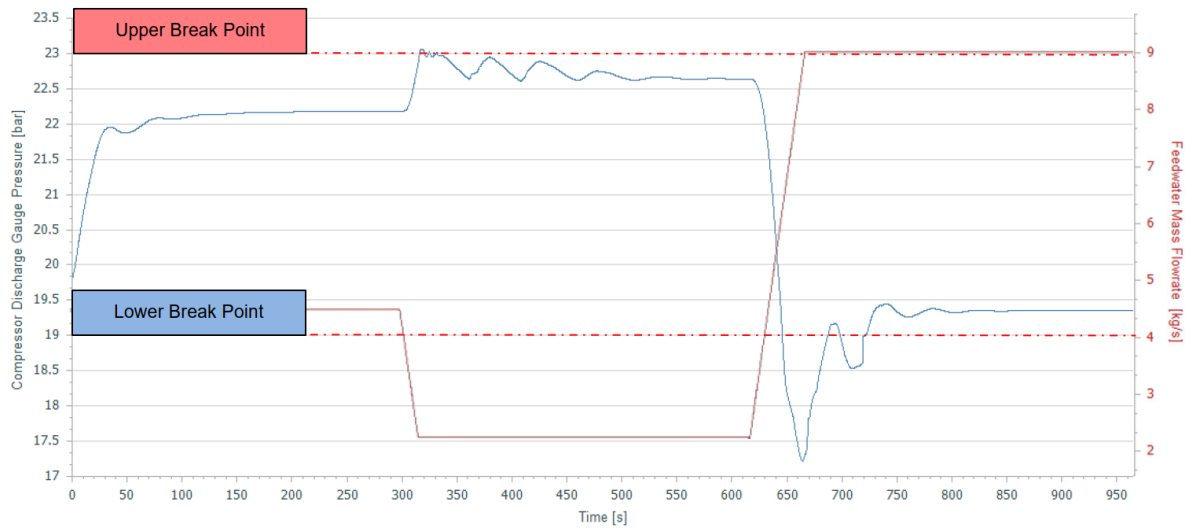


Figure 7: Variation in compressor discharge gauge pressure over time

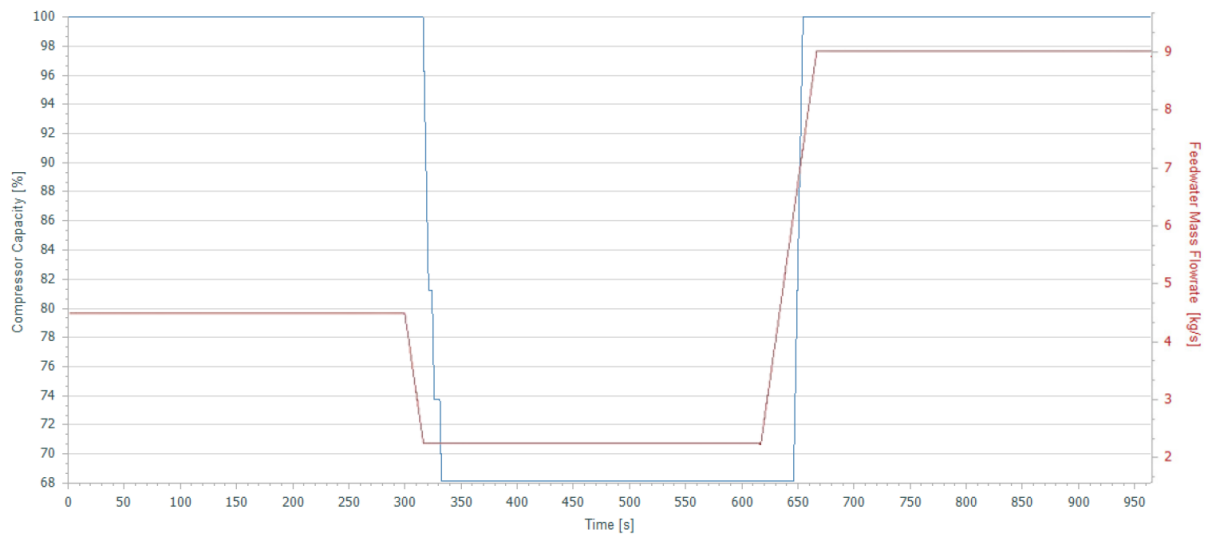


Figure 8: Variation in compressor capacity over time

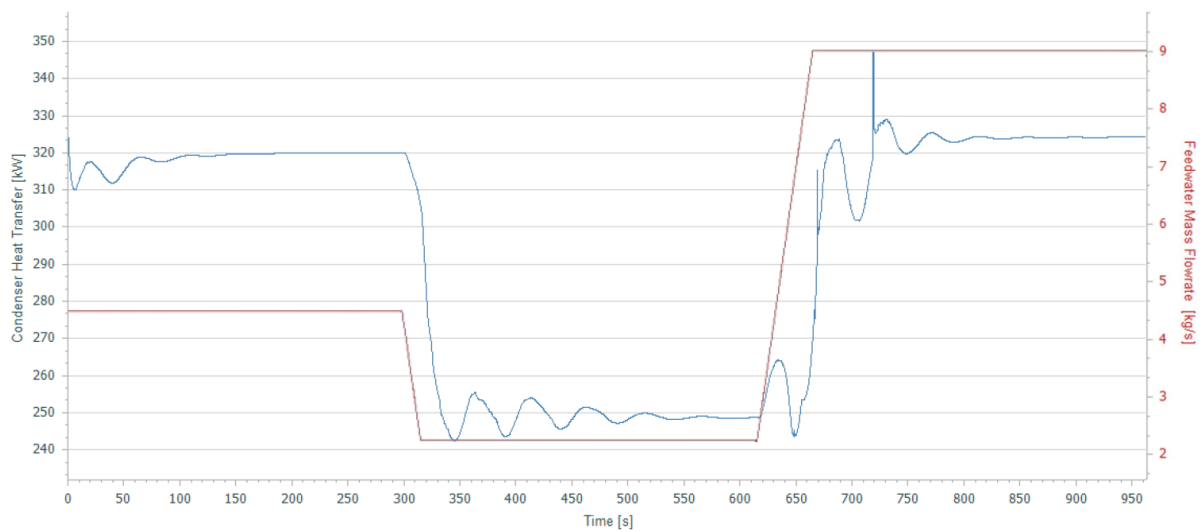


Figure 9: Variation in condenser heat transfer over time

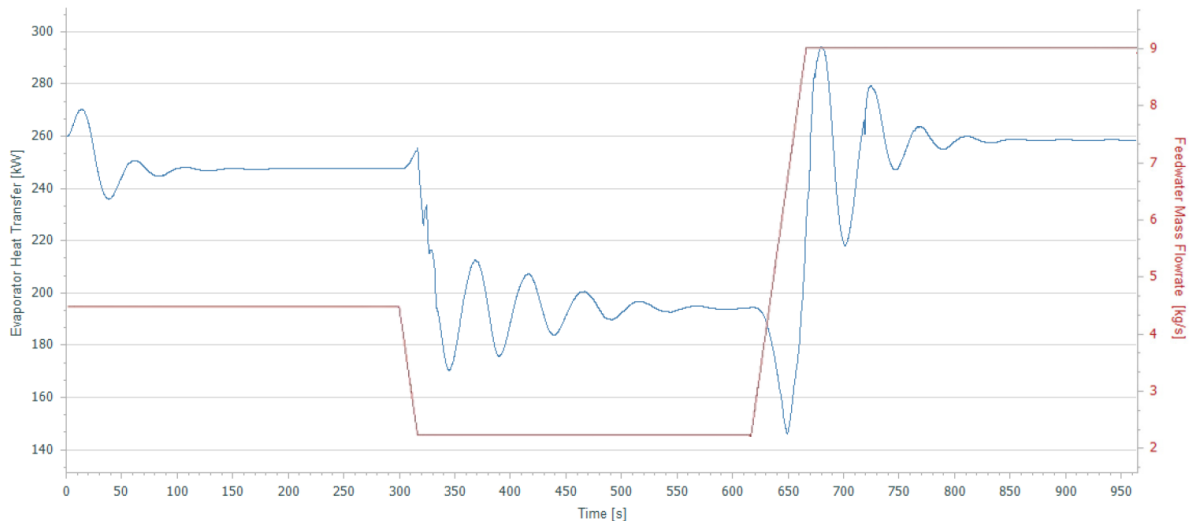


Figure 10: Variation in evaporator heat transfer over time

From 0 to 668s, the ACU model demonstrated its ability to restore cooling capacity as feedwater supply recovered. When feedwater dropped from 4.5 to 2.25kg/s, the compressor discharge pressure exceeded the 23bar upper break point, triggering a capacity reduction to 68.1%, which lowered refrigerant flow and reduced condenser and evaporator heat transfer. As feedwater gradually returned to 9kg/s, the improvement in condenser heat transfer resulted in a reduction in the discharge pressure to below the 19bar lower break point, allowing the compressor to ramp back up to 100% capacity. This demonstrates how infinite capacity control dynamically restores full cooling performance when feedwater availability improves.

Case 3: Blocked-off air supply to half of the evaporators

Case purpose: To investigate the system response if the air supply to half of the face area of the evaporator packs was cut off. This scenario is likely to occur when the ACU is placed too close to a wall, forcing all the air to be sucked in by the fan through the unblocked evaporator packs.

Procedure: The ACU operates at the baseline condition for 5 s when the air supply to half of the evaporator packs is cut-off, with the total flow of air draw in by the fan through the unblocked side for the remainder of the simulation.

Time step size: 100 ms.

Simulation duration: 60 s.

The following four figures will be used to structure the discussion and illustrate the key impact of a blocked-off air supply on the thermal-fluid cycle.

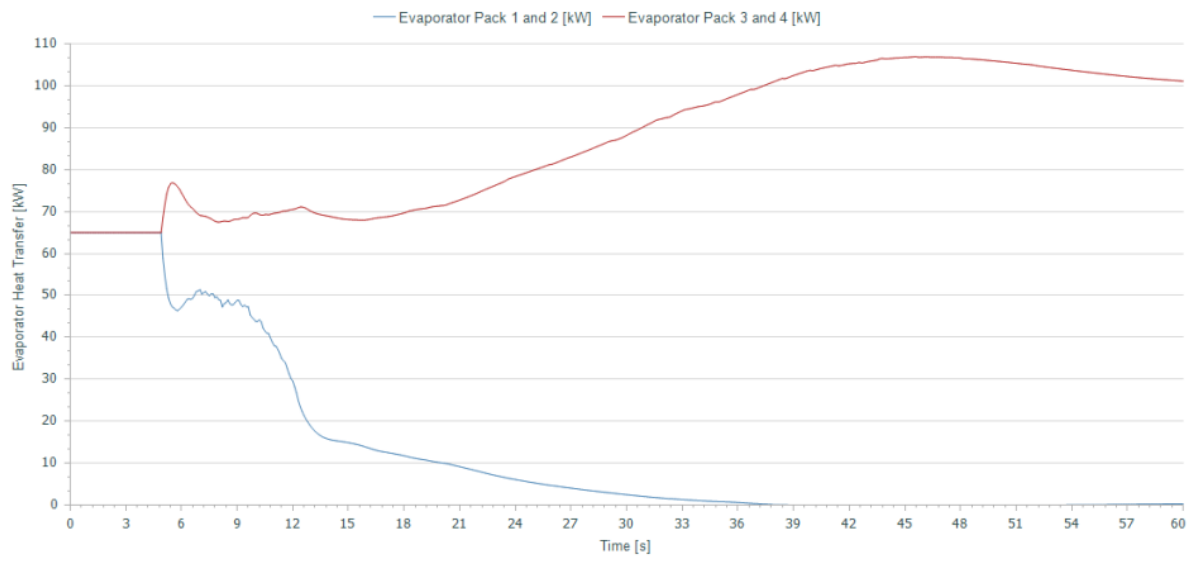


Figure 11: Variation in evaporator heat transfer over time

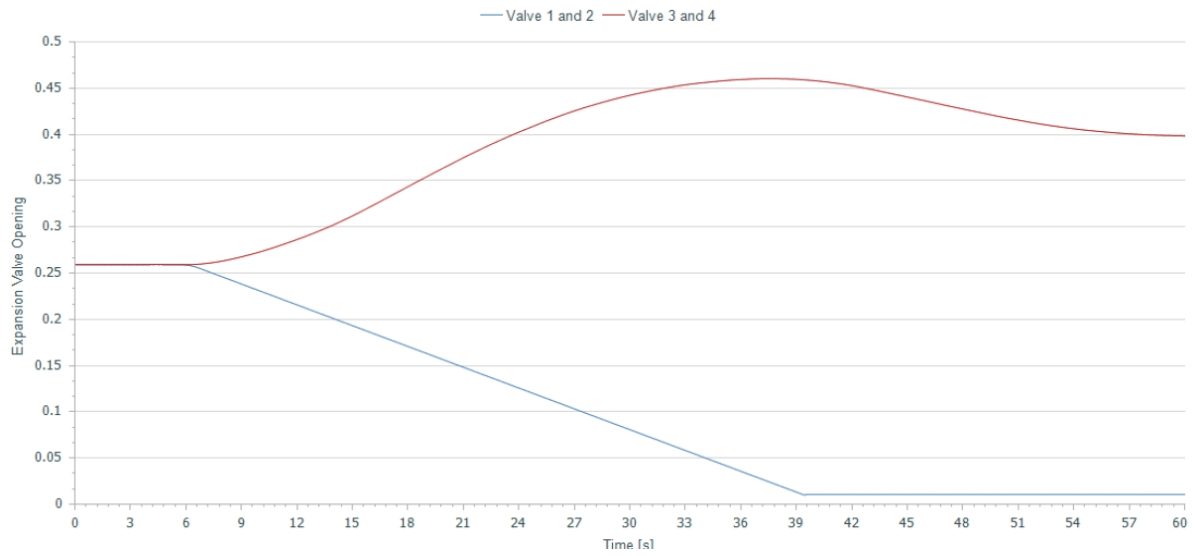


Figure 12: Variation in expansion valve opening over time

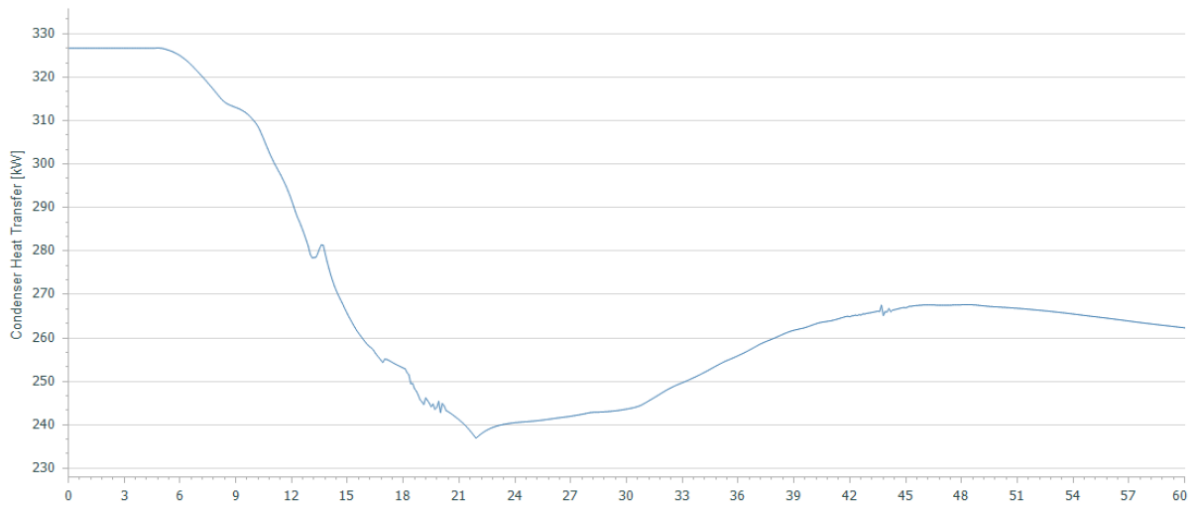


Figure 13: Variation in condenser heat transfer over time

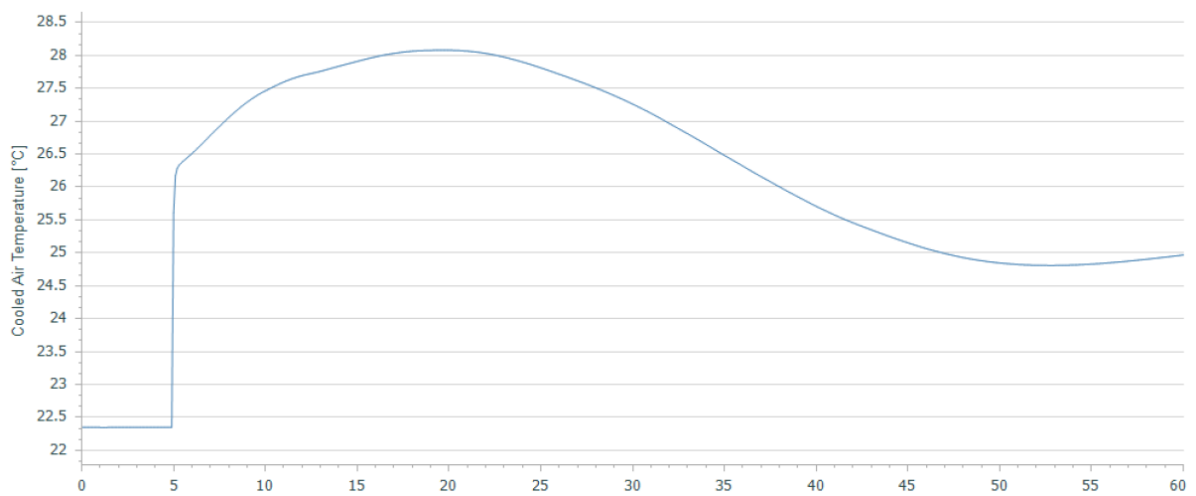


Figure 14: Variation in outlet air temperature over time

This scenario was simulated by redirecting airflow through only half the evaporator packs at 5 s. The blocked side lost heat transfer, while the unblocked side compensated with increased performance. Expansion valves adjusted accordingly to stabilise the superheat, and the system settled with a reduced overall refrigerant flowrate, lower evaporating temperature, and decreased heat duty. Although the cooled air temperature rose slightly from 22.4 to 25 °C, the ACU maintained operation with reduced cooling capacity.

CONCLUSION

Flownex proved invaluable to this study, firstly by providing an environment to create a validated simulation model of the ACU, and then by enabling analysis of the system's thermal-fluid response to fluctuating environmental conditions. Through this, it was possible to identify the operational limits for cooling feedwater supply, the obtainable cooling duty under constrained conditions, and the unit's response to changes in both feedwater and air supply.

From the first case study, it is clear that the feedwater supply should remain between 1 and 4 kg/s. Anything below this range risks tripping the unit, while anything above is wasteful. Within this range, the obtainable cooling duty varies between 100 kW and 320 kW for feedwater at 21 °C with an ambient air temperature of 37.4 °C.

The infinite capacity control strategy proved well suited for an ACU operating in an environment with fluctuating feedwater supply. In the second case study, it maintained ACU operation under reduced feedwater conditions by lowering operational capacity and was able to return the unit to full operation when the feedwater supply was restored, an especially valuable trait in the mining environment.

Lastly, in the third case study, the unit maintained operation at reduced capacity despite half of the evaporator face area being blocked. Unlike water scarcity, such air supply restrictions are typically easier to prevent.