Utilizing a Digital Twin for the Troubleshooting of a Geothermal Power Station

Ben Strode-Penny[1]

[1]Mercury Energy Ltd., 283 Vaughn Road, Rotorua 3010, New Zealand

ben.strode-penny@mercury.co.nz

Keywords: *Digital Twin, Symmetry Modelling, ORC*

ABSTRACT

A digital twin of the Rotokawa power station is under development. The quasi-empirical model is intended to replicate the behaviour of the real plant, based on process engineering first principles. This paper highlights how an initial version of the model was successfully used to troubleshoot a performance decline in the plant's Organic Rankine Cycle (ORC) bottoming units. Calculation of key plant parameters highlighted potential causes of this decline, and the initial model could then be used to quantify the impacts of different changes. The study results have been used to inform and direct a campaign to restore plant performance.

1. INTRODUCTION

Rotokawa is a combined cycle geothermal power plant, located near Taupo, with a net capacity of 34 MW. The power plant was commissioned in 1997 and underwent modifications in 2021 as part of the RKA rebalancing project. The station contains several Organic Rankine Cycle (ORC) units, and one steam turbine (Steam Turbine Generator, STG) as follows:

- STG10, a 16.4 MWg steam turbine

- OEC 01, a 4.43 MWg brine ORC unit

- OEC 21, a 9.3 MWg brine ORC unit

- OEC 11 and 12, 2x 3.6 MWg bottoming ORC units

As part of the rebalancing project, the Rotokawa station was connected to the neighbouring Nga Awa Purua (NAP) triple flash steam power plant via the H-line separator. The H-line separator supplies additional higher-enthalpy geothermal fluid to NAP, and it supplies additional brine to Rotokawa. This is indicated in figure 1.

"Digital twin" models can be used in the chemical and processing industry to improve plant efficiency, performance and reliability (Mane, Dhote, Sinha, & Thirumalaiswamy, 2024). The definition of a "digital twin" is broad, however a digital twin framework typically includes three major components: a high-fidelity digital representation of a process, machine, or other system, the physical system itself, and the means to update the model with new data at an appropriate frequency (Abdelrahman, et al., 2025; Wanasinghe, et al., 2020).

Due to changes in reservoir and plant condition, there is a desire to improve Mercury's digital models of the Rotokawa power station. An improved digital model would allow better prediction of plant performance under off-design conditions, improved plant troubleshooting, and could be used for investigating future opportunities to improve plant performance. For these reasons, Mercury started a project to develop a "digital twin" of the Rotokawa station in 2024. This digital model was developed using Schlumberger's Symmetry™ process simulation software.

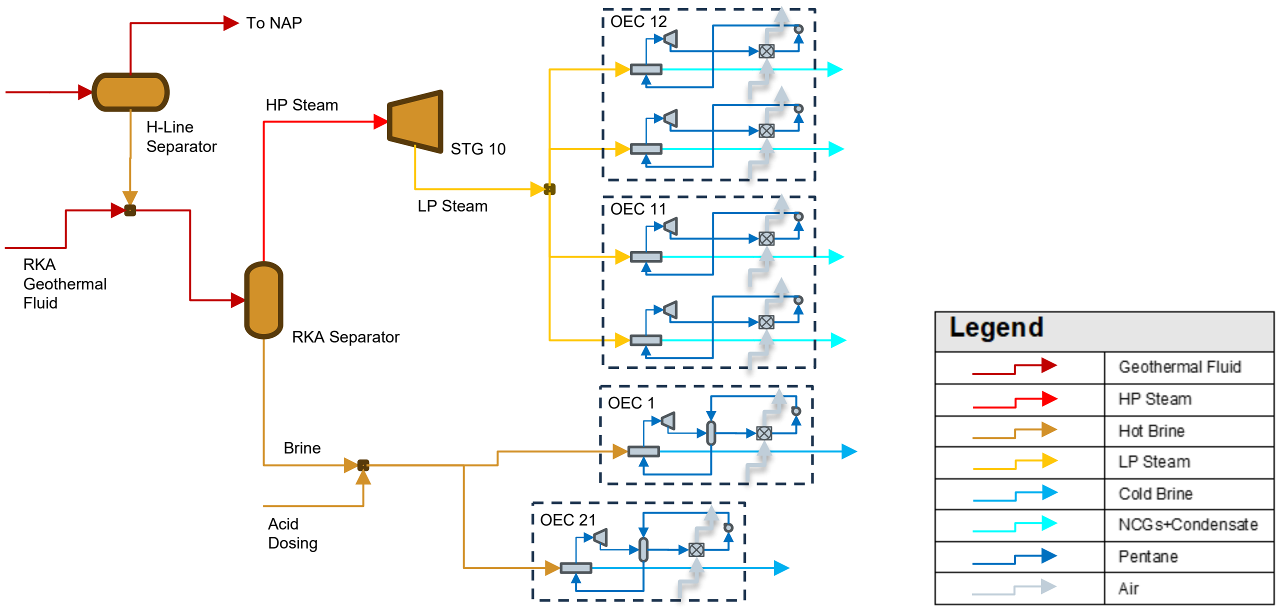

Figure 1: Overview of the Rotokawa Station Model

2. METHODOLOGY

An initial version of the Rotokawa station model has been developed. Figure 1 gives a general overview of how the model has been constructed. The quasi-empirical, steady-state model takes a variety of input parameters, including turbine constants, heat exchanger constants, ambient conditions, and geothermal fluid compositions and enthalpy. It then uses these input parameters to predict plant performance.

"Design" models of station unit operations were used to calculate key input parameters. These models are input data, and use these inputs to calculate unit characteristics, such as turbine efficiencies, Stodola coefficients, and heat exchanger heat transfer coefficients. These characteristics then become input parameters for a central "Ratings" model. This is shown in Figure 2.

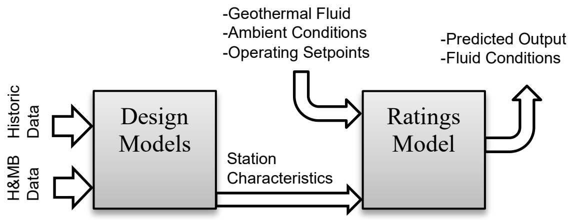

Figure 2: Overview of Modelling Methodology

The station ratings model can be divided into the steam separation system and STG, and the four ORC units. The following sections describe how these model components have been constructed. Note that specific process data has been excluded, due to commercial sensitivity.

2.1. Steam Separation and STG

As indicated in Figures 1 and 3, RKA is supplied with 2-phase geothermal fluid from several production wells, and brine from the H-line separator. This resulting lower-enthalpy mixture then enters the RKA separator, where it is separated into steam and brine.

The steam is fed to STG10, where energy is extracted to generate current. The steam flowrate is a function of turbine inlet pressure, outlet pressure, and the characteristics of the turbine. This relationship can be modelled using Stodola's Law of the Ellipse (Cooke, 1985), which can be rearranged to give Equation 1.

$$\dot{m} = \frac{K_S{'}}{\sqrt{T_i}} \cdot \sqrt{{P_i}^2 - {P_o}^2} \qquad (1)$$

Here, $\dot{m}$ is the mass flow through a turbine, T_i is turbine inlet absolute temperature (i.e. in Kelvin), P_i is inlet pressure, P_o is outlet pressure, and $K_S{'}$ is the full Stodola Coefficient, which is a unique constant for the turbine.

In addition, when inlet conditions are near saturation, and variations in turbine inlet temperature are small, the influence of temperature on flowrate can be neglected. Equation 1 can therefore be simplified to give Equation 2, which describes the pressure-flow relationship through a turbine.

$$\dot{m} = K_S \cdot \sqrt{{P_i}^2 - {P_o}^2} \qquad (2)$$

Where $\dot{m}$ is again mass flow through a turbine, P_i is inlet pressure, P_o is outlet pressure, and K_S is the simplified Stodola Coefficient for a turbine.

Lastly, when outlet pressure squared is small relative to inlet pressure squared, the outlet pressure term can also be neglected. In addition, if flow through the turbine nozzles is choked, outlet pressure will have no influence on mass flow. Under these conditions, the relationship can be further simplified to give $\dot{m} = K_S \cdot P_i$.

In the station ratings model, the Rotokawa separator pressure is set at a given setpoint. The Rotokawa geothermal fluid flow is then adjusted in Symmetry™, using a controller operation, so the STG inlet steam flow matches the flowrate calculated according to a Stodola relationship. This is highlighted in Figure 3. This control scheme mirrors typical station operation, where separator pressure is maintained by manipulating flow from production wells.

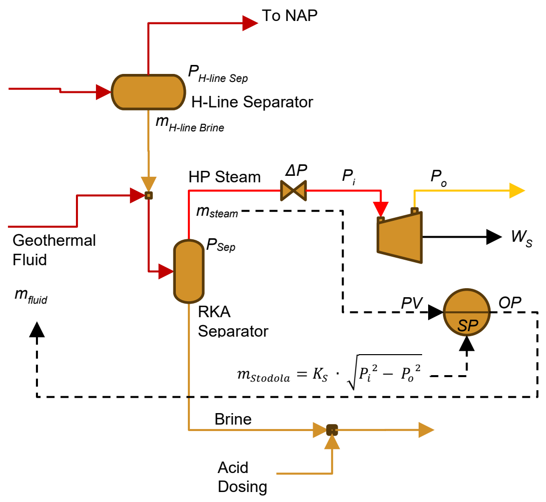

Figure 3: Steam separation system and STG section of the Rotokawa Station Model.

The resulting brine from the RKA Separator is mixed with acid-dosed condensate, before being fed to the brine units. Key input and output variables for the steam separation and STG section of the ratings model are given in Table 1.

Table 1: Key inputs and outputs for the steam separation and STG section of the ratings model.

Inputs	Outputs
STG Stodola Coefficient	STG Output
STG Adiabatic Efficiency	Geothermal Fluid Flow
STG Outlet Pressure	Brine Flow
Pressure Drop	STG Outlet Conditions
Geothermal Fluid Enthalpy and Composition	
Separator Pressures	
H-line Brine Flow	

2.2. ORC Units

Rotokawa station contains four ORC units, which use n-pentane as a working fluid. This includes two brine units, OEC 1 and 21, and two bottoming units, OEC 11 and 12. The bottoming units consist of a left-hand and right-hand train, which drive a common generator. For this reason, the bottoming units have been modelled as separate left-hand and right-hand units, giving a total of six ORC units in the station model.

A similar methodology has been used for modelling all ORC units. Key differences are the fuel source used (brine vs low pressure steam), and the absence of recuperators in the bottoming units. This is indicated in Figure 1. The following section will describe the OEC 1 model, however the methodology used is applicable to the other units.

The OEC 1 vaporizer is fed hot brine, which is used to boil motive fluid (pentane). This pentane then passes through a turbine, performing work to generate current. In OEC 1 and 21, turbine exhaust gas is first cooled in a recuperator, which provides heat recovery. The pentane is then condensed in an air-cooled condenser (ACC). Due to condenser geometry, the pentane is assumed to exit the ACC in equilibrium with the atmosphere of the condenser collector. The liquid pentane is then pressurized by a pump and returned to the vaporizer. This is shown in Figure 4.

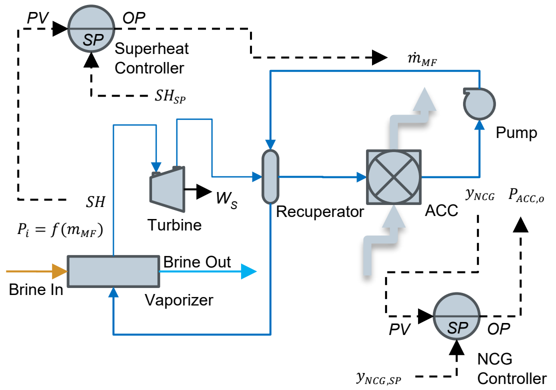

Figure 4: OEC 1 section of the Rotokawa Station Model.

In the ratings model, the ORC unit models have two key setpoints: superheat, and condenser non condensable gas (NCG) content. The superheat controller adjusts pentane mass flow. Pentane mass flow is also used to calculate vaporizer pressure via a Stodola relationship. The ACC controller adjusts the condenser outlet pressure to achieve an NCG content setpoint, which is calculated according to Rault's law using Equation 3.

$$y_{NCG} = 1 - \frac{P_{Pentane}^{\circ}}{P_{ACC,o}} \quad (3)$$

Here, $P_{ACC,o}$ is the condenser outlet pressure, $P_{Pentane}{}^{\circ}$ is the vapour pressure of pentane at the condenser outlet temperature, and y_{NCG} is the NCG vapour fraction in the condenser collector.

Additional error terms for turbine inlet quality and condenser outlet quality were included in the control scheme, to improve model convergence.

This control scheme has parallels with typical station operation. Under typical operation, pentane mass flow is controlled by a vaporizer level control loop. The superheat in the vaporizer outlet can be manipulated by increasing and decreasing the vaporizer level setpoint. Condenser NCG content is controlled by the operation of vapour recovery units (VRUs).

As described previously, ORC unit characteristics were first calculated using design models. These characteristics, as well as operating setpoints, ambient conditions and geothermal fluid enthalpy and composition can be used to predict unit performance using the central ratings model. Key inputs and outputs for ORC units in the ratings model are given in Table 2.

Table 2: Key inputs and outputs for the ORC unit sections of the ratings model.

Inputs	Outputs
Vaporizer UA	Unit Output
Turbine Stodola Coefficient	Vaporizer Pressure
Turbine Adiabatic Efficiency	Condenser Pressure
Recuperator UA (OEC 1 and 21 only)	
ACC UA	
ACC Airflow	
Pump Efficiency	
Pressure Drops	
Air Temperature	
Fuel flow	
Superheat and NCG Setpoints	

3. MODEL APPLICATION

The bottoming units OEC 11 and 12 have experienced a reduction in generation since 2019. This is shown in Figure 5. The Rotokawa station model was used to troubleshoot this decrease in performance, and it provided new insights into what has been driving this decline.

To troubleshoot the bottoming units, ten years of historical data were first cleaned, and then input into station design models using Symmetry™'s case study function. By taking a whole-of-station approach, many potential drivers of unit performance decline could be assessed simultaneously. The characteristics calculated by design models can be used to describe station performance under off-design conditions, and long-term trends of these characteristics were generated. Several key trends are presented in Figure 6, noting that values have been hidden due to commercial sensitivity

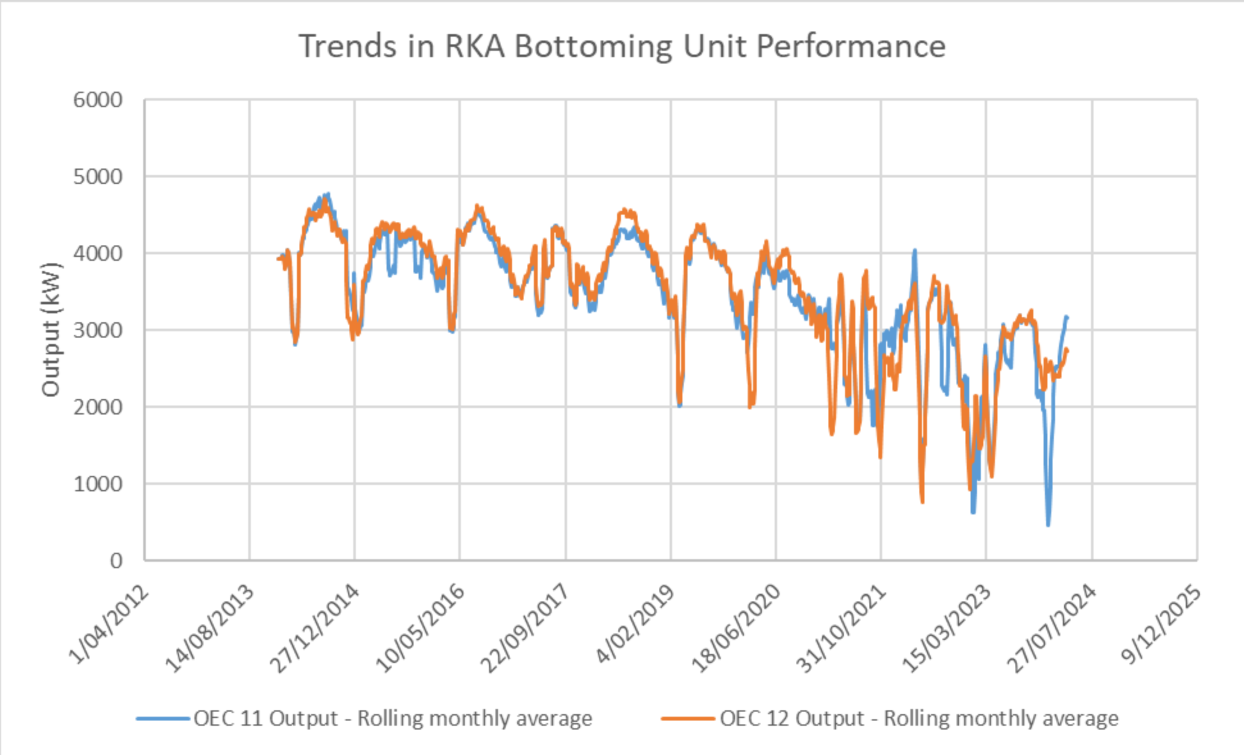

Figure 5: Trends in RKA Bottoming Unit Performance

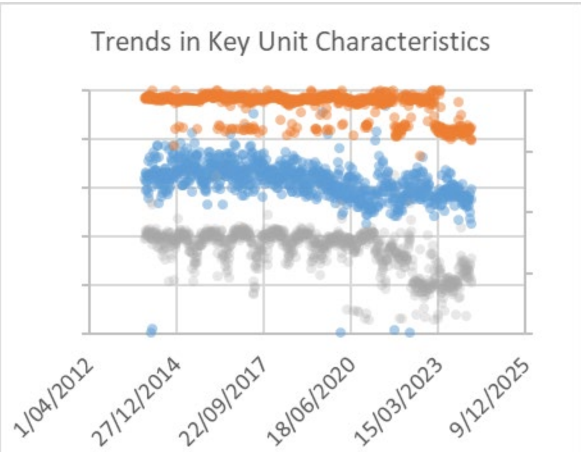

Figure 6: Trends in key unit characteristics

The station ratings model could be used to generate correction curves, which in turn could be used to readily predict the effect of changes in unit characteristics on performance. A drawback of using Symmetry™ can be long calculation times. However, correction curves generated in Symmetry can be utilized in other programs to more quickly analyse large datasets. Correction curves and unit characteristic data could be used to predict the past 10 years of hourly and average monthly generation, with an average root-mean squared error of ~6% when outliers were excluded.

By using trends in station characteristics, other relevant variables, and the central ratings model, the potential impacts of various changes on performance under typical operating conditions could be quantified. These results are presented in Figure 7. This information could then be used to inform targeted interventions, in order to address the identified issues and restore unit performance.

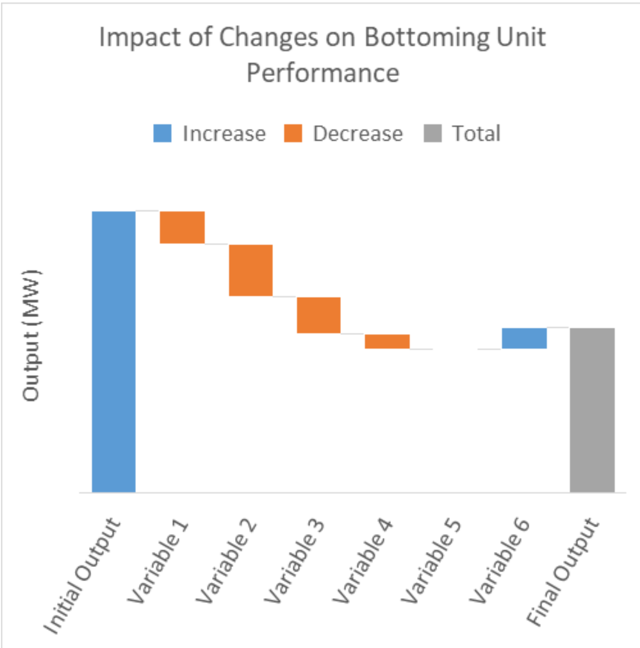

Figure 7: Impact of changes in key variables on bottoming unit performance.

As a result of these targeted interventions, unit performance has been increased by approximately 20%. Additional improvement initiatives are currently planned, to further increase performance.

4. DISCUSSION

We were able to successfully apply an initial version of the model to diagnose the causes of unit performance decline. By using a whole-of-station, first-principles approach, we were able to investigate multiple causes simultaneously. A key advantage of a full-station model, that accurately reflects real-world behaviour, is its adaptability. It can readily be applied to identify and diagnose new issues as they arise.

There remains significant potential to improve the fidelity of the model. Opportunities for improvement include incorporating pump and valve curves, increasing the number of control loops - including vaporizer pressure control in ORC unit models and brine and steam control loops in the station model - and the integration of production and reinjection lines and wells. An increased level of accuracy improves the model's ability to mimic real-world behaviour, however this can come at the cost of longer computation times.

Additionally, there is an opportunity to improve the model's data input capabilities. Automated calculation of station and unit characteristics, utilizing automatically updated data and station design models, would enable faster diagnosis of and response to plant issues.

A key assumption made for the ORC unit models is that pentane leaves the condenser in equilibrium with the vapour space of the condenser collector. This assumption is explored further, by analysing the expected flow regime of the condenser tubes.

The equilibrium level expected for steady liquid flow through a tube can be estimated using equations for open channel flow. Under conditions of steady, uniform open channel flow, the mechanical energy balance can be expressed using equation 4 (Tilton, 1997).

$$\frac{\Delta h}{\Delta x} = S = f \cdot \frac{\left(Q/A\right)^2}{2g \cdot D_H} \qquad (4)$$

Where S is the tube slope, f is the Darcy friction factor, Q is liquid volumetric flowrate, A is liquid cross-sectional area, and D_H is the wetted hydraulic diameter of the liquid. A and D_H will vary with liquid level, and f will vary with velocity which also varies with liquid level.

Equation 4 can be rearranged to give Q as a function of level:

$$Q = A(l) \cdot \sqrt{\frac{S \cdot 2g \cdot D_H(l)}{f(l)}} \qquad (5)$$

Where:

$$A = r^2 \cdot cos^{-1}\left(1 - \frac{l}{r}\right) - (r - l) \cdot \sqrt{2rl - l^2} \qquad (6)$$

$$D_H = {}^{4A}/_{P_w} \qquad (7)$$

$$P_w = 2r \cdot cos^{-1}\left(1 - \frac{l}{r}\right) \qquad (8)$$

Here, r is condenser tube inner radius, l is condenser tube level, and P_w is liquid wetted perimeter.

Equations 5 to 8, as well as a suitable method for determining the friction factor, could be used iteratively to determine Q and f as a function of level. At design liquid flowrates, the equilibrium tube level was estimated to be ~20 - 40% of tube diameter; this provides an estimate for the exit conditions of the condenser tube. This analysis highlighted that the liquid motive fluid has insufficient velocity to fully plug the condenser tubes.

Within the condenser tubes, we can predict that annular flow will initially develop as pentane condenses on the internal walls. As more liquid accumulates at the bottom of the tube, the flow regime will take on a more stratified character. The liquid will then exit the tubes with a level of ~20-40%. This is indicated in Figure 8.

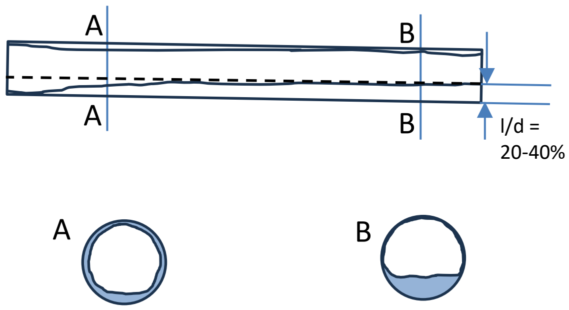

Figure 8: Expected flow regime within the condenser tubes.

Liquid pentane exits the condenser tubes, into a partially filled horizontal vessel – the condenser collector. This shown in Figure 9.

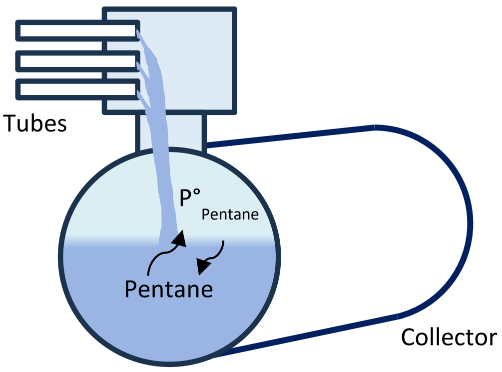

Figure 9: General cross-section of a condenser collector.

The condenser collector vapour space is static, and the vapour therefore has sufficient residence time to reach equilibrium with the average outlet conditions of the condenser tubes. If pentane begins to leave the tubes with some average amount of subcooling, due to e.g. a decrease in ambient temperature, then this will result in disequilibrium in the collector. The pentane vapour within the collector will cool and condense, reducing the collector pressure, restoring equilibrium, and eliminating the subcooling. Similarly, if there is a net increase of pentane vapour entering the collector, this will raise the condenser pressure until equilibrium is reached.

Pentane travelling through the bottom pass of the condenser may leave with some subcooling, as the bottom tubes are exposed to colder air, and there will be some thermal resistance across the liquid pentane. Similarly, some pentane may leave the top tube passes uncondensed. However, the average outlet conditions of the pentane will tend towards equilibrium with the collector vapour space. Critically, all measured or false subcooling, defined in equation 9, arises due to the presence of non-condensable gasses in the collector. These non-condensable gasses generate additional turbine backpressure, reducing unit efficiency.

$$T_{Subcool} = T_{Sat,\ Pentane}\left(P_{ACC,out}\right) - T_{ACC,out} \quad (9)$$

5. CONCLUSION

An initial version of a Rotokawa station model, built in Symmetry^{TM}, has been developed. This quasi-empirical, steady-state model has been successfully applied to troubleshoot a performance decline in the station's bottoming units. The model provided actionable insights, that have been used to direct a campaign to restore unit performance. This programme has already successfully increased unit output by approximately 20%.

A key strength of taking a whole-of-station, first-principles approach is the ability to readily model the effect of many different variables upon station performance. Key characteristics describing the station have been calculated using unit design models, from design and historical data. These characteristics, as well as other inputs such as operating setpoints and ambient conditions, can be input into a ratings model to predict output. Major achievements of the model include the incorporation of Stodola coefficients to describe turbines, accurate representation of ORC unit behaviour via inclusion of superheat and NCG content as key input variables, and development of correction curves for efficient performance impact analysis.

Open channel flow analysis provided additional insights into the flow conditions within the condenser. This work indicated that liquid leaves the condenser tubes with a level of approximately 20-40%, and that the liquid has insufficient velocity to fully plug the condenser tubes. This provides validation to the assumption that fluid leaves the condenser in equilibrium with the collector vapour space. In particular, this re-affirms that measured subcooling arises due to the presence of NCGs in the condenser, which increase turbine backpressure and reduce efficiency.

While the initial model has provided significant utility, several opportunities for model improvement have been identified. These include the incorporation of the steamfield, inclusion of unit operating limits via additional control loops, and automated data input and output capabilities. These improvements could increase model fidelity, and improve real-time analysis, although additional complexity can come at the cost of computation time and model utility. This trade-off remains an important consideration.

The success of this whole of station modelling approach at Rotokawa, using dedicated process modelling software, demonstrates the opportunity for similar approaches at other stations. The model's first-principles approach, and adaptability, makes it a powerful tool for station trouble-shooting and optimisation, as well as for investigating future development opportunities. As New Zealand's geothermal industry seeks to increase energy supply, high-fidelity, first-principles digital models and "digital twin" technologies represent a valuable advancement in geothermal power plant management and optimization.

5. ACKNOWLEDGEMENTS

I would like to acknowledge my friends and colleagues at Mercury, in particular Olivia Goh and Neil Davis, who were more than happy to provide me with advice, and to answer all my questions. I would also like to acknowledge the support and encouragement I received for this project from my previous manager, Richard Maginness. Lastly, I would like to acknowledge my lecturers at the University of Auckland, in particular Paul Collins, Professor Brent Young and Dr Robert Kirkpatrick, who provided me with a robust and invaluable foundation in geothermal power station modelling.

REFERENCES

Abdelrahman, M., Macatulad, E., Lei, B., Qintana, M., Miller, C., & Biljecki, F. (2025). What is a Digital Twin anyway? Deriving the definition for the built environment from over 15,000 scientific publications. *Building and Environment*, 112748.

Cooke, D. H. (1985). On Prediction of Off-Design Multistage Turbine Pressures by Stodola's Ellipse. *J. Eng. Gas Turbines Power*, 596-606.

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, 1016-1022.

Mane, S., Dhote, R. R., Sinha, A., & Thirumalaiswamy, R. (2024). Digital twin in the chemical industry: A review. *Digital Twins and Applications*, 118-130.

Tilton, J. N. (1997). Fluid and Particle Dynamics. In R. H. Perry, D. W. Green, & J. O. Maloney, *Perry's Chemical Engineers' Handbook (7th ed.)* (pp. 12-13). New York: McGraw-Hill.

Wanasinghe, T. R., Wroblewski, L., Petersen, B. K., Gosine, R. G., James, L. A., & Silva, O. D. (2020). Digital Twin for the Oil and Gas Industry: Overview, Research Trends, Opportunities, and Challenges. *IEEE Access*, 104175-104197.