Validating a Thermodynamic Model of the Otahuhu B Combined Cycle Gas Turbine Power Station

Hannon Lim[1], Jonathan Currie[2], David I. Wilson[2]
[1]Electrical and Electronic Engineering
AUT University
Auckland, New Zealand
Email: hannonlim@gmail.com
[2]Industrial Information and Control Centre
AUT University

Abstract—**Contact Energy, which operates a large 400 MW combined cycle gas turbine (CCGT) power plant in Auckland, offers its generation, as do all electrical generators in New Zealand, into the national electricity market. To be commercially viable, the station must be able to be dispatched to follow the time-varying electricity market, and be able to cost effectively generate sufficient energy to meet its dispatched load. Optimising plant performance for least cost generation requires models that accurately predict steam and water cycle thermodynamics, heat transfer within the boiler, and combustion thermodynamics in the gas turbine. The Industrial Information and Control group has developed a comprehensive thermodynamic modelling package capable of accurately calculating water/steam and combustion thermodynamics. The software also comes supplied with numerous unit operations suitable for modelling components of a CCGT power station. This paper describes the application of a steady-state modelling project applied to an actual 400 MW power station. The paper develops a model using current software functionality, validates the model using actual plant data and suggests possible improvements.**

Keywords-Modelling; Simulation

I. INTRODUCTION

In the past two decades New Zealand's electricity industry has undergone numerous major organisational changes. Prior to 1994 the Electricity Corporation of New Zealand, (ECNZ), a state owned enterprise, was responsible for generation, transmission, regulation, and policy advice. Distribution and retailing was taken care of by local electric power boards (EPB) or Municipal Electricity Departments (MED). In 1994 Transpower was formed to handle the ECNZ's transmission assets [9]. In 1996 ECNZ's generation and gas assets were split between the ECNZ and newly formed Contact Energy Limited. This was accompanied by the creation of New Zealand's Wholesale Electricity Market [5, 9]. In 1999 the breakup of the ECNZ was completed with the remaining generation assets being divided amongst three new state owned enterprises: Meridian Energy, Genesis Energy and Mighty River Power. Contact Energy was privatised and the distribution and retailing businesses were separated [5, 9]. The retail businesses were then sold, primarily to generation companies [5]. These events have led to the formation of New Zealand electricity industry as it is today, with the four generation companies both bidding to sell electricity on the wholesale electricity market while simultaneously purchasing electricity to cover their retail commitments [5]. Significant organisational changes in the electricity industry still continue, most recently with the partial privatisation of Mighty River Power. In addition Rio Tinto is threatening to sell Tiwai Point Aluminium smelter which currently consumes 15 percent of the national electrical power. One consequence of the current commercial electricity landscape is that power companies are strongly incentivized to optimise their operation, including the generation of electricity.

The geography, resource and population distribution of New Zealand has a strong influence on the way electricity is generated and used. Approximately 55 to 60 percent of New Zealand's electricity is generated from hydroelectric power stations [10]. New Zealand's greatest hydrological resources are located in the lower South Island while the largest population centres and greatest power consumption are located in the upper North Island [1]. The long, narrow geography of New Zealand dictated the need for a High Voltage DC (HVDC) transmission line linking the two islands [11]. This set up the current situation where electricity generated in the south is primarily consumed in the north.

The above factors have contributed to creating a highly competitive electricity market in New Zealand. With the hydrological resources of the south available throughout New Zealand via the HVDC transmission link and the major energy companies effectively operating on both sides of the fence, by both selling and buying electricity, the day to day operational decisions of these energy companies have become increasingly complex. This is especially so for energy companies operating fossil fuel power stations, being subject to additional operational restrictions and costs not applicable to renewable electricity generation. To remain competitive in such an environment, detailed knowledge and efficient operation of such assets becomes essential. Due to the complexity of thermal power stations both of these goals can be best achieved through accurate modelling [3].

Currently the most efficient fossil fuel thermal power plants are Combined Cycle Gas Turbines (CCGT). These power stations operate on two cycles. The gas turbine operates on the Brayton cycle [4, 8] where air is compressed into the combustion chamber, mixed with natural gas and then combusted. The hot exhaust gases are then allowed to expand through the gas turbine generating work. This work is used to drive both the gas turbine compressor and a generator to generate electricity. However, the exhaust gases leaving the turbine are still very hot (over 500°C) [8]. These exhaust gases are used as the heat source for the second stage which operates on the standard Rankine cycle [4]. This heat is extracted by feeding the hot exhaust gases through the Heat Recovery Steam Generator (HRSG). The HRSG is essentially a large duct containing many heat exchangers. It is through these heat exchangers that heat from the exhaust gases is extracted and used to convert compressed water in the heat exchanger coils to superheated steam [4]. The steam is then allowed to expand through steam turbines, again generating work which is used to generate more electricity [4, 8]. The steam leaving the turbines is then condensed back into water and compressed, completing the cycle [4, 8]. Modern CCGT power stations are capable of achieving efficiencies of greater the 60% (LHV) compared to the approximately 40% for single cycle plants [8].

This project has been undertaken to develop a steady-state thermodynamic model of the Otahuhu B CCGT power station, owned and operated by Contact Energy. The intended application for the model is to predict fuel consumption at various levels of demand, forecast changes in plant output capacity due to environment conditions, such as pressure and temperature, and to provide a reference from which plant degradation can be monitored. This paper describes the development of the initial model using the functionality currently available in the JSteam software package. The current functionality is analysed in the context of the goals of the project and possible improvements including areas for future work are discussed.

II. CASE STUDY

The Otahuhu B CCGT power station is located in the Auckland suburb of Otahuhu, 9m above sea level. Otahuhu B consists of a single train (gas turbine, generator and steam turbine on a single shaft) with a total combined cycle generation capacity of 400MW. It has a single gas turbine providing the energy for a three pressure level steam cycle via the HRSG. The gas turbine burns natural gas with no secondary firing in the HRSG. The natural gas is sourced from the Maui and Kapuni gas fields. A typical composition for the natural gas is shown in Table 1.

Table 1. Typical composition of the natural gas consumed at Otahuhu B.

Compound	*Mole Fraction*
Methane	80.668%
Ethane	7.540%
Propane	3.534%
n-Butane	0.712%
IsoButane	0.638%
n-Pentane	0.111%
IsoPentane	0.151%
n-Hexane	0.080%
Carbon Dioxide	5.923%
Nitrogen	0.643%

III. JSTEAM

The static mass and energy balance model was created using the JSteam thermodynamic modelling software developed by the Industrial Information and Control Centre (I^2C^2) [7]. The software itself utilises industry standard IAPWS 2007 correlations for water and steam thermodynamics [6] and the Peng-Robertson Equation of State for combustion thermodynamics. The JSteam library may be accessed via several interfaces [2]. For the purposes of the modelling described in this paper, the Excel add-in and Matlab interfaces have been used.

A. Process Flow Diagram

The process flow diagrams (PFD) for this plant are easily generated by simply selecting the icon for each unit operation and connecting them together via arrows as shown in Fig 1. The purpose of the PFD in JSteam is to provide a logical framework on which to start building the model.

B. Unit Operations

The JSteam software comes supplied with numerous unit operations commonly encountered in steam utility systems. The unit operations are functions that can be pasted directly into the Excel spreadsheet. The inputs are then entered into the

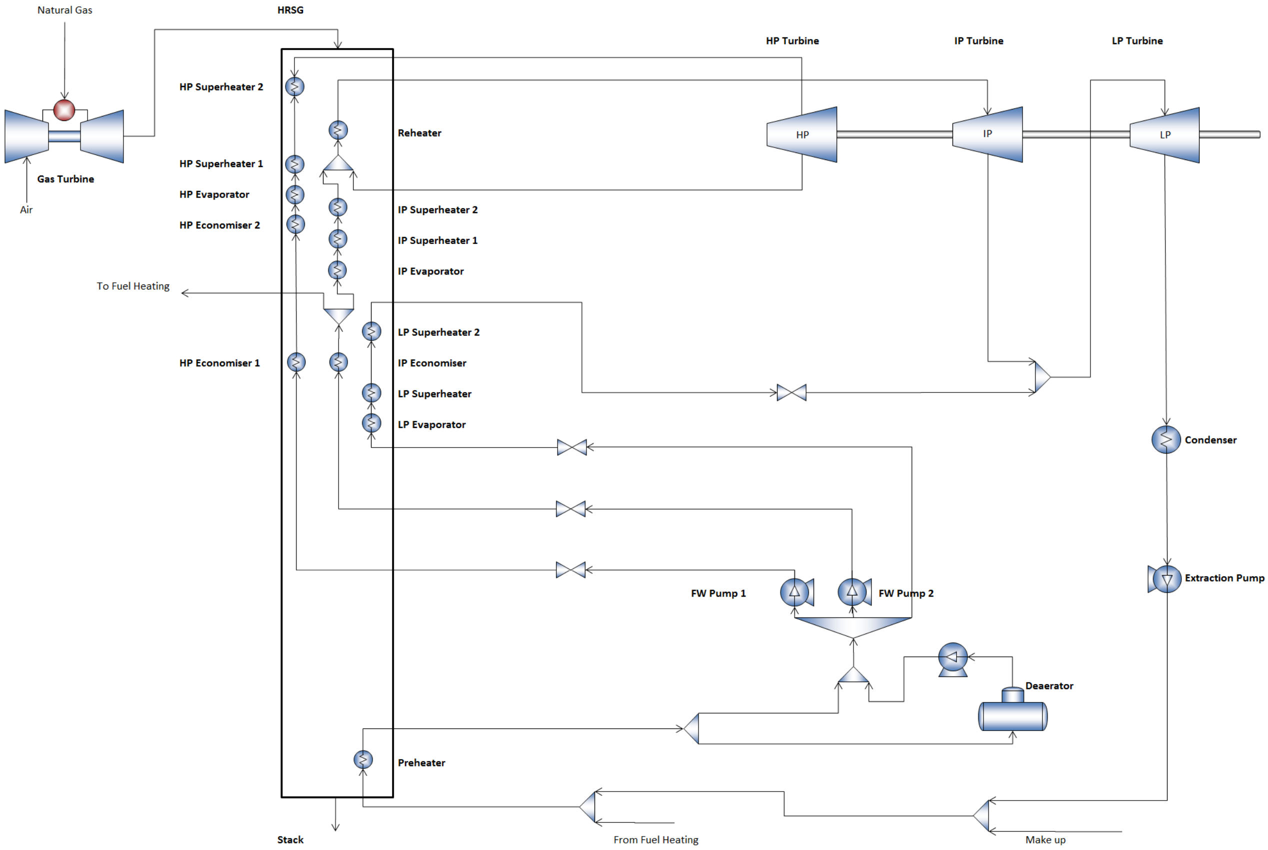


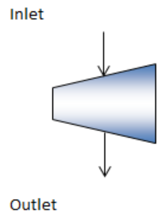
Fig 1. A Simplified process flow diagram of Otahuhu B.

appropriate cells, the function evaluated and the outputs returned in the associated cells. The key unit operations used to model the steam cycle were the steam turbine, pump and deaerator. Otahuhu B has a bypass deaerator that is not normally in service. It is used for example, to provide deaerated water used to fill the boilers after an outage. As such during steady-state operation it does not affect the thermodynamics of the plant and while included in the PFD of Otahuhu B it is not operational. Multiple configurations of steam turbines are available. For this model the mass flow based, single stage steam turbine was used for each of the three steam turbines required. This allowed the shaft work to be determined based on the working fluids state and mass flow rate.

The gas turbine is modelled by the supplied gas turbine combustion unit operation. Again, this model is simply pasted into the excel spreadsheet. As this model involves the combustion of fuel, the fuel composition (as in Table 1) must be specified.

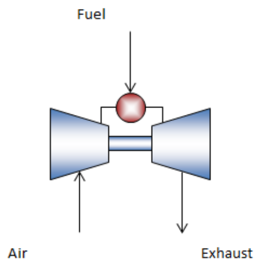
C. Heat Exchangers

Heat exchangers in the HRSG and condenser were modelled using simple mass and energy balances across each exchanger.



Inlet Enthalpy	
Inlet Pressure	
Outlet Pressure	
Efficiency	
Outlet Mass Flow	
Power	0.00 kW
Outlet Enthalpy	0.00 kJ/kg

a) The JSteam symbol and Excel template for the single stage, mass flow based steam turbine



Fuel Composition	
Fuel Temperature	
Air Temperature	
Exhaust Temperature	
Compressor Pressure	
GT Power	
GT Efficiency	
Air Mass Flow	0.00 tonne/hr
Fuel Mass Flow	0.00 tonne/hr
Exhaust Mass Flow	0.00 tonne/hr
O2 Mole Fraction	0.00
CO2 Mole Fraction	0.00
SO2 Mole Fraction	0.00
CO2 Mass Flow	0.00 tonne/hr
SO2 Mass Flow	0.00 tonne/hr
Status	Fuel Error

b) The JSteam gas turbine symbol and Excel template.

Fig 2. JSteam unit operations.

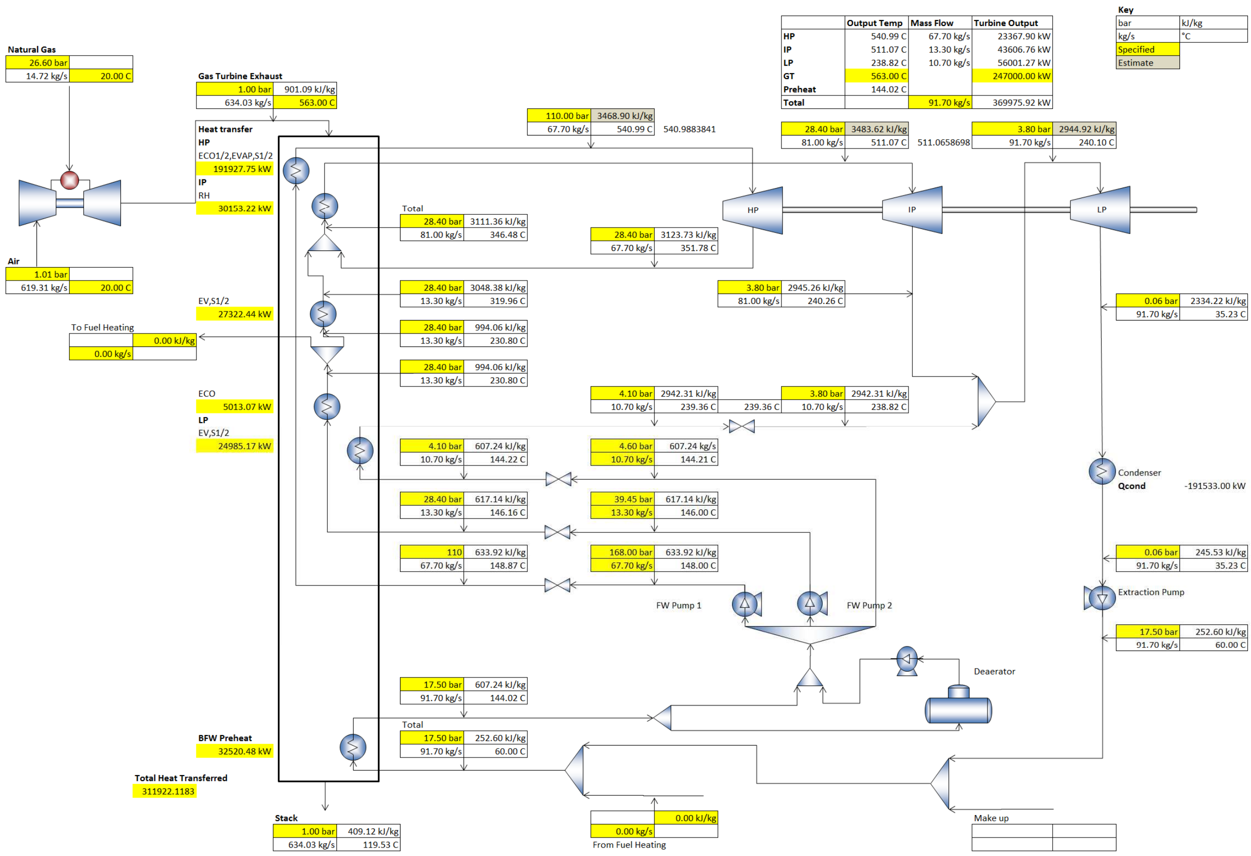


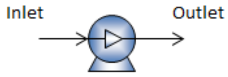
Fig 3. Complete process flow diagram of the Otahuhu B model

IV. Model Development

The process flow diagram of the combined cycle plant at Otahuhu B is shown in Fig 1. Three key simplifications were made in the development of this model. For each pressure level, all sequentially arranged heat exchangers sharing the same mass flows were aggregated into a single heat exchanger. This was justified by the fact that only the state of the steam at the inlet to each steam turbine and the heat required to generate this steam was needed to model the behaviour of the plant with respect to fuel consumed and power generated. The second simplification involved neglecting small mass flows of less than 0.5 kg/s. The actual plant has numerous small mass flows taken off at various points throughout the system which are subsequently redirected throughout the plant and are used for tasks such as gland sealing, heating and cooling. While these activities are essential to plant operation and control, for the purposes of this project the effect they have on plant performance has been considered small enough to be neglected for a first approximation. The affect these mass flows have on the performance of the model are discussed in more detail in section V. The final simplification involved aggregating the small pressure drops occurring across the heat exchangers in the HRSG into single pressure drops prior to entering the HRSG. These pressure drops have been indicated by the addition of valves seen on the HP, IP and LP streams entering the HRSG in Fig. 1.

A. *Turbine Models*

The steam cycle at Otahuhu B operates on three distinct pressure levels, each with its own steam turbine designated as high pressure (HP), intermediate pressure (IP) and low pressure (LP). Fig. 2a shows the JSteam symbol and template for the single stage, mass flow based steam turbine used to model each of the three steam turbines. The first column identifies the values in the cells of the second column. Cells above the bold horizontal line are used to enter the input values for the model, and those below this line show the output values of the model. The heat flow diagram of Otahuhu B specified the state of the working fluid at the inlet and outlet of each steam turbine. To determine the isentropic efficiency of each steam turbine the inlet and outlet values specified in the heat flow diagram were entered into the model. The efficiency was then adjusted until the output values of the model matched those specified in the heat flow diagram. This was done using Excel's built-in goal seek function which will alter a given function input until the output matches a predefined value. The single gas turbine at Otahuhu B was represented by the JSteam symbol and template shown in Fig. 2b. The isentropic efficiency of the gas turbine was determined in the same way as the steam turbines.



Inlet Enthalpy	
Inlet Pressure	
Inlet Mass Flow	
Outlet Pressure	
Efficiency	
Outlet Enthalpy	0.00 kJ/kg
Power	0.00 kW

Fig. 4 JSteam pump unit operation, symbol and Excel template.

B. Pump model

The model requires three pumps to maintain the three different pressure levels. The pumps were modelled using JSteam's pump unit operation, shown with its symbol and Excel template in Fig 4. Each pump had its efficiency adjusted as previously detailed above.

C. Defining suitable thermodynamic states

With the turbines set up, the rest of the PFD was completed and is shown in Fig. 3. Four values have been used to display information about the fluids between each unit operation. These are pressure, temperature, enthalpy and mass flow, and they are displayed with units according to the key shown in Fig. 5. Each pressure level is considered a separate loop. To complete a loop each state was related to the previous state according to the unit operation encountered. If a value remained unchanged, it was referenced to the previous value. If a value changed, it was related to the previous value by the corresponding function depending on the unit operation. In this way all the properties and mass flow of the fluid at the points between unit operations were defined, eventually closing the loop once arriving back at the beginning. In order to solve each loop in the system of nonlinear algebraic equations, an initial estimate had to be made. This was chosen to be the input enthalpy to each turbine. JSteam includes a function called `Estimate` which is given the function for the calculated value and an initial estimate. If an error is generated during the solution iteration procedure, and subsequently propagated through the loop contaminating other values, the estimated value will be used, otherwise the value is calculated based on the function provided.

D. Heat Exchangers

The final step was to set up the energy and mass balances for the heat exchangers. This included the condenser and HRSG. In general an HRSG consists of three heat exchangers per pressure level. These are called the economiser, evaporator and superheater. For pressure levels where multiple stages of each kind of heat exchanger were present, i.e. HP economizer 1 and 2, a single heat exchanger was used for simplification. The system also included a preheat stage for the feed water and a reheat stage for the intermediate pressure level. The heat flow diagram did not specify all of the states of the working fluid and exhaust gases between individual heat exchangers, although some of these properties may be measured online and be available from the plant's historian. These values were determined by estimating the vapour fraction of the working fluid at the unknown points. For example, the water entering the evaporator should be close to a saturated liquid at the boiling point temperature, while the steam leaving the evaporator should be a saturated vapour at the boiling point temperature. Once all of the states were known, the amount of heat transfer occurring in each heat exchanger was determined. Heat exchangers that shared a common mass flow had their heat transfer values combined together and are represented by a single symbol resulting in the simplified arrangement for the HRSG shown in fig. 3. With the heat transfer in each heat exchanger known, the model was set up to determine the HRSG outlet temperature for each pressure level based on the specified mass flow rates.

Key

bar	kJ/kg
kg/s	°C

Fig 5. State properties and mass flows of fluids are displayed in the PFD using this format.

V. RESULTS AND DISCUSSION

The heat flow diagram used to develop the model represented a design specification for Otahuhu B. This diagram was ideal for the initial development of the model because the state of the system at all points was either known or could be estimated from the physical situation, as discussed in section IV. A comparison of the steam turbines power output determined by the model and that stated in the heat flow diagram resulted in a reasonably small error of 1.396%. This indicated that the simplifications and assumptions made while developing the model were reasonable and helped to validate the unit operations used in the model. It should be noted that a small error would be expected as the model was developed directly from the heat flow diagram.

A more rigorous test of the model was to simulate the operation of the Otahuhu B at different levels of plant output. A second set of data was compiled from human machine interface (HMI) screen shots of Otahuhu B. This data was gathered over a three minute interval with a combined cycle power output of 375MW. The data set was incomplete, missing the LP and IP steam turbine outlet states as well as air and exhaust mass flows of the gas turbine. This meant that the isentropic efficiency of these unit operations could not be determined and so were assumed to be the same as those calculated based on the previous data. This was also true for the extraction pump whose inlet state was dependent on the outlet state of the steam from the LP steam turbine. A summary of key results from the model is shown in Table 2. These results are compared with the corresponding values from the measured data and the percentage error calculated. The model calculated a total steam cycle output power 3.925% lower than the actual output power. For the previous simulation the plant was operating at capacity and it would be expected that the efficiency of the steam turbines would be lower at the new CCGT operating point of 375MW. Therefore, the use of previously obtained efficiency values for the LP and IP steam turbines cannot explain this decrease in output power as the correct efficiency values should in fact decrease the power output even further. Table 3 shows the affect the addition or subtract of 0.5 kg/s has on each of the three pressure levels. As the model is currently unable to model off-design performance (discussed next) these figures should be taken as a guide to the possible size of the error due to the neglected mass flows. The steam turbine models calculate the work output base on the mass flow through the turbine, it is therefore reasonable to assume that neglecting these small mass flows would have contributed to the observed error. Due to the limited data available to construct the model, more information regarding the exact points where these mass flows leave and reenter the main streams as well as their magnitudes will be required to confirm their affect.

In order to efficiently model plant behavior at different operating points, several modifications to the model would need to be made. Shifting to a new operating point alters the specified values used in the model. These specified values include all pressures, unit operation efficiencies and mass flows. Instead of entering new pressures and efficiencies manually for a given change in plant output, it would be best to develop correlations between these values and plant output. The heat exchangers have been modelled using simple mass and energy balances. This fixes the heat transferred in each heat exchanger to a particular value which must be determined from the data. To accurately model the behaviour of the heat exchangers, a more in depth model is required, either based on the physical geometry of the heat exchangers or regressed from input/output data at different operating points. These alterations will enable the model to predict fuel consumption at different operating points, and the same model could be applied to as a tool to monitor plant degradation.

As the steam cycle essentially operates as a closed system, environmental factors would primarily influence the plant via the gas turbine. Currently the gas turbine model takes ambient temperature into account but is unaffected by ambient pressure changes. Further investigation into the effect on ambient pressure on gas turbine performance is required to adapt the model to the task of forecasting performance based on environmental conditions.

Table 2. Comparison of key values from the actual plant and model.

	Actual Plant	*Plant Model*	*% Error*
Steam Turbines			
Inlet Temperature			
HP	541.00 °C	540.99 °C	0.003%
IP	513.00 °C	511.07 °C	0.377%
Outlet Temperature			
HP	351.00 °C	351.78 °C	0.221%
Power			
Total Steam Cycle Power Output	128 MW	123 MW	3.925 %

CONCLUSION

This paper detailed the development of a steady state thermodynamic model of the Otahuhu B CCGT power station, using the JSteam thermodynamic modelling software. The model was developed from a heat flow diagram representing an initial design specification of Otahuhu B. Two sets of data were used to evaluate the model. The first data set was taken from the design specification and the second was compiled from HMI screenshots from Otahuhu B. The calculated values for steam cycle output power were compared to the corresponding data values. The first simulation resulted in an error of 1.5%. It was noted that as the model was developed from this data and that specific simplifications and assumptions were made in developing the model, a relatively small error was to be expected. The second simulation resulted in a steam cycle output power 3.925% lower than the actual value. Two important modifications required to extend the model for use at different operating points were discussed. The first was the development of relationships between fixed plant parameters at different levels of demand. The second modification called for a heat exchanger model capable of determining outlet temperatures and heat transfer, given inlet temperatures and fluid mass flow.

Table 3. Percentage change in key model values due to the addition or subtraction of mass flows up to 0.5 kg/s.

	± 0.5 kg/s
Steam cycle output power	
HP	±1.61%
IP	±1.47%
LP	±1.25%
Total output power	
HP	±0.54%
IP	±0.49%
LP	±0.42%
HRSG outlet temperature	
HP	±1.57%
IP	±1.54%
LP	±4.36%

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REFERENCES

[1] Cheng, B. C. M. and D. I. Wilson, "How sustainable is our electricity industry? A robust quantitative approach." In Claus-Heinrich Daub, Paul Burger, and Yvonne Scherrer editors, *Creating Values for Sustainable Development: Proceedings of the 2nd International Sustaionability Conference*, Basel Switzerland, 21-22 August 2008.

[2] Currie, J. and D. Wilson, “Rigorously Modelling Steam Utility Systems for Mixed Integer Optimization.” 10th International Power and Energy Conference, Ho Chi Minh City, Vietnam, IEEE, 12-14, 2012.

[3] Currie, J., D. I. Wilson, et al. “Steam utility systems are not business as usual for chemical plant simulators,” *American Institute of Chemical Engineers* (AIChE) *Spring Meeting*, Chicago, USA, 13-17 March, 2011.

[4] Currie, J., D. I. Wilson, B. R. Young, W. Yu, “Rethinking the modelling of energy and utility systems” *9th World Congress of Chemical Engineering*, Seoul, Korea, 18-23 August, 2013.

[5] D. Lindsley, *Power-plant control and instrumentation the control of boilers and HRSG systems*, London, United Kingdom: The Institution of Electrical Engineers, 2005, pp 1-23.

[6] Genesis Energy. (undated). *Electricity trading in the New Zealand electricity market*. [online]. Viewed 2012 June 29. Available: http://www.genesisenergy.co.nz/shadomx/apps/fms/fmsdownload.cfm?file_uuid=42F2E11E-7E95-D748-07D0-4721F0FC48B7&siteName=genesis

[7] IAPWS, “Revised release on the IAPWS industrial formulation 1997 for the thermodynamic properties of water and steam,” 2007.

[8] Industrial Information & Control Centre, www.i2c2.aut.ac.nz, 33 Symonds St, Auckland New Zealand.

[9] M. A. Boles and Y. A. Çengel, *Thermodynamics: An Engineering Approach*, 6th ed., New York: McGraw Hill, 2007, pp 597-602.

[10] Ministry of Business, Innovation and Employment. (2012, June). *Chronology of NZ electricity reform*, Available: http://www.med.govt.nz/sectors-industries/energy/pdf-docs-library/electricity-market/electricity-industry/chronology-of-electricity-reform/Chronology%20of%20NZ%20electricity%20reform.pdf

[11] Ministry of Business Innovation and Employment. (2012, Dec.). New Zealand energy quarterly September quarter 2012 [Online]. Available: http://www.med.govt.nz/sectors-industries/energy/energy-modelling/publications/new-zealand-energy-quarterly/NZEQ-September-2012.pdf

[12] Wilson, D. I. and B. C. M. Cheng “Predicting the unpredictable: Is the electrical spot price chaotic?” *International Conference on Sustainability Engineering and Science*, Auckland, New Zealand, 6-9 July, 2004.