Modelling and Optimisation of the Otahuhu B Combined Cycle Gas Turbine Power Station

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Abstract—**The generation of electrical power in New Zealand is currently complicated by the governments desire to sell 49% of the state-owned existing power stations, the fact that Rio Tinto are threatening to sell Tiwai Point Aluminium smelter which currently consumes 15% of the national electrical power, and the geographical peculiarities of New Zealand where the hydro is generated in the south, and the energy consumed in the north, transmitted along a thin and narrow corridor.**

Contact Energy, which run a large 400 MW combined cycle gas turbine (CCGT) power plant in Auckland, bid, as do all electrical generators in New Zealand, on the national electricity market. To be profitable, the station must closely follow the time-varying electrical market, and be able to produce sufficient energy on demand. Optimising such a production requires models that accurately predict steam thermodynamics and the heat transfer within the boiler, and models that predict the combustion thermodynamics in the gas turbine. The Industrial Information and Control group have developed a comprehensive heat-recovery steam generator (HRSG) package that can be use to predict the steady-state operating conditions of the power station over a wide operating range. In addition, the group have developed a widely-used optimisation platform that can be used to establish optimal operating conditions for given external environmental conditions such as electrical closing price and gas prices.

However the one thing missing to date is consideration of the dynamic response of the plant. Currently it is known that the combined plant is relatively slow to respond to the quickly changing market demands, especially when the steam boiler is used. If however, the less efficient gas turbine is used alone, (with the boiler switched off), the dominant time constants of the plant are considerably reduced. This complicated the optimisation problem since using the boiler restricts the ability of the plant to respond quickly to market demands, but if used, improves the overall energy efficiency.

This paper describes the application of an optimal dynamic modelling project applied to an actual 400 MW power station. The paper validates the first-principle steady-state models, and develops simple dynamic models of the boiler and the gas turbine using historical plant data. The paper then explores various optimisation scenarios and illustrates the possible benefits.

Keywords-Modelling; Optimisation; Simulation

I. INTRODUCTION

In the past two decades New Zealand's electricity industry has under gone 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 [4]. In 1996 ECNZ's generation and gas assets were split between the ECNZ and newly formed Contact energy. This was accompanied by the creation of New Zealand's Wholesale Electricity Market [2, 4]. 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 distribution and retailing businesses separated [2, 4]. These retail businesses were sold, primarily to generation companies [4]. These events have led to the formation of New Zealand electricity industry as it is today with the four generation companies bidding to sell electricity on the wholesale electricity market while simultaneously purchasing electricity to cover their retail commitments [2]. Large organisational changes still continue, most recently with the partial privatisation of Mighty River power.

The geography, resource and population distribution of New Zealand has a strong influence on the way electricity is generated and used. The majority of New Zealand's electricity is generated from hydroelectric power stations. New Zealand's greatest hydrological resources are located in the lower South Island while the largest population centres and greatest power consumption is located in the upper North Island. The long, narrow geography of New Zealand dictated the need for a High Voltage DC (HVDC) transmission line linking the two islands. 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, 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 the renewable alternatives that dominate New Zealand's electricity industry. To remain competitive in such an environment detailed knowledge and efficient operation of such assets becomes essential. Due to the complexity of power stations both of these goals can be best achieved through accurate modelling and optimisation.

Currently the most efficient fossil fuel power plants are Combined Cycle Gas Turbines (CCGT). These power stations operate on two cyclesThe gas turbine operates on the Brayton cycle [1, 3] whereair 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 a generator to generate electricity. However the exhaust gases leaving the turbine are still very hot (over 500°C) [1] and these exhaust gases are used as the heat source for the second stage which operates on the standard Rankine cycle [1]. 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 convert compressed water in the heat exchanger coils to superheated steam [1]. The steam is then allowed to expand through steam turbines, again generating work which is used to generate more electricity [1, 3]. The steam leaving the turbines is then condensed back into water and compressed, completing the cycle [1, 3]. Modern CCGT power stations are capable of achieving efficiencies of greater the 60% compared to the approximately 40% for single cycle plants [3].

II. Case Study

This paper details modelling and optimisation of the Otahuhu B Combined Cycle Gas Turbine (CCGT) power station, owned and operated by Contact Energy. Otahuhu B is located in the Auckland suburb of Otahuhu, 9m above sea level. Otahuhu B consists of a single train with a total combined cycle capacity 400MW. It has a single gas turbine providing the energy for a three pressure level steam cycle via the Heat Recovery Steam Generator (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. The composition of the natural gas is shown in Table 1. This paper also investigates the optimisation potential for the operation of this plant. .

III. JSteam

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

A. Process Flow Diagram

The process flow diagrams for this plant (PFD) 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.

Table 1. Composition of the natural gas used at Otahuhu B.

Natural Gas Composition	
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%

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

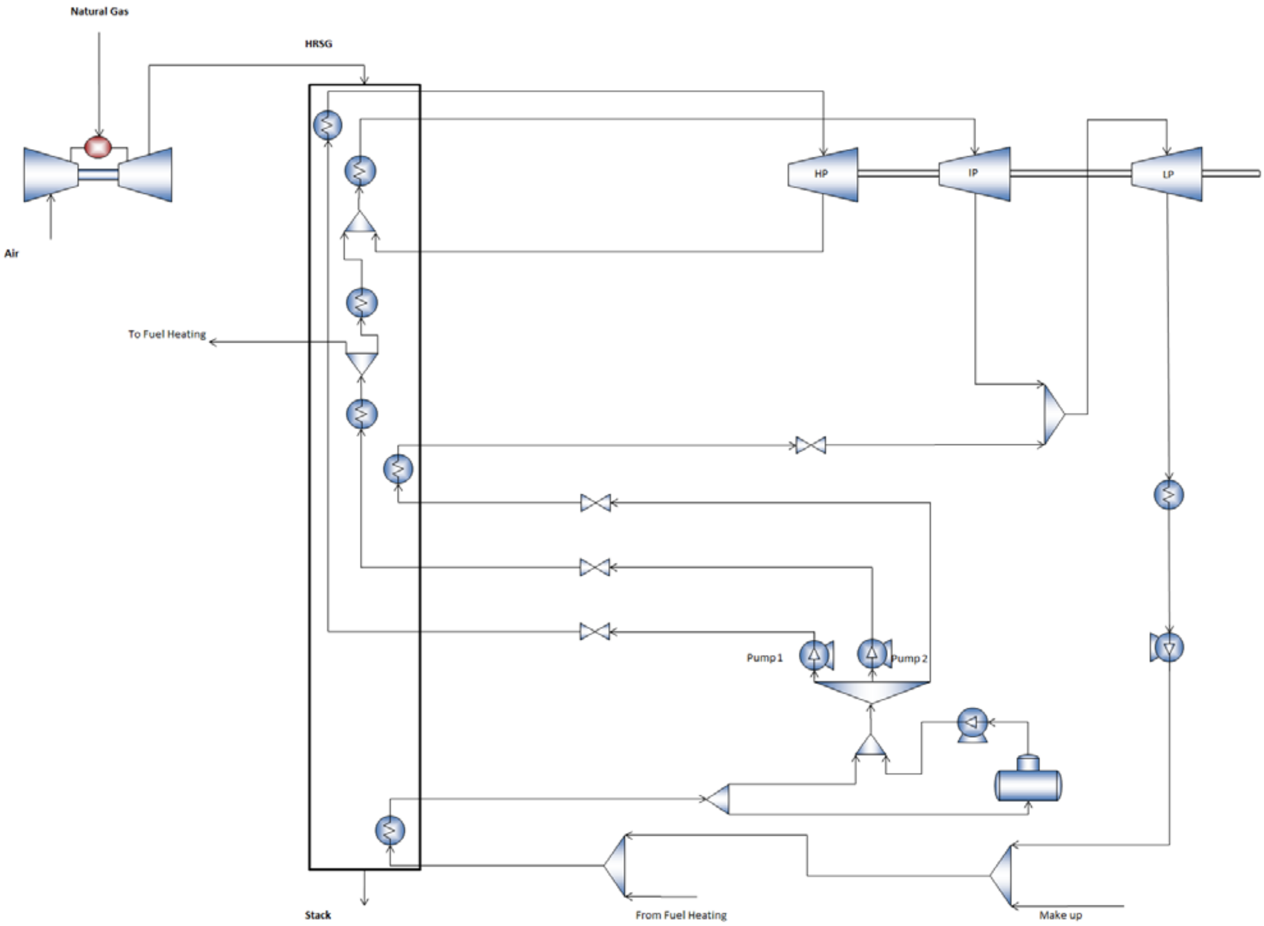


Fig 1. A Simplified PFD of Otahuhu B.

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. 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.

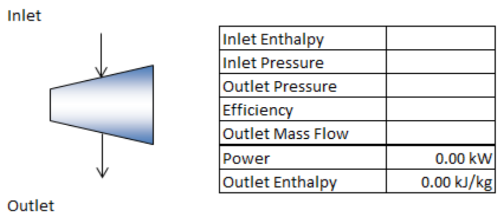
The gas turbine is modelled by the supplied gas turbine combustion unit operation. Again this model is simply pasted into the excel spreadsheet. As this model involves the combustion of fuel, the fuel composition (as in Table 1) must be specified.

C. Heat Exchangers

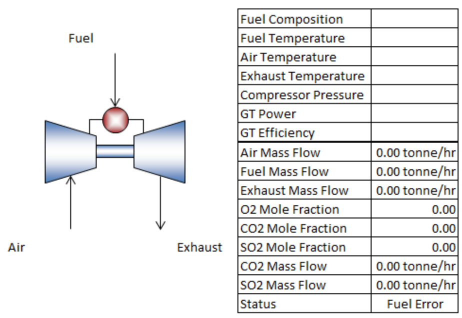
Heat exchangers in the HRSG and condenser were modeled using simple mass and energy balances across each exchanger.

IV. Model Development

The process flow diagram of the combined cycle plant at Otahuhu B operating at capacity 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) JSteam symbol and excel model for the single stage, mass flow based steam turbine



b) JSteam gas turbine symbol and excel model.

Fig 2. JSteam unit operations.

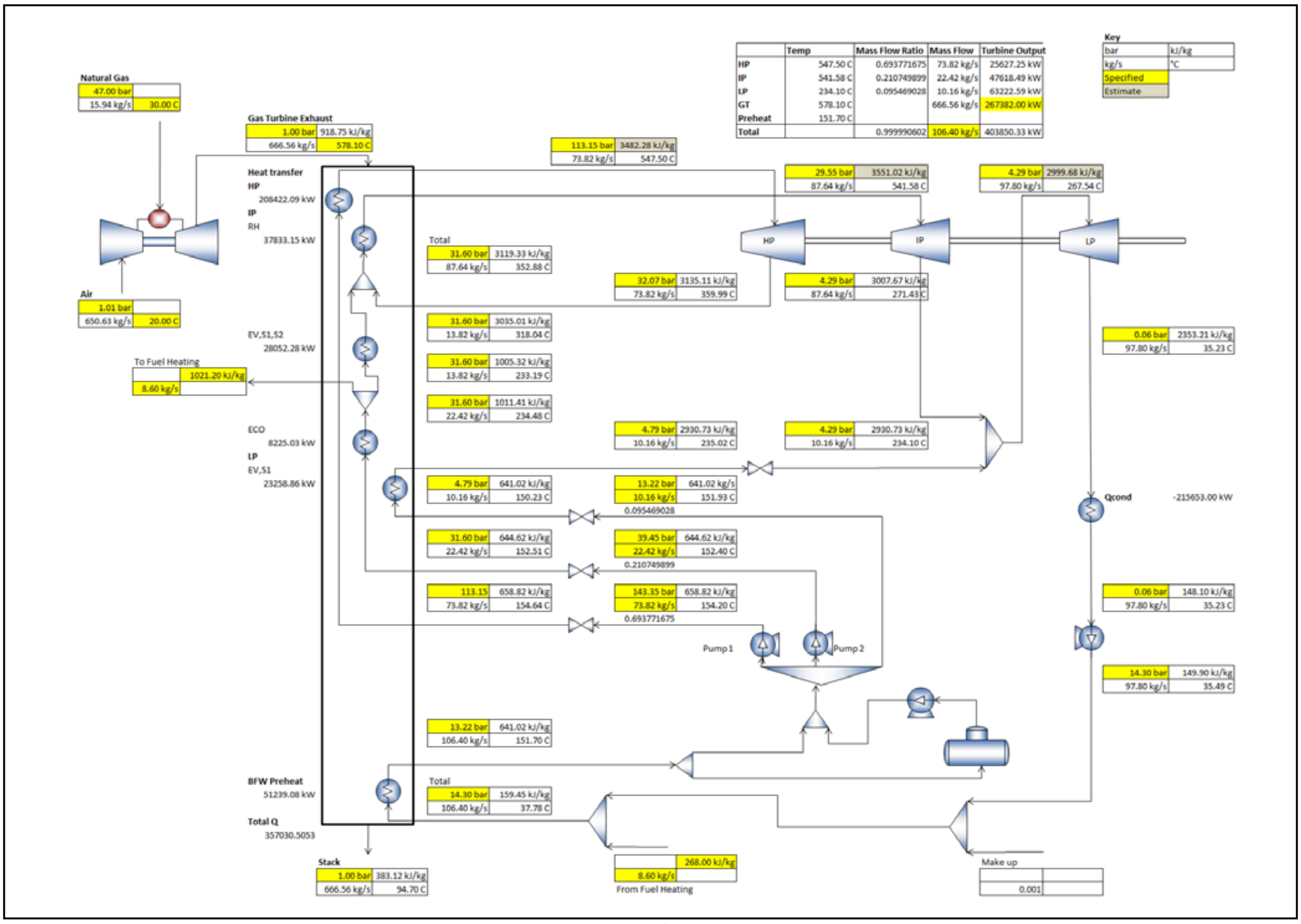


Fig 3. Complete PFD of the Otahuhu B model

a single heat exchanger. This was justified by the fact that only the state of the steam at the input 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 systemwhich are subsequently redirected throughout the plant and are used for auxiliary tasks such as additional 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. 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 high pressure (HP), intermediate pressure (IP) and low pressure (LP). Fig. 2a shows the JSteam symbol and model 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 model shown in Fig. 2b. The isentropic efficiency of the gas turbine was determined in the same way as the steam turbines.

B. 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 fluid between each unit operation. These are pressure, temperature, enthalpy and mass flow and are displayed with units according to the key shown in fig. 4. 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

Key

bar	kJ/kg
kg/s	°C

Fig 4. State properties and mass flows of fluids are displayed in the PFD using this format.

it was referenced to the previous value, and 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 start. 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.

C. 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 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 available from the 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 were combined together 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.

V. RESULTS AND DISCUSSION

A summary of key results from the model are shown in Table 2. These results are compared with the corresponding values from the original heat flow diagram and the percentage error calculated. The error in the values determine by the model are reasonably small. This indicates that the simplifications and assumptions made while developing the model were reasonable and helps to validate the unit operations used in the model. It should be noted that the small errors should be expected as the model was developed directly from the heat flow diagram. A more rigorous test of the model would be to simulate the operation of the plant at different levels of plant output. To do this several modifications to the model would need to be made. Firstly shifting to a new operating point will alter 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 modeled using simple mass and energy balances. This fixes the heat transferred in each heat exchanger to a particular value. 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.

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

Comparison of key values			
	Actual Plant	**Plant Model**	**% Error**
Gas Turbine			
Fuel Mass Flow	16.06 kg/s	15.94 kg/s	0.759%
Air Mass Flow	647.21 kg/s	644.25 kg/s	0.458%
Exhaust Mass Flow	663.27 kg/s	660.19 kg/s	0.465%
Steam Turbines			
Inlet Temperature			
HP	549.90 C	547.63 C	0.413%
IP	541.60 C	541.70 C	0.019%
LP	271.00 C	267.64 C	1.239%
Outlet Temperature			
HP	359.30 C	360.09 C	0.220%
IP (approx.)	275.33 C	271.52 C	1.381%
LP	35.23 C	35.23 C	0.000%
Power			
Total Steam Cycle Power Output	134589.00 kW	136468.46 kW	1.396%

CONCLUSIONS

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