DYNAMIC MODELLING AND CONTROL DESIGN FOR ORGANIC RANKINE CYCLE SYSTEMS

Matthew Lie[1], Boaz Habib[2], Wei Yu[1] and Brent R. Young[1]

[1] Department of Chemical and Materials Engineering, Faculty of Engineering, University of Auckland, New Zealand

[2] Heavy Engineering Research Association of New Zealand, 17-19 Gladding Place, Auckland, New Zealand

mlie198@aucklanduni.ac.nz

Keywords: *Organic Rankine Cycle (ORC), process modelling, control design*

ABSTRACT

Organic Rankine Cycle (ORC) systems are able to utilize low-temperature heat sources, such as geothermal reservoirs, to generate power. One aim of the Above Ground Geothermal and Allied Technologies (AGGAT) programme is to develop an ORC manufacturing industry in New Zealand. The control system which regulates the plant is a key component of any ORC system. For effective control of an ORC system, it is important to develop an understanding of the dynamic behaviour of an ORC system and its various components. However, in many situations it can be impractical to perform testing on a real plant as it may compromise plant safety.

Instead, this paper endeavours to use simulation models as a means to aid plant and control design, overcoming the limitations of practical testing on a real operating plant. A dynamic simulation model of an ORC plant was built using a commercial flowsheet simulator, VMGSim. The dynamic behaviour of the plant was studied under a variety of step tests and process disturbances. This paper describes the results of these simulations and their implications on the design of control systems and plant operating procedures.

1. INTRODUCTION

Between the rapid growth of the world's population and the advancement of developing countries, the stress placed on conventional energy sources rises. In response, the amount of research and development of various alternative energy sources has increased. Biomass (Tchanche *et al.*, 2011), solar (Quoilin *et al.*, 2013), geothermal (Madhawa Hettiarachchi *et al.*, 2007) and industrial waste heat (Sun and Li, 2011) are just some of many alternative sources that have shown promise in their ability to alleviate the world's energy demand.

However, conventional power generation methods are unable to efficiently convert the above heat sources into power due to their lower temperatures and enthalpies. For instance, a steam Rankine cycle does not allow efficient utilization of heat below 370°C (Hung, Shai and Wang, 1997). One solution to this problem that has been investigated is the use of the Organic Rankine Cycle (ORC). The ORC applies the same operating principles as the steam Rankine cycle to generate energy, but instead uses an organic working fluid that has a lower boiling point than water, allowing for the recovery of usable energy from lower enthalpy heat sources such as geothermal and waste heat sources.

One aim of the Above Ground Geothermal and Allied Technologies (AGGAT) programme is to develop an ORC manufacturing industry in New Zealand. As a power generation method that utilises medium-to-low enthalpy heat sources, ORC systems are particularly applicable to the recovery of geothermal energy (Habib *et al.*, 2015). The programme is now reaching a stage in which demonstration sites for proof of concept are required. The first site is slated to utilise exhaust gas from a landfill site. Hence, this proposed ORC system forms the basis of investigations in this paper, but as will be explored later, is equally applicable to a low-enthalpy geothermal source.

Of particular importance in any ORC is the heat exchanger that acts as the system's vaporizer, as the amount of heat able to be extracted from the heat source is a major factor in determining the plant's thermal efficiency. In order to maximize the heat extracted from gaseous heat sources, finned tube heat exchangers are utilized, with the working fluid flowing in the tube side and the heat source passing through the shell side. This allows for an increase in the effective heat transfer area, off-setting the lower convective heat transfer coefficient of gas streams (Sinnott, 2005).

The most important condition on the vaporizer in an ORC is that no liquid phase exists at the vaporizer outlet/turbine inlet, as liquid droplets within the turbine can cause serious damage to the rotating blades. When the working fluid is passed through the shell side of the vaporizer, the level of the working fluid in the shell side can be controlled fairly easily, ensuring that only vapour exits the vaporizer. In contrast, it can be difficult to implement level control when the working fluid passes in the tube side of a finned tube heat exchanger due to the arrangement of tubes within the vaporizer. The most common alternative to level control is superheat control – maintaining a minimum degree of superheat at the vaporizer outlet to ensure that the working fluid stream entering the turbine is always in a vapour phase. Therefore, effective superheat control is a key aspect in ensuring plant safety of ORC systems (Zhang *et al.*, 2012).

This paper seeks to build a simulation model for a ~75kW ORC plant such that its dynamic behaviour can be studied and the results used to inform the control design process – in particular, the implementation of control strategies without a large computational requirement. The ORC model used in this study is first presented, followed by an examination of its dynamic behaviour and the performance of several control strategies compared and evaluated.

2. SYSTEM DESCRIPTION

A schematic diagram of the ORC plant investigated in this paper is shown in Figure 1. In this ORC, R245fa is used as the working fluid, being heated by two heat sources: hot jacket water followed by hot exhaust gas from a set of landfill gas engines. The working fluid is vaporized at constant pressure to a superheated vapour state before it is passed through the turbine to generate power. The fluid at the turbine outlet is then passed through an air cooled condenser to condense it to a liquid. The liquid is then pressurized in a pump before being passed back to the vaporizer.

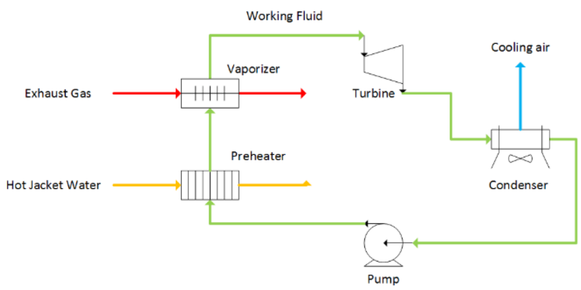

Figure 1: Schematic diagram of the modelled ORC plant

3. DYNAMIC MODELLING

The majority of ORC modelling done in literature shows that the general approach is to model the system using a series of partial or ordinary differential equations and algebraic equations that represent the thermodynamic and physical relationships throughout the system. The equations are typically solved in an iterative manner. This approach is used in most papers on ORC modelling, with some good examples shown in (Quoilin *et al.*, 2011) and (Sun and Li, 2011).

In contrast, the ORC system studied in this paper is modelled using VMGSim, a commercial flowsheet simulator. VMGSim contains pre-built unit operations that model the various components within the system, including heat exchangers, pumps, expanders, valves and controllers. The models within VMGSim are much simpler than their numerically modelled counterparts from literature, allowing for a modelling process that is simpler, easier to understand and requires less computational effort. Although the VMGSim unit operations lack some of the complexity and detail that is present in numerical models (particularly in the heat exchanger models), studies (Proctor *et al.*, 2016) have shown that these models still have a reasonable amount of accuracy compared with real results. Since the plant to be modelled in this study is a pilot plant that is not yet operational, black-box validation of the model has not been completed.

3.1 Model specification

In a VMGSim model, the connections between unit operations, equipment specifications and stream characteristics are specified. In this model, the thermodynamic state of the hot jacket water stream, exhaust gas stream and cooling air streams are provided, as well as the composition of the working fluid (R245fa). The pressure is specified at all boundary streams in the model. Specific unit operations require more specifications as appropriate to their function. For example, to model control valves, the valve type and valve flow coefficient (Cv) value must be provided. PID controllers can be modelled by specifying controller parameters (gain, integral time and derivative time). A screenshot showing the model layout can be seen in Figure 2.

3.2 Turbine model

The turbine to be used in the ORC system is a multistage radial inflow turbine. The performance of this turbine is modelled using a built-in curve in the VMGSim unit operation that can predict off-design behaviour (Proctor *et al.*, 2016). At the time of writing a performance curve was not able to be obtained for the particular turbine to be used in the plant. Instead, a design point (including speed, power, flow and efficiency) is specified for the turbine.

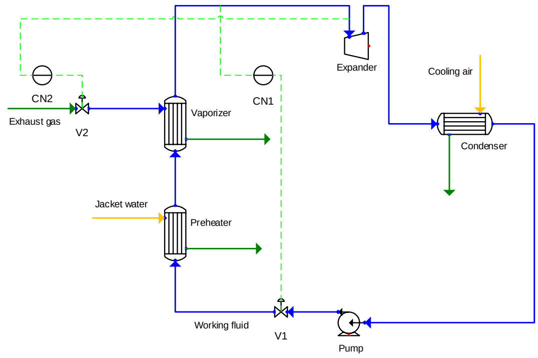

Figure 2: ORC model in VMGSim

This is used alongside a “Simple Curve” derived from (Stepanoff, 1957) obeying fan laws. Whilst the curves may be applicable to a wide variety of rotating equipment, it is not specific to radial turbines, and as such may be increasingly inaccurate at conditions far away from the specified design point. It is likely that using the actual design curve of the turbine would improve the accuracy of the model.

3.3 Pump model

As with the turbine, a performance curve was not available for the particular pump selected for the plant at the time of writing. Instead, a design point was specified and used alongside the same “Simple Curve” as in the turbine model. Therefore, the same caution should be taken in considering the results of the model with regards to the pump at conditions away from the specified design point.

3.4 Heat exchanger model

The heat exchangers are the most simplified unit operation used in the VMGSim model when compared with models in literature. Whilst the preheater, vaporizer and condenser are all different types of heat exchangers, they are all modelled using the same heat exchanger unit operation. This unit operation contains some simplifying assumptions:

- That the heat exchanger acts as a single node;
- That the UA value (the overall heat transfer coefficient, U, multiplied by the heat transfer area, A) of the heat exchanger is a constant value; and
- That the pressure drop across any side of the heat exchanger can be represented by a ‘k’ value, representing flow resistance (defined in equation 1).

$$\dot{m} = k \times \sqrt{\Delta P \cdot \rho} \quad (1)$$

where $\dot{m}$ refers to the mass flow rate, ΔP is the pressure drop across the heat exchanger, and ρ is the density of the inlet fluid.

Based on these assumptions, each heat exchanger is specified by supplying a constant overall UA value and a ‘k’ value for each of the tube and shell side of the heat exchanger. The UA value is calculated using equations 2 and 3 using values from the plant design point.

$$\dot{Q} = UA \cdot LMTD \quad (2)$$

where, for counter current heat exchangers:

$$LMTD = \frac{\left(T_{h,in} - T_{c,out}\right) - \left(T_{h,out} - T_{c,in}\right)}{\ln \frac{\left(T_{h,in} - T_{c,out}\right)}{\left(T_{h,out} - T_{c,in}\right)}} \quad (3)$$

where the subscripts 'h' and 'c' represent the hot and cold streams of the heat exchanger respectively. The subscripts 'in and 'out' represent the inlet and outlet streams respectively. $\dot{Q}$ represents the amount of heat transferred per unit time.

It should be noted that the method used to obtain the constant UA value of each heat exchanger does not rely on knowledge of the heat exchanger geometry, significantly reducing the complexity of heat exchanger modelling. In particular, this means that the geometry of the finned tubes do not need to be known in order for the heat exchanger to be modelled.

Furthermore, the abstraction of the heat exchanger geometry means that this model is still applicable to an exchanger with the fluid passing through the shell side rather than the tube side due to the LMTD remaining constant. Hence, it is equally applicable to a low-enthalpy geothermal application.

4. CONTROL SYSTEM

Typically, the control system in a power plant has two main objectives: to regulate the power generated at the turbine, as well as ensure process safety. In order to achieve these control objectives, two key process variables must be controlled in the system: the pressure and temperature in the turbine inlet stream. The high end pressure dictates the amount of power generated by the turbine. As mentioned previously, it is difficult to practically control the level in the tube side of the vaporizer. Instead, the turbine inlet temperature is controlled as a proxy for superheat. Maintaining a minimum degree of superheat in the turbine inlet stream will ensure that no liquid droplets are sent into the turbine, ensuring process safety.

After a degree of freedom analysis is performed on the system, it can be seen that there are two variables available for the control of the aforementioned key process variables. These are the mass flow rate of the working fluid stream (manipulated using a control valve at the pump outlet) and the mass flow rate of the exhaust gas stream (also manipulated using a control valve).

Relative gain array (RGA) analysis was then performed on the system. The RGA matrix is given below.

$$\Lambda = \begin{bmatrix} 1.52 & -0.52 \\ -0.52 & 1.52 \end{bmatrix}$$

Therefore, the best control pairing for these variables is to manipulate working fluid flow to control temperature, and exhaust gas flow to control pressure. The Niederlinski index for this proposed control scheme was also calculated and found to result in a value of 0.86. Since this value is not negative and the control system has only two loops, we can conclude that this pairing will result in a stable system.

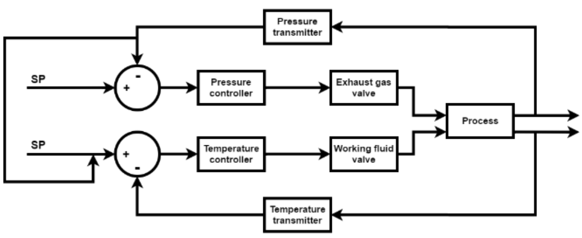

Figure 3: Control structure used in the ORC model

This control configuration agrees with that of models developed in literature such as (Horst *et al.*, 2013). Whilst other studies into control of ORC systems use complex model-based predictive control, we will utilise simple PID control to form a baseline control strategy and examine its suitability for regulation of the plant. Figure 3 shows a block diagram summarising the control structure.

4.1 Controller tuning

In order to specify the control response of the loops, the PID controller parameters must first be specified. Initially, the auto-tune variation (ATV) method was used to tune the controllers. This method sets up a cyclic disturbance between the manipulated and process variables. VMGSim has a built in function to automate this process.

However, it was found that the PID parameters given by the ATV method for the temperature controller resulted in a very slow process response. Therefore, a manual iterative method was employed by adjusting the PID parameters such that the amount of overshoot, fluctuation and response time were minimised. The final PID parameters for each controller appear to be within the expected range of values for pressure and temperature controllers (Svrcek, Mahoney and Young, 2014). Table 1 shows the final PID parameters used for the two controllers, where K_c is the controller gain, τ_i is the integral time and τ_d is the derivative time of the controller.

Table 1: Controller parameters

Controller	K_c [dimensionless]	T_i [min]	T_d [min]
Pressure	0.40	1.70	-
Temperature	8.00	2.00	1.00

4.2 Importance of superheat control

It should be noted that the turbine inlet temperature is heavily dependent on the turbine inlet pressure. As such, even though the degree of superheat set point may not change, the actual controller set point (i.e. the required turbine inlet temperature) will change, as it takes the saturated temperature and adds a nominal degree of superheat. Therefore, process disturbances will cause variation in both the process variable and set point of the superheat controller.

Furthermore, should the degree of superheat drop to zero at any point in the operation of the plant, there will be liquid formation at the turbine inlet. As previously discussed, this may result in damage to the turbine blades and compromise plant safety. This situation must be avoided to protect plant equipment and ensure process safety.

There are two ways in which the situation can be avoided: increasing the degree of superheat on the turbine inlet stream, or design a control system which is tightly tuned such that the variation of the turbine inlet temperature is minimised.

4.2.1 Degree of superheat

The ORC system is particularly sensitive to changes in the available heat input to the system – be it exhaust gas or geothermal fluids. Practically, the degree of superheat in the working fluid provides an energy buffer to these changes in the available heat input. A higher degree of superheat will require a larger and more sudden change in the energy supplied for liquid to form at the turbine inlet. Therefore, increasing the degree of superheat will improve the plant's resilience to changes in heat supply (an external disturbance).

However, more superheating on the working fluid stream will lower the plant efficiency, as there is a lower working fluid mass flow through the system available for power generation. Therefore, plant efficiency influences economic feasibility.

Therefore, there must exist an optimal degree of superheat which maximises plant efficiency whilst keeping plant resilience at an acceptable level. This optimisation will depend on the possible disturbances that the plant may be exposed to, as well as economic considerations which may affect the investment decision. This is an area for future work.

4.2.2 Advanced superheat control strategies

The challenge of the non-linear response of the superheated temperature and the multitude of process disturbances that may affect the system lead to a basis for the development of advanced control strategies. There are a number of examples of these in literature.

(Zhang *et al.*, 2014) constructed a constrained model predictive controller with potential for set point optimisation. (Hou *et al.*, 2011) developed a supervisory predictive control system in a cascade-like system. (Peralez *et al.*, 2012) constructed a reduced-order model that was inverted and used in conjunction with a decentralised PI control scheme.

These examples from literature all utilise complex model-predictive based methods which generally appear to contain less variation between the process variable (superheat) and the set point (i.e. control superheat more tightly). It is difficult to properly evaluate and compare the relative benefits of each method used as they all use a different basis, and often also do not use a baseline PID control system to compare results.

Although model-predictive control methods may provide some improved level of control, their likely increase in computational requirement, complexity and capital cost make it hard to justify their implementation in a real plant over using a control system that can be built from simple PID controllers. Further investigation should be done to evaluate the practical feasibility of using more complex control structures and analysing their relative costs and benefits.

5. SIMULATION

In order to examine the dynamic response of the plant, a series of step tests and disturbance tests were performed. The responses of the manipulated and process variables were both tracked. The degree of superheat in the turbine inlet stream was also calculated and tracked to check if there was any liquid formation. The design point of the plant was used as a baseline condition to begin simulations from. The important values associated with this point are summarized in Table 2. This section looks at the tests performed and their implications on further control design.

Table 2: ORC plant design point

Parameter	Value
Exhaust gas temperature	365°C
Exhaust gas pressure	101.3 kPa
Jacket water temperature	99°C
Jacket water flow rate	4400 kg/h
Cooling air temperature	21°C
Low end pressure	280 kPa
Turbine inlet pressure set point	2400 kPa
Degree of superheat set point	3°C

5.1 Set point tracking ability

Step changes in the pressure and superheat set points were performed to determine the tracking ability of the controllers. The response of the process variables is shown in Figure 4. The following step changes were made:

1) The set point of the high end pressure is decreased from 2400 kPa to 2350 kPa;
2) The set point for the degree of superheat was increased from 3°C to 5°C;
3) The set point of the high end pressure is increased from 2350 kPa to 2400 kPa; and
4) The set point for the degree of superheat is decreased from 5°C to 3°C.

When there is a change in the pressure set point, it can be seen that the pressure follows quickly with no overshoot in the response. The degree of superheat deviates from set point due to the disturbance created by the pressure set point change. Interestingly the response of the superheat loop is not the same when comparing a step up and a step down in the pressure set point. This is evidence of non-linear behaviour in the system, which is largely attributed to the behaviour within the vaporizer (Horst *et al.*, 2013).

When there is a change in the degree of superheat, the turbine inlet temperature also follows quickly. However, the behaviour of the response is different when comparing a step up and step down in the degree of superheat. When there is a step up in the degree of superheat, the turbine inlet temperature overshoots the set point value, whereas there is no overshoot when there is a step decrease in the degree of superheat. Again this shows that non-linear behaviour exists within the ORC system. The pressure deviates from the set point due to the disturbance created by the superheat set point change and returns to the set point value fairly quickly.

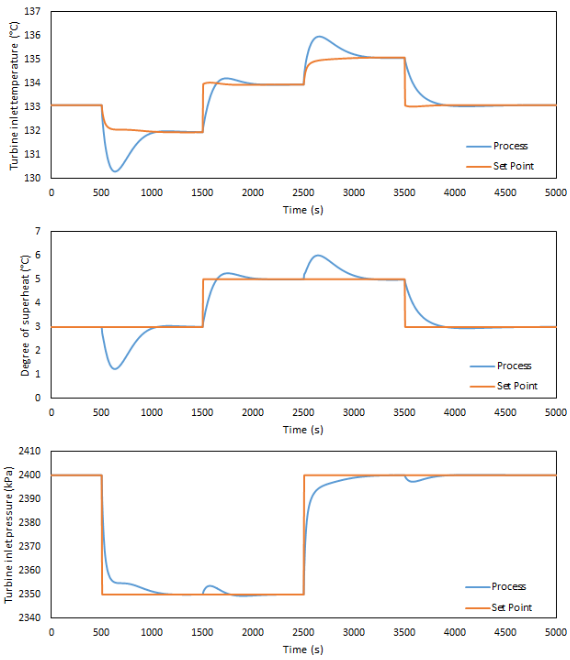

Figure 4: Dynamic response for set point changes

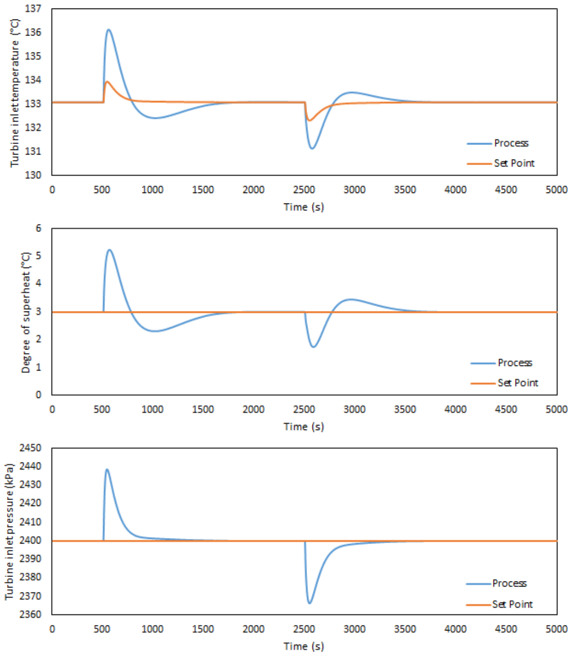

Figure 5: Dynamic response for temperature disturbance rejection

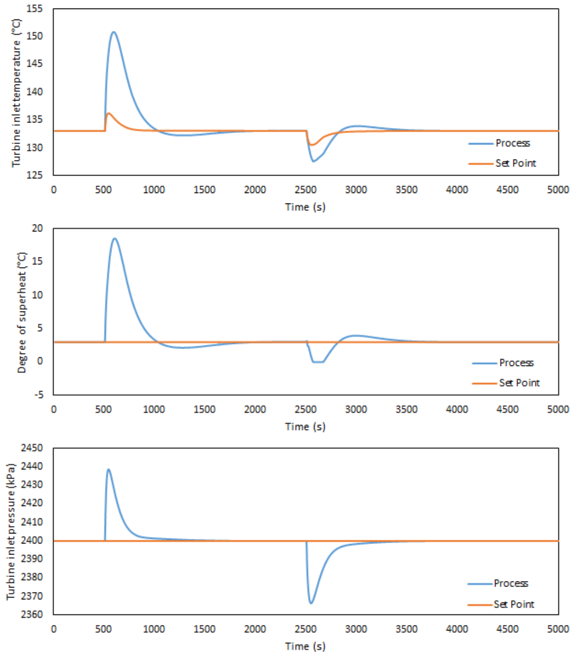

Figure 6: Dynamic response for pressure disturbance rejection

5.2 Disturbance rejection ability

With any heat source for an ORC plant (both waste heat and geothermal fluids alike), their thermodynamic and flow parameters are likely to fluctuate over time. Hence, there are highly likely to be process disturbances which affect both the high end pressure and the degree of superheat in the turbine inlet stream. The main parameters which may vary are the exhaust gas temperature, exhaust gas pressure and cooling air temperature. Variation in the cooling air temperature mostly affects the low pressure end of the ORC system and can be mitigated through variation of the cooling air mass flow rate, which in turn is controlled by the condenser fan speed. Since the condenser fans are not able to be modelled in VMGSim, the cooling air disturbance has not been investigated in this study. To examine the effect of exhaust gas temperature and pressure disturbances, a series of tests were performed.

5.2.1 Exhaust gas temperature disturbance

The model is first run at the design point at equilibrium. Then, a step increase in the exhaust gas temperature was made from 365°C to 400°C. Afterwards, a step decrease in the exhaust gas temperature was made from 400°C to 365°C. The response of the process variables is shown in Figure 5.

It can be seen that the disturbance causes the process variables (both superheat and pressure) to vary from their set point, and that both variables are returned to their set point values.

When comparing the response of the pressure and superheat loops, it can be seen that the pressure response appears to exhibit similar behaviour when there is either a step up or step down in the exhaust gas temperature. However, although the response time is the same for both step changes, the superheat response exhibits a different amount of overshoot when there is a step increase in the exhaust gas temperature as opposed to a step decrease. This again supports the idea that there exists non-linear behaviour in the system.

5.2.2 Exhaust gas pressure disturbance

For this disturbance, a step increase in the exhaust gas pressure was made from 101 kPa to 103 kPa. Afterwards, a step decrease in the exhaust gas temperature was made from 103 kPa to 101 kPa. The response of the process variables is shown in Figure 6.

It can be seen that both process variables deviate from their set point due to the influence of the exhaust gas pressure disturbance. The pressure disturbance has a much greater effect on the system in general due to the bigger impact it has on the total heat flow into the system (through the pressure-flow relationship governed by the control valve).

As with the exhaust gas temperature disturbance, we can clearly identify the difference between the behaviours of the pressure and superheat loops. The pressure response exhibits the same behaviour under both a step up and step down disturbance, whereas the superheat response clearly exhibits a different amount of overshoot when there is an increase in the exhaust gas pressure compared with a decrease, highlighting the non-linear behaviour that exists within the system.

5.2.3 Exhaust gas noise disturbance

The previous step tests involved clean signals. However, it is expected that there will be high amounts of fluctuations in the exhaust gas temperature due to the nature of the landfill's gas engines. Therefore, random noise was introduced to the exhaust gas temperature with a magnitude of 30°C and a decay time of 1.0 s. The response of the process variables is shown in Figure 7.

It can be seen that the total amount of deviation from the set point is not significant in either the turbine inlet temperature or pressure. Furthermore, the degree of superheat remains within ±0.2°C of the nominal set point, indicating that the temperature controller is adequate for dealing with this level of random noise.

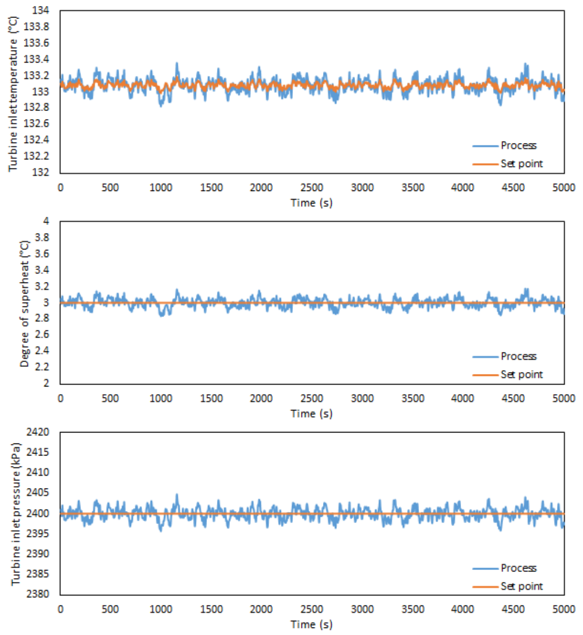

Figure 7: Dynamic response for noise rejection in temperature disturbance

5.3 Applicability to geothermal ORCs

As discussed earlier, the abstraction of the heat exchanger geometry in this simulation means that, even though the heating fluid is passing through the shell side in this study, the simulation is equally applicable to an exchanger with the heating fluid passing through the tubes, which is the usual arrangement for an ORC in a geothermal application. Hence, the analysis of the dynamic response of the ORC plant in this study shows that the degree of superheat may successfully be used as a control variable in any ORC application.

6. CONCLUSIONS

In this paper, a dynamic model (including a baseline control system) for an ORC plant is successfully built using VMGSim and some initial analysis of its dynamic behaviour performed. The following conclusions can be drawn:

- The superheated working fluid temperature at the turbine inlet exhibits a non-linear response that changes between step ups and downs.
- The baseline PID control system is suitable for set point tracking; however, it may not response fast enough to large, sudden changes in the heat supply.
- The baseline PID control system is adequate for dealing with noisy signals.
- There exists some optimal degree of superheat which is a trade-off between plant resilience and plant efficiency/economic feasibility.
- Further work can be done to investigate the optimal degree of superheat or model and analyse the relative costs and benefits of advanced model predictive control strategies.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Heavy Engineering Research Association for their support of this research.

REFERENCES

Habib, B., Young, B. R., Yu, W., Zheng, H., Proctor, M. J., Zealand, N. and Zealand, N. (2015) ‘The conceptual development of an expert process design tool for above ground power generation technologies’, in *Proceedings 37th New Zealand Geothermal Workshop*.

Horst, T. A., Rottengruber, H.-S., Seifert, M. and Ringler, J. (2013) ‘Dynamic heat exchanger model for performance prediction and control system design of automotive waste heat recovery systems’, *Applied Energy*, 105, pp. 293–303. doi: 10.1016/j.apenergy.2012.12.060.

Hou, G., Sun, R., Hu, G. and Zhang, J. (2011) ‘Supervisory predictive control of evaporator in Organic Rankine Cycle (ORC) system for waste heat recovery’, *The 2011 International Conference on Advanced Mechatronic Systems*, pp. 306–311.

Hung, T. C., Shai, T. Y. and Wang, S. K. (1997) ‘A review of organic rankine cycles (ORCs) for the recovery of low-grade waste heat’, *Energy*. Pergamon, 22(7), pp. 661–667. doi: 10.1016/S0360-5442(96)00165-X.

Madhawa Hettiarachchi, H. D., Golubovic, M., Worek, W. M. and Ikegami, Y. (2007) ‘Optimum design criteria for an Organic Rankine cycle using low-temperature geothermal heat sources’, *Energy*, 32(9), pp. 1698–1706. doi: 10.1016/j.energy.2007.01.005.

Peralez, J., Tona, P., Sciarretta, A., Dufour, P. and Nadri, M. (2012) ‘Towards model-based control of a steam Rankine process for engine waste heat recovery’, *2012 IEEE Vehicle Power and Propulsion Conference, VPPC 2012*, (October), pp. 289–294. doi: 10.1109/VPPC.2012.6422718.

Proctor, M. J., Yu, W., Kirkpatrick, R. D. and Young, B. R. (2016) ‘Dynamic modelling and validation of a commercial scale geothermal organic rankine cycle power plant’, *Geothermics*, 61, pp. 63–74. doi: 10.1016/j.geothermics.2016.01.007.

Quoilin, S., Broek, M. Van Den, Declaye, S., Dewallef, P. and Lemort, V. (2013) ‘Techno-economic survey of Organic Rankine Cycle (ORC) systems’, *Renewable and Sustainable Energy Reviews*, 22, pp. 168–186. doi: 10.1016/j.rser.2013.01.028.

Quoilin, S., Declaye, S., Tchanche, B. F. and Lemort, V. (2011) ‘Thermo-economic optimization of waste heat recovery Organic Rankine Cycles’, *Applied Thermal Engineering*, 31(14), pp. 2885–2893. doi: 10.1016/j.applthermaleng.2011.05.014.

Sinnott, R. (2005) *Coulson and Richardson’s Chemical Engineering Volume 6 - Chemical Engineering Design (4th Edition) - Knovel*. Available at: https://app.knovel.com/web/toc.v/cid:kpCRCEVCE2/viewer Type:toc/root_slug:coulson-richardsons-chemical/url_slug:kt007SFVV1.

Stepanoff, A. J. (1957) *Centrifugal and axial flow pumps : theory, design and application*. New York: John Wiley & Sons.

Sun, J. and Li, W. (2011) ‘Operation optimization of an organic rankine cycle (ORC) heat recovery power plant’, *Applied Thermal Engineering*. Elsevier Ltd, 31(11–12), pp. 2032–2041. doi: 10.1016/j.applthermaleng.2011.03.012.

Svrcek, W. Y., Mahoney, D. P. and Young, B. R. (2014) *A Real-Time Approach to Process Control*. Wiley Publishing.

Tchanche, B. F., Lambrinos, G., Frangoudakis, A. and Papadakis, G. (2011) 'Low-grade heat conversion into power using organic Rankine cycles – A review of various applications', *Renewable and Sustainable Energy Reviews*, 15(8), pp. 3963–3979. doi: 10.1016/j.rser.2011.07.024.

Zhang, J., Zhang, W., Hou, G. and Fang, F. (2012) 'Dynamic modeling and multivariable control of organic Rankine cycles in waste heat utilizing processes', *Computers and Mathematics with Applications*. Elsevier Ltd, 64(5), pp. 908–921. doi: 10.1016/j.camwa.2012.01.054.

Zhang, J., Zhou, Y., Wang, R., Xu, J. and Fang, F. (2014) 'Modeling and constrained multivariable predictive control for ORC (Organic Rankine Cycle) based waste heat energy conversion systems', *Energy*. Elsevier Ltd, 66, pp. 128–138. doi: 10.1016/j.energy.2014.01.068.