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Model Predictive Control

LEARNING MODULE 1: LOW-LEVEL MPC

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Executive Summary

Throughout the Modeling Predictive Control workshop, the goal is to develop an improved controller for a tankless water heater (TWH). A Simulink model is given for low-flow and high-flow characteristics separately. These models work under the assumption that the TWH contains three heating chambers. The models will be linearized through the use of the Model Predictive Control Toolbox which is built into Simulink. This linearized model will then be put into a more realistic scenario in order to validate the control characteristics.

Using both low and high-flow models, the MPC controllers will be designed through the investigation of several characteristics. The ultimate goal in doing so, is to create a controller that makes it possible for the TWH model match the actual temperature. An analysis of optimized characteristics is also included throughout the report.

Accurate control is important in a tankless water heater for comfort and safety especially when the heated water is not mixed at the end, such as in a shower. MPC controllers function by predicting the plant state a certain prediction horizon into the future into and then optimizing plant parameters based on the predicted future state. The primary tuning variables of interest in this analysis were the prediction and control horizons which were manually varied to attain optimal plant performance for both high flow and low conditions. Subsequent to the tuning of the MPC controllers, a comparison was made to a PID controller and a standard controller packaged with a typical Keltech TWH. The optimally tuned MPC controller outperformed the PID controller by 40.5% and the Keltech controller by 77.8% with respect to integral-squared error.

Methodology

LINEARIZATION

Models will be linearized for a low-flow scenario of 2 L/min and a high-flow scenario of 8 L/min. This process is done through creating a low-flow and high-flow MPC controls using the MPC Toolbox.

CONTROLLER DESIGN – parameters and measured disturbances

An MPC controller will be designed through the use of the MPC Toolbox after the models are linearized. The toolbox provides parameters and various inputs in order to adjust the control for low and high flow scenarios. The three main parameters that require further investigation to design both controllers are control interval, prediction horizon, and control horizon. Intervals are measured in seconds which will directly affect prediction and control horizons. The prediction horizon is the time interval in which conflicts will be detected or in other words, how far ahead the controller will need to look to create good control. The control horizon is the amount of intervals within the prediction horizon that are specifically controlled.

The measured disturbances are the flow rate and water inlet temperature. It is especially important for these to be classified as measured disturbances due to the fact that it creates a better control scenario. For example, when the flow rate is classified as an unmeasured disturbance, the rate is not being tracked and sent to the controller, therefore its control quality is not as good. Figure 1 compares the control tracking with flow rate classified as unmeasured and measured disturbances. As seen from the graph, the control with an unmeasured flow rate exhibits temperatures that are further away from the setpoint than the control that does track flow rate.

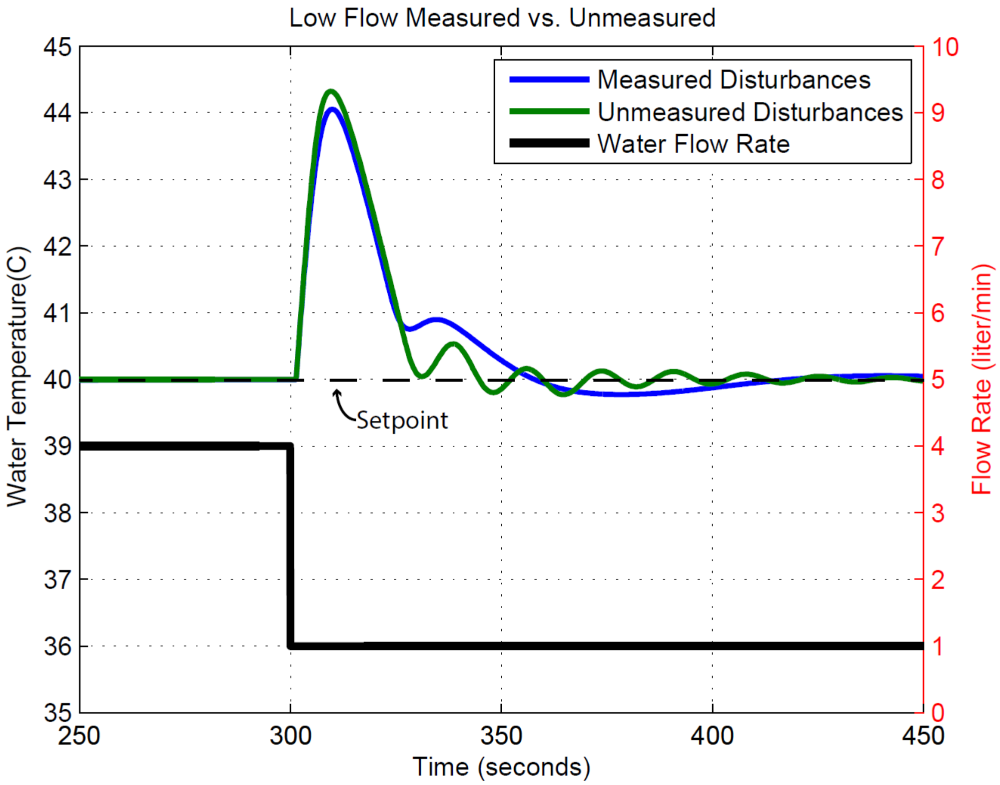

Figure 1: Measured vs. Unmeasured Flow

VALIDATION

After tuning the MPC controls to exhibit good control for low and high flow scenarios, the controls were imported into a non-linearized Simulink testing environment. It is expected that the results will look different from the fully linearized graphs produced in the toolbox because the validation settings will provide a more sophisticated model for testing the control quality. As with the linearized models, good control will be determined by how closely the temperature setpoint of 40°C can be maintained.

Realistically in an actual application, both low and high flows will be present. To integrate both flow scenarios into one model, a concept called bumpless transfer will be used. This allows optimal control to be attained in both high flow and low flow scenarios by allowing the model to select the optimal controller based on actual conditions.

CONTROLLER COMPARISON

Finally, once each MPC controller has been designed, it will be compared with an optimal PID controller using a realistic testing environment. This environment will incorporate the bumpless transfer concept in addition to comparing the MPC and PID control.

The chosen MPC controllers for high and low flow scenarios will be modeled and compared with an optimal PID controller as well as a standard Keltech controller. The better control is expected to have a lower integral-squared error (ISE) metric. For analysis of this error metric, the Integral Squared Error method will be used to support the results.

Results & Discussion

First, to tune and design the controllers, it was decided to use graphing techniques to determine the best control parameters. We started by changing the interval, prediction horizon, and control horizon to many different value combinations and graphing them all against each other to be able to analyze which scenario exhibited the best control of the 40°C setpoint. Then, the idea was to take the control setting that looked the best and fine tune them to create even better control for the flow rates. This process was done for both low and high flow rates. Graphs were made to compare the flow rates with all scenarios run with an interval of 1. Figures 2 and 3 show the results for low and high flows, respectively.

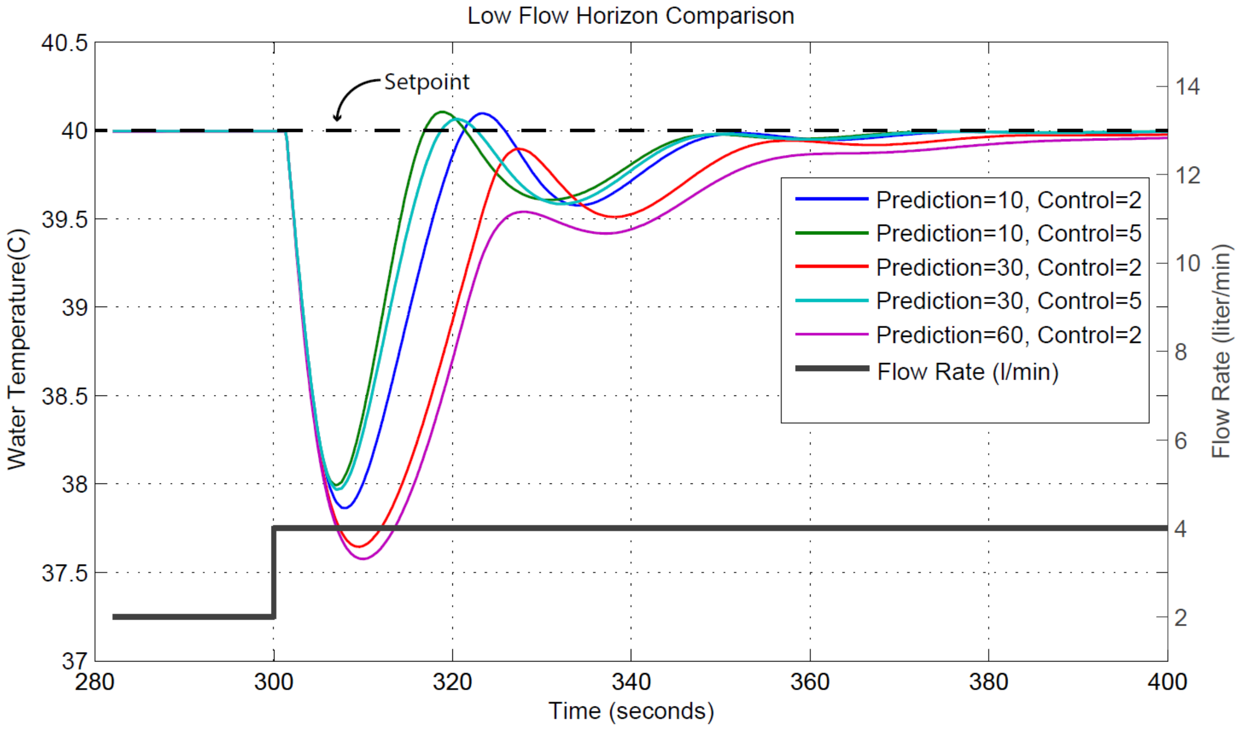

Figure 2: Low Flow Horizon Comparison

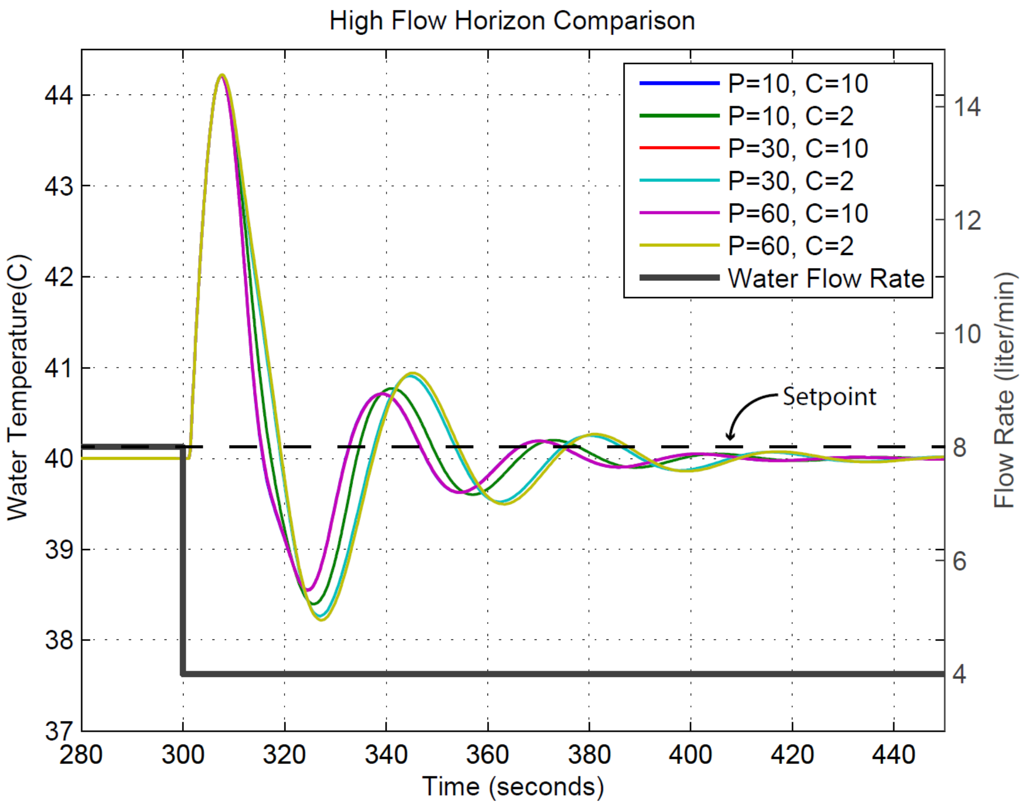

Figure 3: High Flow Horizon Comparison

From the graphs, the controller that was the closest in reaching setpoint was chosen. The initial controllers that were selected are shown in the table below.

Table 1: Inital Controller Parameter Selection

Flow	Interval	Prediction Horizon	Control Horizon
Low-Flow	1	10	5
High-Flow	1	60	10

The next step was to validate the given controls. Low and high flow controls were run separately and also run together in the bumpless transfer model. When this step was complete, the results showed that especially when the low and high flow controllers were paired together, the low flow characteristics caused poor setpoint control. In a low flow setting, the temperature reached almost 50°C which is unacceptable especially for safety purposes. Through reevaluation of the chosen setting for low flow, it was realized that in selecting this controller, the variation in water inlet temperature was not taken into account. To gain a better understanding of why the initial controller selection was poor, a separate model with Gaussian variation (noise) with regard to water inlet temperature was produced and graphed. The comparisons with noise take the varying entering temperature into account while the comparisons without noise in Figures 2 and 3 do not. The new graphs in Figures 4 and 5 are analyzed and better control parameters are selected.

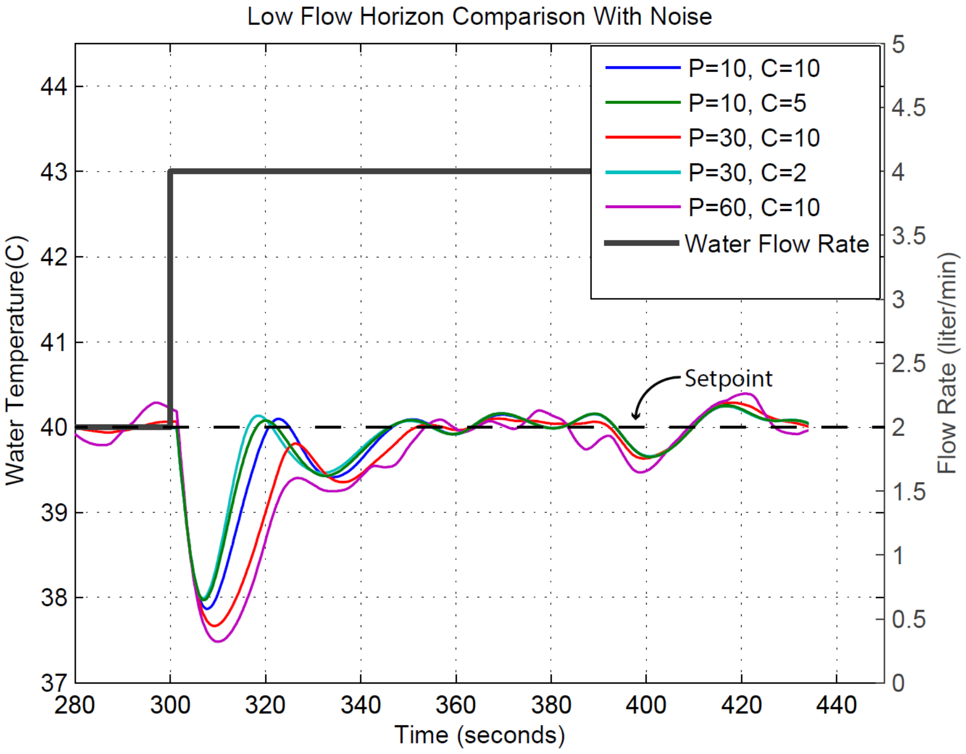

Figure 4: Low Flow Horizon Comparison with Noise

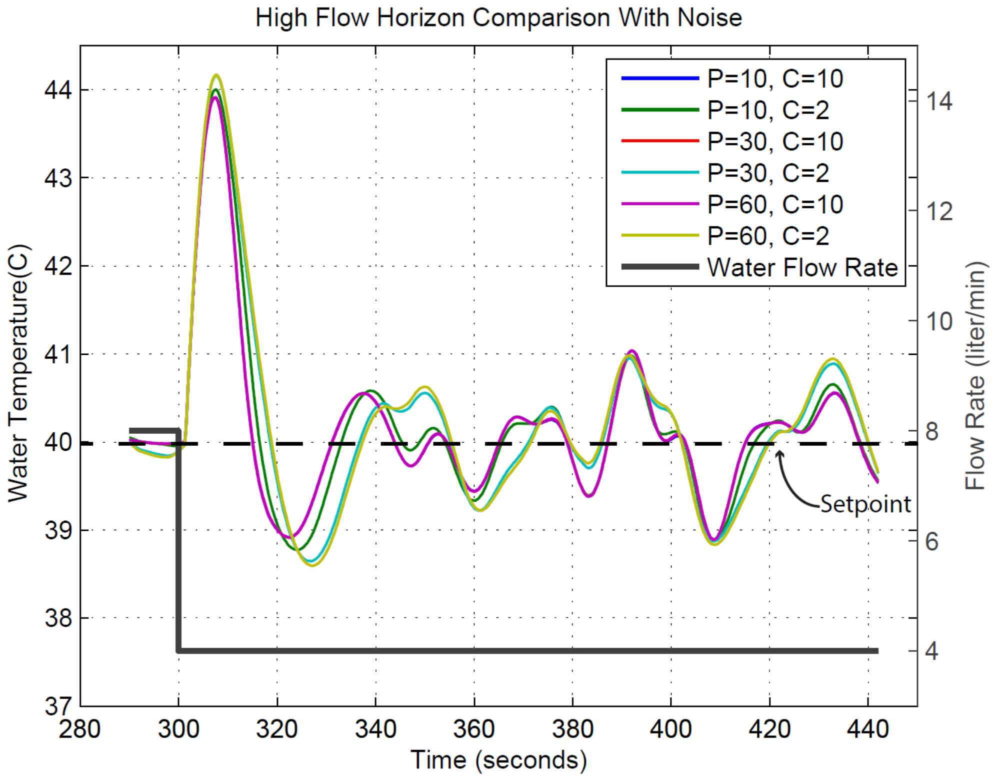

Figure 5: High Flow Horizon Comparison with Noise

In taking a closer look at low flow control settings, when a water inlet temperature disturbance is added (noise), the control with a prediction horizon of 30 and a control horizon of 2 actually performs better than the initial controller chosen. For the high flow settings, no changes were made. The final control choices for both settings are summarized in Table 2.

Table 2: Final Controller Parameter Selection

Flow	Interval	Prediction Horizon	Control Horizon
Low-Flow	1	30	2
High-Flow	1	60	10

The bigger the separation between prediction and control horizons, the better control the MPC seemed to exhibit. Once again, the final choices for low and high flow settings were entered into a validation model and tested.

As previously mentioned, the error metric used is the Integral Squared Error (ISE). An ISE evaluation was done for low and high flows separately before combining the two. A step change in temperature from 20 to 40°C occurring at 300 seconds was added to the validation files to observe how the controls would react. The ISE function was reset at 300 seconds in order to leave out the initial conditions at 20°C since a temperature setpoint of 40°C is the main interest.

Table 3: Integral Squared Error for Low and High Flows

Flow	ISE
Low-Flow	4987
High-Flow	3129

These ISE values are much better than those exhibited with the initial selected controller parameters. Previously, with the selected low flow control settings of prediction horizon and control horizon of 10 and 5, respectively, the ISE value was 7895. Changing this controller to have settings of 30 and 2 instead of 10 and 5 clearly improved the results.

When combined, the two flow rates create an efficient system with an ISE of 314.4. This value was found by utilizing the bumpless transfer model and setting the ISE constant to 100 seconds. It is able to be set to a lower value because there is no longer a step change implemented at 300 seconds. Therefore, 100 seconds was used because initial conditions were overcome by this point in time.

MPC vs. PID

Finally, the MPC controllers created were compared with an optimal PID controller for the Keltec 1214 TWH model. The ISE error metric was applied to both controller types.

Table 4: Integral Squared Error for MPC, PID, and Keltech Controllers

Controller	ISE
MPC	314.4
PID	528.3
Reference Keltech Controller	1407

From the values, it is clear that the PID control exhibits a larger error. From Figure 6, the MPC controller clearly maintains a temperature closer to the setpoint of 40°C. The reference data comes from the standard control given by the Keltec file used to model the tankless water heater.

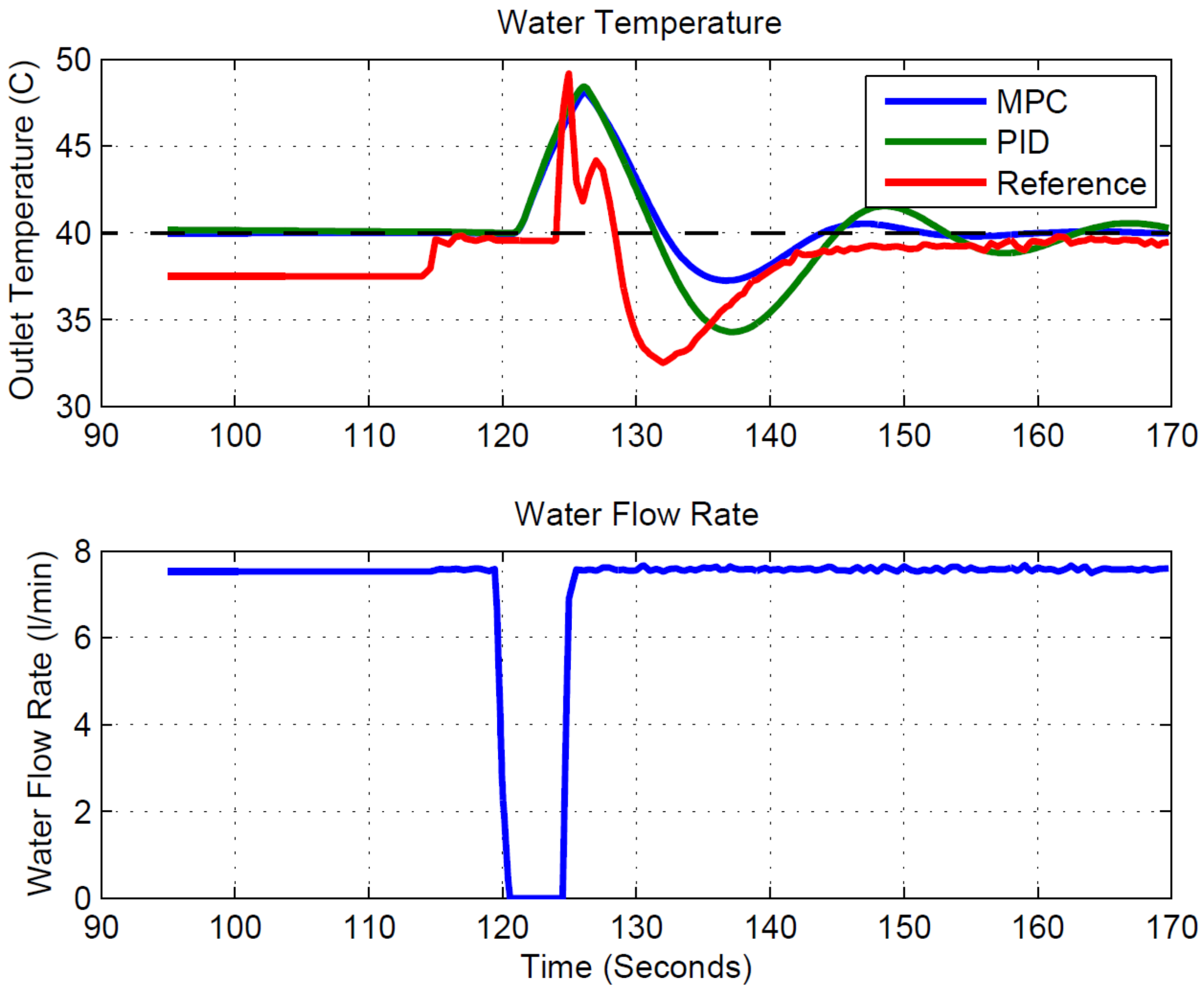

Figure 6: MPC vs. PID

Conclusions

Through the investigation of MPC controllers, it was found that the bigger the difference between prediction and control horizons, the better the control quality was. However, if the prediction horizon was too large, the control quality either decreased or did not change at all. Finding the balance between the two was done iteratively through the MPC toolbox. The higher flow scenario required a larger prediction horizon to achieve good control. Because of this increased prediction horizon, the control horizon for high flow was also higher than the low flow scenario. As far as measuring the error of each scenario goes, the high flow did have a lower ISE and this could be due to the fact that the prediction and control horizons were larger. Fine tuning the MPC to have a better balance between the horizons might have improved its control. When compared with the PID controller, it was proven that the MPC controller was a better choice for the tankless water heater model.

References

Henze, Gregor, David Yuill, and Andrew Coward. *Development of a Model Predictive Controller for Tankless Water Heaters*. 2008. Print.