Modelling and Control of Shell and Tube Heat Exchanger using Model Predictive Controller

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Abstract. In this article, A Multi-Input Multi-Output system is mathematically modelled using energy balancing differential equations. To model a MIMO system, specifications are very important. The data samples of MIMO are collected from a shell and tube heat exchanger hardware setup. The real time data samples collected are substituted in the predefined differential equation to create a Shell and Tube heat exchanger model. The model output would result as the output obtained from a shell and tube heat exchanger hardware setup. Since shell and tube heat exchanger modelled has two inputs and two outputs, system model is also a TITO system. The System identification method was employed for TITO system modelled to obtain the linear model as the output was highy nonlinear and its transfer function model was determined that had process interaction. The interaction in process doesn't allow the system to attain its steady state value faster. Classical controllers were employed for the process to attain steady state faster but the results were not satisfactory. So, Model Predictive controller was used for the designed system to obtain the output responses faster to the desired value by minimizing the error drastically. The nonlinear model response, linearized model response, open loop response and closed loop response with MPC for the designed system were compared and analyzed.

Keywords. MPC; Heat Exchanger; MATLAB; TITO System.

1. Shell and Tube Heat Exchanger

One of vital systems in industries is the temperature exchange amongst elegant liquids. In exchangers the heat of every fluid fluctuations as it flows via the exchanger, and the heat of the separator between the liquids also variations along the span of the device.

There are three main category of heat exchanger: the very important kind is recuperator in which the fluids are exchanging heat on sideways of a separating wall; the next one is the regenerator in which the warm and cold fluids flow alternately through a space covering a matrix of material that offers alternatively a final tank and a foundation for temperature flow; the third one is the evaporative kind in which a fluid is cooled evaporative and uninterruptedly in the same area as the coolant.

In order to do the device more solid, which is wanted form of space reflexions, and also to decrease the temperature drop from the outdoor plane, it is needed to have some pipes and perhaps some flows or packs of pipes. The flow can be moreover cross flow or a blend of parallel flow, counter flow and cross flow. A shell and tube type mixed flow exchanger is shown figure 1.

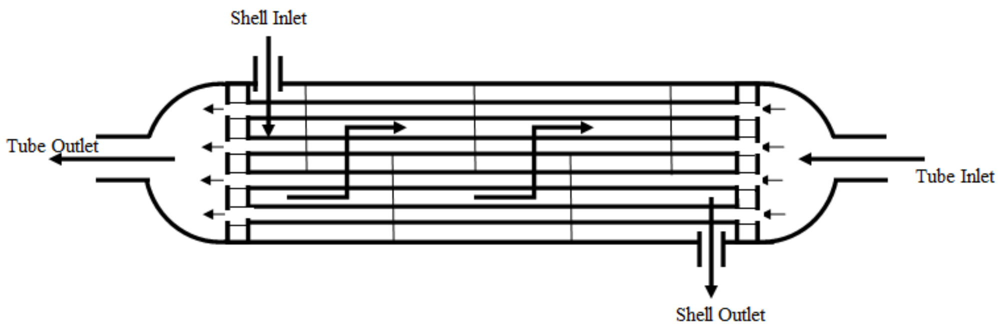

Figure 1. Diagram of Shell and Tube Heat Exchanger

2. Mathematical Modelling

The model is one which helps the structure dynamic responses and the formulations. It needs the calculation of some readings according to the sort of system in cooperated and the calculated data from the dynamics of the plant. Prior data about the elementary outline of the system is essential for the modelling.

$$\dot{T_{co}}(t) = \frac{W_c}{\rho_c V_c (T_{ci}(t) - T_{co}(t))} + \frac{U_c A_c}{\rho_c V_c C_{pc} (T_{ho}(t) - T_{co}(t))}$$
$$\dot{T_{ho}}(t) = \frac{W_h}{\rho_h V_h (T_{hi}(t) - T_{ho}(t))} + \frac{U_h A_h}{\rho_h V_h C_{ph} (T_{co}(t) - T_{ho}(t))}$$

Where, T_{co}, T_{ci}, T_{ho} and T_{hi} are outlet and inlet cold and warm liquid heat correspondingly (ºC), W_h and W_c are mass flow rate of hot and cold liquid correspondingly (kg/sec), C_{ph} and C_{pc} are the temperature capacity of hot and cold liquid correspondingly (J/kg.ºC), V_h and V_c are volume of hot and cold liquid correspondingly (cm^3), A_h and A_c are temperature transfer surface area of hot and cold fluid correspondingly (cm^2), U_h and U_c are the temperature transfer coefficient of hot and cold liquid correspondingly (W/cm^2 ºC). ρ_h and ρ_c are the density of hot and cold liquid correspondingly (kg/ cm^3).

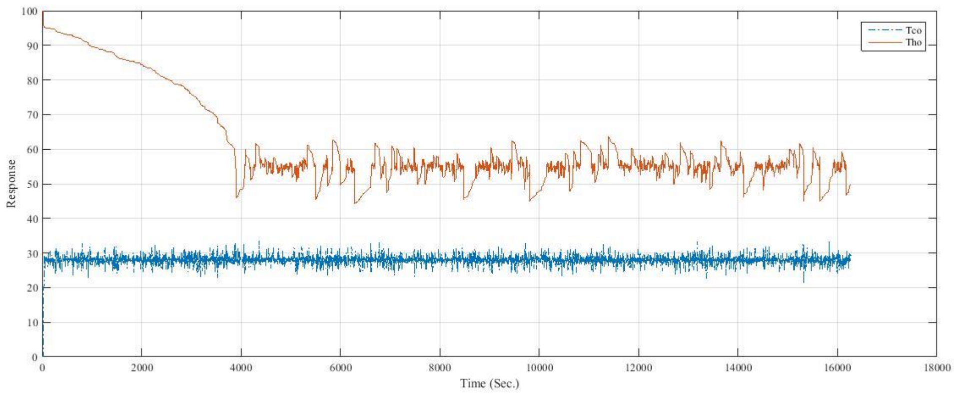

Figure 2. Output Response of Heat Exchanger

Figure 2 represents the outlet fluids temperature of heat exchanger, Where T_{ho} is decreased from the T_{hi} (100˚C) and T_{co} is increased from the T_{ci} (0˚C). Both T_{co} and T_{ho} are highly nonlinear in nature.

3. Heat Transfer Calculation

Heat is transferred from high to low temperature. This powerful temperature change across the heat transfer plane varies with location. To find for this in simple systems, the Log Mean Temperature Difference (LMTD) is used as middling temperature. We undertake that a nonspecific exchanger consumes two ends at which the hot and cold liquids enter or exit on either place; then, the LMTD or ΔT_{LM} is explained by the logarithmic mean as follows:

$$\Delta T_{LM} = \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)}$$

Where, ΔT_A is the heat variance among the streams at side A, and ΔT_B is the temperature variance among the two streams at side B. With this explanation, the LMTD may be used to discover the heat transferred among the fluids which are flowing in a heat exchanger:

$$Q = UA\,\Delta T_{LM}$$

Where, Q is the heat exchanged rate (in Watts), U is the temperature exchange coefficient (in Watts per Kelvin per square meter) and A is the transfer area. Measure that approximating the temperature exchange coefficient may be pretty complex. Seeing a stream flowing in and out of a exchanger, the temperature exchange rate Q (in Watts) is derived from the flow rate m (in kilogram per second) and the heat (in Kelvin) at the inlet and outlet of the device:

$$Q = mc\Delta T$$

Where, c is specific heat capacity (in Joule per kg per Kelvin).

Table 1. Specification of Shell and Tube Heat Exchanger

1.	Shell's Inner Diameter	D_s	150 mm
2.	Shell's Length	L	615 mm
3.	Total Number of Tubes	n	32
4.	Inner Diameter of Tube	d_i	12.5 mm
5.	Outer Diameter of Tube	d_o	15.5 mm
6.	Pitch	P_T	20 mm Sq.
7.	Baffle spacing	B	100 mm
8.	Baffle's Count	N	4
9.	Collection Tank's Area	A_T	0.04 sq. m

4. System Identification

The design of the control system needs a model for the analysis of system dynamics; often a dynamical model can be hard to get the complexity of the system, whose dynamics may be unidentified even if a mathematical model is designed. Sometimes, it is very complex to design controller, model decrease is way to go, but wants a linear model to start with. System identification is the process to obtain output without model of system. It deals with the statistics only. Here the input and output information which are reserved from the designed system is fed into the system identification tool box to find the transfer function. Since the model is TITO system, four transfer functions are got from the system identification tool box.

$$\begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} = \begin{bmatrix} \frac{T_{co}(s)}{W_c(s)} & \frac{T_{ho}(s)}{W_c(s)} \\ \frac{T_{co}(s)}{W_h(s)} & \frac{T_{ho}(s)}{W_h(s)} \end{bmatrix}$$

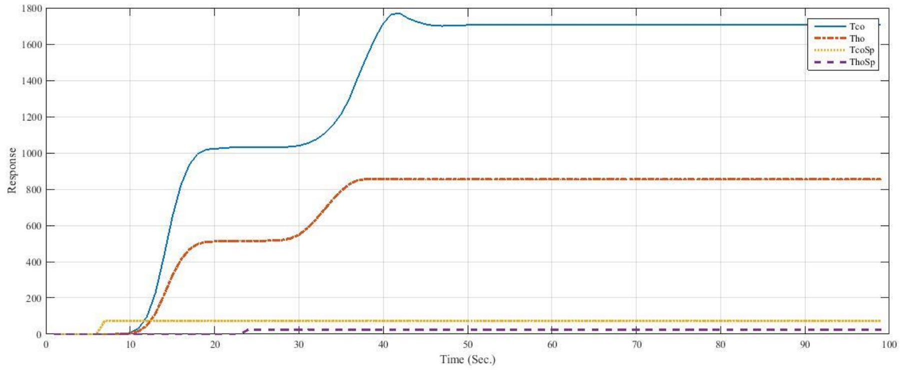

Figure 3.Open loop Responses of outlet temperatures and inlet flow rates of fluids

Figure 3 shows the open loop response of transfer function model. It gives the linear response for T_{co} and T_{ho} but these responses are neither settled nor saturated at a desired value with respect to the operation of heat exchanger.

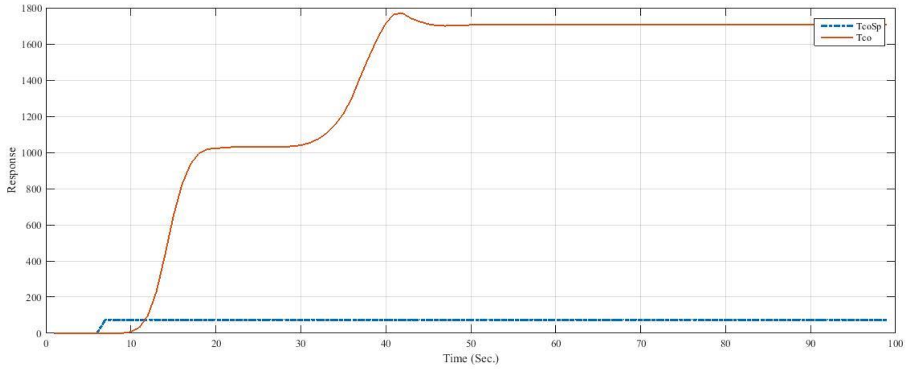

Figure 4. Open loop responses of Inlet flow rate and the outlet Temperature of cold fluid

Figure 4 and 5 clearly shows the response of outlet temperatures which are taken from the transfer function model of heat exchanger. Temperature responses T_{co} and T_{ho} of heat exchanger attains a steady state around 900˚C and 1800 ˚C respectively. It is very high when compared to the real time operating points. To bring back the responses to the desired value, implementation of controller is very important.

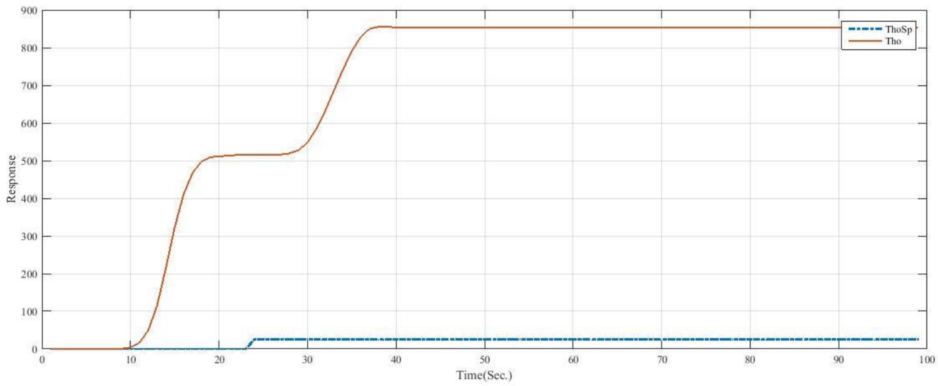

Figure 5. Open loop responses of Inlet flow rate and the outlet Temperature of hot fluid

5. Model Predictive Controller

The basic knowledge of MPC is to practice a process model to estimate the best variations in the operated variables will attain a quantified wanted outcome in the controlled variable. At every argument in time the responses are measured.

Then the optimization steps estimate the changes in variables for some time step into the upcoming time. These variations are made and has some outcome on the controller outputs. At the next time step the new standards of the controller output parameters are taken and incorporated into the optimization problem, which is determined to get the new operated variable values.

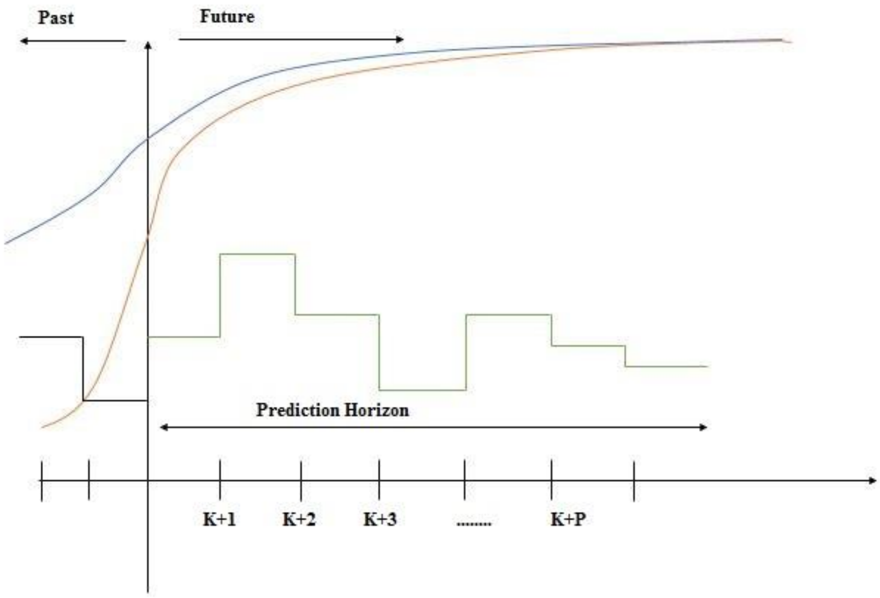

Figure 6. Schematic representation of Model Predictive Control horizons

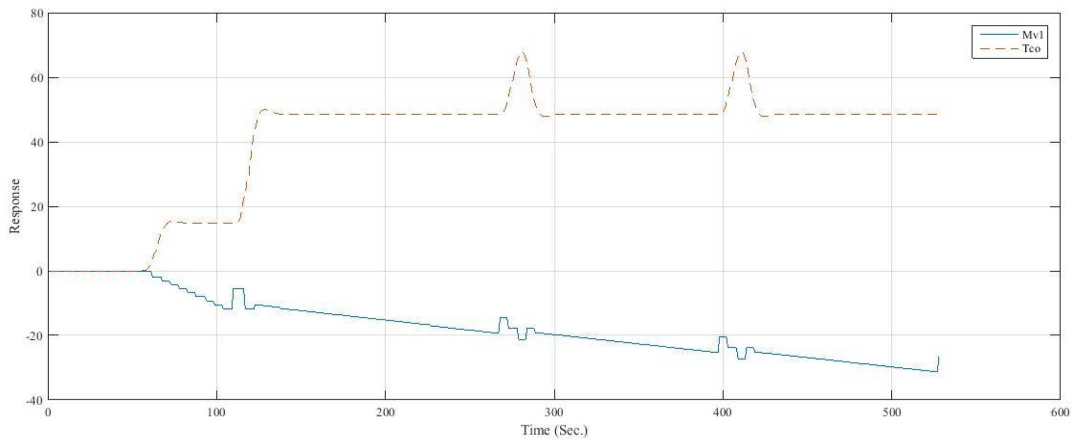

Figure 7. Output response of cold liquid temperature and the respected manipulated variable

In Figure 7, the controlled response of cold outlet temperature and action taken by controller to attain the reference value are shown. Similarly in Figure 8. Shows the controlled response of hot outlet temperature.

Figure 9 clearly shows the Cold outlet temperature with the necessary controller action by MPC on the cold inlet flow rate that has the servo tracking response of reference signal as soon the step change is made in the reference signal.

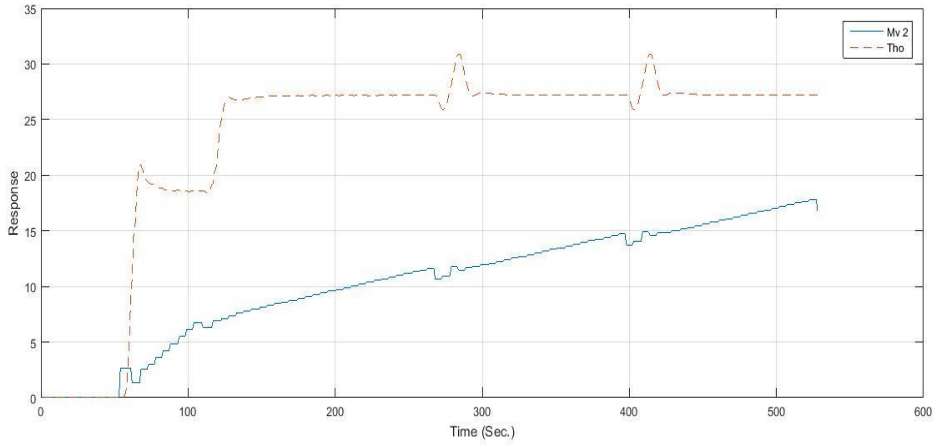

Figure 8.Output response of hot liquid temperature and the respected manipulated variable

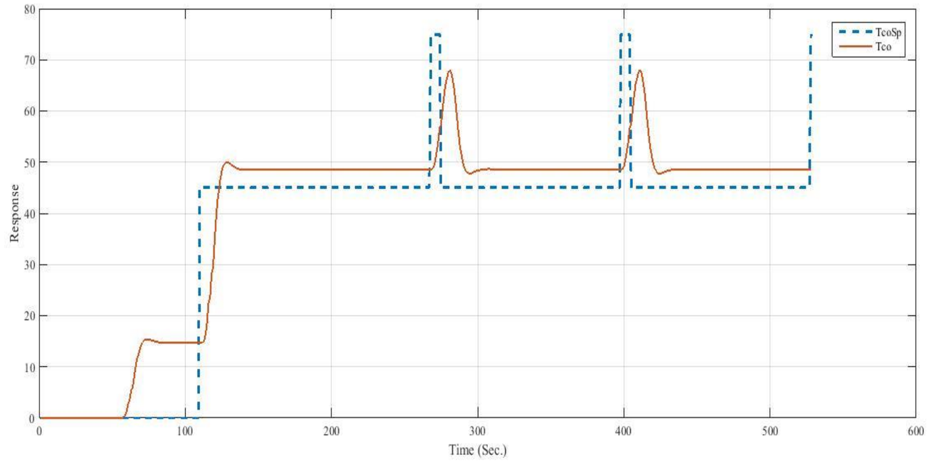

Figure 9. Cold outlet temperature response and its reference signal

In Figure 10, temperature output of a shell and tube heat exchanger's controlled responses are shown. MPC controller drastically takes control action to reduce the error. If the set-point increases, the controller takes respective action on manipulated variable to reach that reference value.

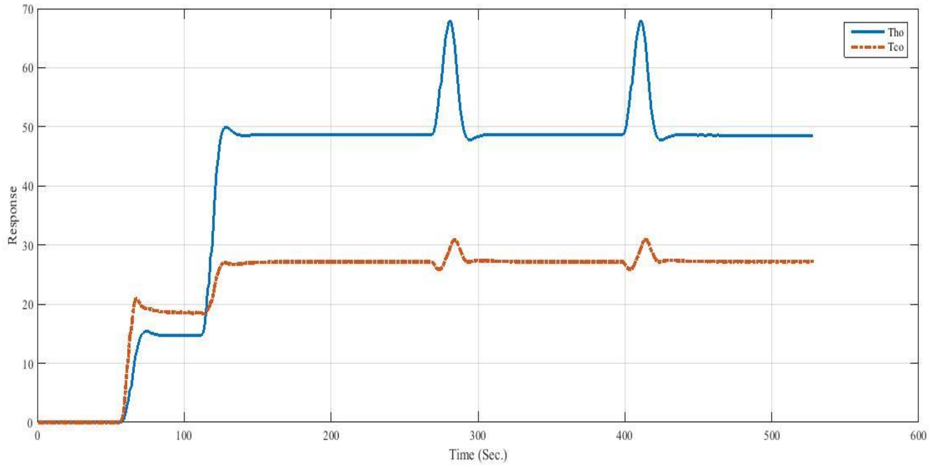

Figure 10. Controlled responses of cold and hot fluids outlet temperature

Once the temperature reaches the set-point value, the controller also maintains the manipulated variables at previous value.

6. Conclusion

The MIMO system shell and tube heat exchanger were mathematically modelled using the energy balance equation and responses were obtained which was highly nonlinear. It was highly complex to analyze the dynamics of MIMO process with the data obtained from mathematical model. The linear model for shell and tube heat exchanger was modelled with the system identification method and output responses were obtained. The output response of the heat exchanger was linear but attained a steady state beyond the desired value which required the control action to reach a desired value. Therefore, the Model Predictive Controller was employed for the Shell and Tube heat exchanger process. The temperature responses of the MIMO system were controlled with the steady state value attainment. The servo tracking was done with the step change made in reference signals and the error was completely reduced with the help of MPC.

7. References

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