

## Investigation on the Application of Kalman Filter for Heat Exchanger Process

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### Abstract

Heat exchanger is a chemical process with dynamic characteristics. Due to internal and external disturbances, it is very difficult to provide stringent control action for dynamic process. If the state variable of the process is free from noise, it is easy to control the process variable. In our work, the key controlled variable is the cold fluid outlet temperature of the heat exchanger process. Due to physical limitations, the installation of temperature sensors in heat exchanger is not viable and moreover the signal from the sensor will be perturbed by internal and external noise. Estimating the state variables can lead to reduce the hardware components and truthfully following the process variable can make a way for better control. In this work, Kalman filter is employed to estimate the state variable as cold fluid temperature. The performance of the Kalman filter is validated by error covariance matrix.

**Keywords:** Heat Exchanger, Kalman Filter, Estimation.

### 1. INTRODUCTION

The use of heat exchanger in food processing, chemical and power plants is of prime importance. The product quality of these plants are monitored and maintained by controlling the plant temperature. The transfer of heat between two fluids is the main purpose of heat exchanger. [1]. The reasons for heat transferring are one of the following

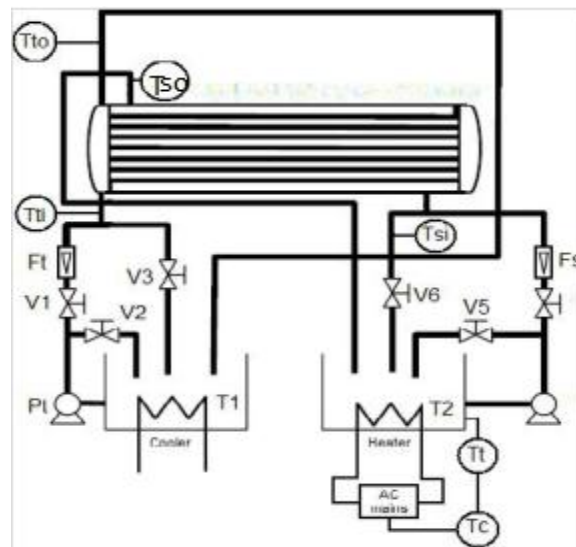
1. To heat cold fluid by hot fluid.
2. To boil a liquid by hot fluid.
3. The hot fluid temperature is reduced by cold fluid.

Without any surface contact the heat transfer process between two fluids is done. Here the hot and cold fluid temperatures acts as controlled variables and the inlet flow rate of hot fluid and cold fluid act as manipulated variables. To implement a controller it is a must to develop the mathematical model of the heat exchanger. Two ways are there to develop a model. One way is by using first principle and other way is by using empirical method. Obtaining a model using the first principle involves the development of equations that describes all the physics and principle taking place in the process [7]. By taking Laplace transform of all the equations, the time domain equation of the system is transformed to s domain. The number of equations that describes the system gives the accuracy of the equation. To define all the equations that describing the system is practically impossible. So empirical method of obtaining a model is mostly preferable [8]. Here, a user defined set of inputs and its response is plotted. System identification is used to derive transfer function and state space model.

To provide “acceptable” estimates of the process state, a state observer is needed, for use in implementation of a controller [2]. The state estimation technique is used for estimating states amidst the presence of noise. The technique used is Kalman filter. In many chemical processes the use of Kalman filter has received extensive study [5-6].

Here, the work is presented to get an idea based on application of Kalman filter and to know performance of the Kalman filter in heat exchanger.

## 2. SCHEMATIC DIAGRAM



**Fig. 1:** Schematic Diagram of Heat exchanger setup [8]

$T_{to}$  = tube outlet temperature

$T_{si}$  = shell outlet temperature

$T_{ti}$  = tube inlet temperature

$T_{si}$  = shell inlet temperature  
 $F_s$  = shell inlet flow rate  
 $F_t$  = tube inlet flow rate  
 $T1$  = cold fluid tank  
 $T2$  = hot fluid tank  
 $P_t$  = cold fluid pump  
 $P_s$  = hot fluid pump  
 $V1-V6$  = Valves

Fig.1 The heat exchanger used here is shell and tube which is the most ordinary heat exchanger. As the name suggest, a bundle of parallel tubes present inside the shell [3-4]. There will be no contact between the medium flowing through shell and tube side, but heat exchange takes place between the walls of shell and tube. Hot water flows from Tank T2 through shell side of heat exchanger and cold water flows from Tank T1 through tube of the heat exchanger. The purpose to control the tube outlet temperature ( $T_{to}$ ) is by altering the shell inlet flow rate ( $F_s$ ). Cold fluid temperature is monitored continuously by changing flow rate of hot fluid ( $F_s$ ) i.e. varied in steps.

The cold water is passed through the tube side and the hot water is passed through the shell side. Initially, the shell side is 100% in normally opened (NO) condition and the tube side is 100% normally closed (NC) condition. Initially the pump supplies water to the process tank and the heater is switched ON. The temperature of process tank is set at a constant value. Then process is allowed to run for specified time period to obtain proper values from RTD. After attaining the desired temperature, the valve is made to open 50% in shell side and the tube side is made 100% open. Between the hot water and the cold water, the heat exchange takes place. The temperature of the water from the reservoir that comes out after the heat exchanging process with respect to time was noted. The signal from the computer is converted into mA and it is displayed in the ammeter. Depending upon the signal from the system the current is converted into pressure by the I/P converter which is indicated by the pressure gauge. For 50% open the current is 12 mA and the pressure is 9 psi and the flow is indicated by the rotameter. The hot fluid flow rate is 144l/hr. The input-output data is used to derive the model via system identification.

### **3. KALMAN FILTER**

The best linear estimator is the Kalman filter. The dynamics of continuous time system is

$$\dot{X} = AX + Bu + q$$

The measurement equation is

$$Y = CX + r$$

Where

A = state transition matrix

B = input matrix

C = measurement matrix

$q$  is the process noise (Gaussian distribution curve) with zero mean and covariance factor  $Q_c$

$$q \sim N(0, Q_c)$$

$r$  is the measurement noise with zero mean and covariance factor  $R_c$

$$r \sim N(0, R_c)$$

Kalman filter equations are given as

$$\hat{X}(0) = E[X(0)]$$

$$P(0) = E[(X(0) - \hat{X}(0))(X(0) - \hat{X}(0))^T]$$

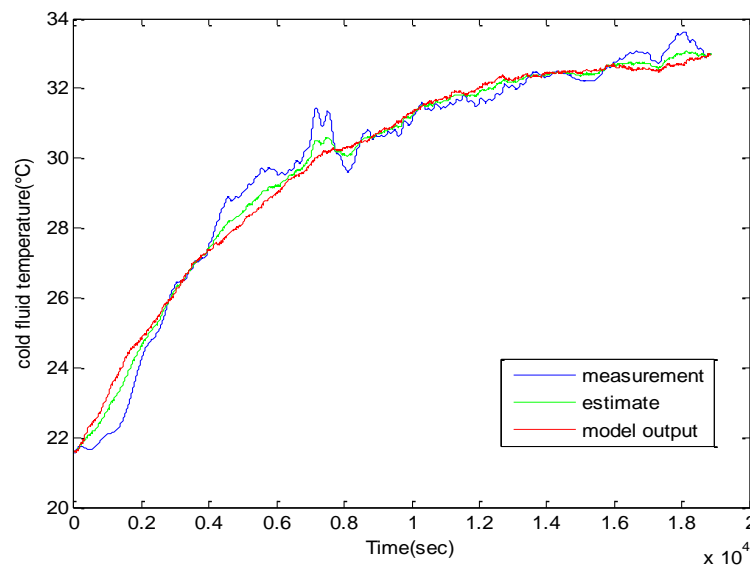
$$K = PC^T R_c^{-1}$$

$$\dot{\hat{X}} = A\hat{X} + Bu + K(Y - C\hat{X})$$

$$\dot{P} = -PC^T R_c^{-1} CP + AP + PA^T + Q_c$$

#### 4. RESULTS AND DISCUSSIONS

In this work, the estimation of cold fluid temperature is attempted. Here the system is considered as Single Input Single Output (SISO) system. Two variables are considered, one is manipulated variable and the other is controlled variable. The hot fluid flow rate act as manipulated variable and cold fluid outlet temperature act as controlled variable. At steady state, the temperature of cold water is 21.4°C. After giving step change of 13°C; the process variable is continuously changing to achieve desired set point. Kalman filter algorithm is used to estimate the process variable as shown in Fig.2. The Kalman filter efficiency can be identified by error covariance matrix.



**Fig. 2:** Evolution of estimated, measurement and model output temperature

At initial condition, the Kalman filter algorithm shows 0.9 (maximum) error covariance values. The estimated state is considered to be very close to true value as the error covariance value tends to zero as shown in Fig.3.

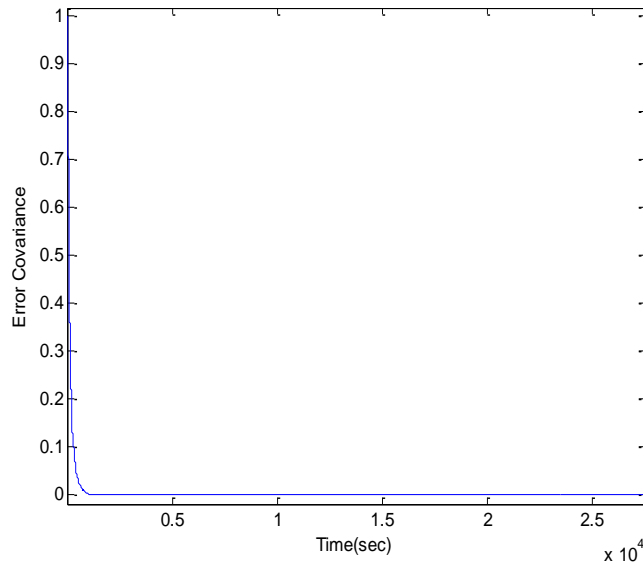


Fig. 3: Error covariance.

Under normal operating conditions, simulation is carried out to show the true and estimated state of cold fluid outlet temperature when hot flow rate is varied from 138 l/hr to 144 l/hr, 144 l/hr to 148 l/hr, 148 l/hr to 152 l/hr, 152 l/hr to 146 l/hr, 146 l/hr to 149 l/hr as shown in Fig. 4.

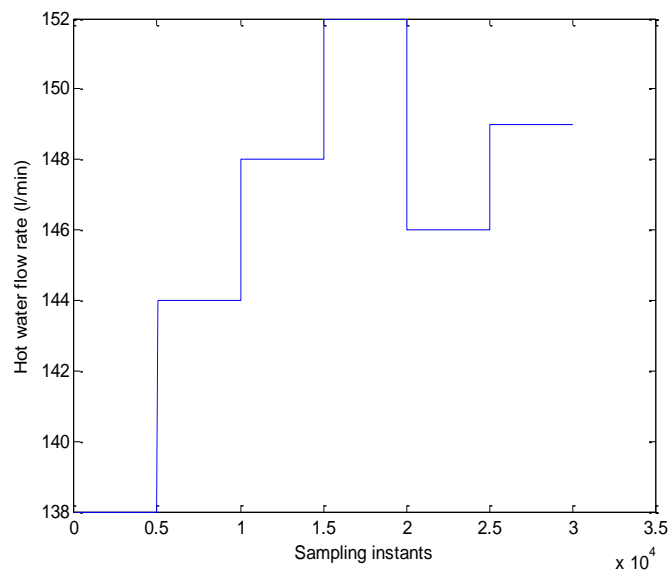
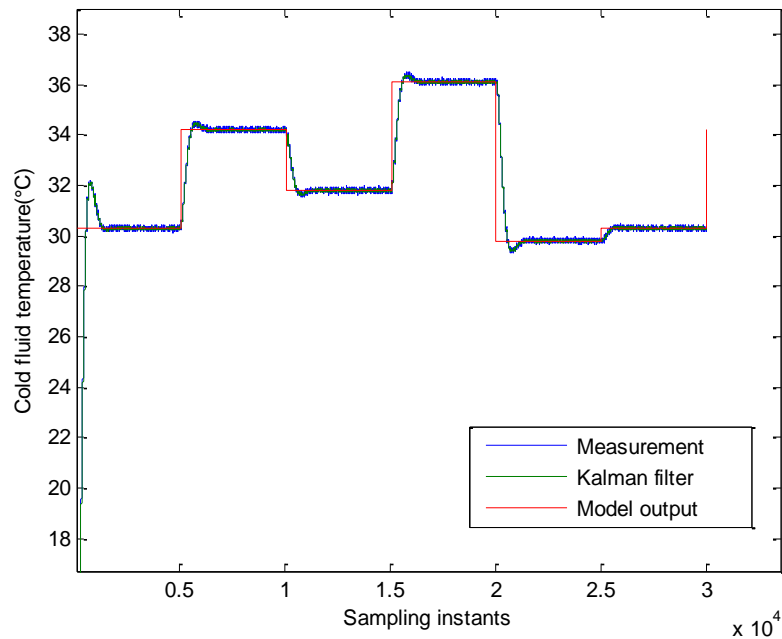


Fig. 4: .variation in hot water flow rate



**Fig. 5:** Evolution of estimated, model and measurement using Kalman filter.

The measurement output is perturbed by noise by providing step change in hot water flow rate from 138 l/hr to 144 l/hr, 144 l/hr to 148 l/hr, 148 l/hr to 152 l/hr, 152 l/hr to 146 l/hr, 146 l/hr to 149 l/hr. The KF implementation to heat exchanger shows that there is lesser effect of noise on the system states for same variation in hot fluid flow rate as shown in Fig.5.

## 5. CONCLUSION

In this paper, the heat exchanger has been successfully modeled and the Kalman filter has been employed to estimate the cold fluid outlet temperature. It is found that the functioning of the KF algorithm is satisfactory and the outputs of cold fluid temperature are estimated with greater accuracy amidst the presence of noise.

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