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MODELLING AND EVALUATION OF THE OVERALL HEATING AND COOLING PERFORMANCE OF JACKETED REACTOR

Optimizing control of non-flow jacketed processes

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ABSTRACT

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The thermal analysis and control performance of non-flow jacketed batch reactor utilizing steam-jacketed heating and water as cooling agent was investigated by an experiment and a theoretical simulation was conducted. Industrial systems are often characterized by their responses. However, determining the dynamic parameters of most systems as precisely as possible can be challenging. Nevertheless, it is important to determine the unknown dynamic parameters of the step response as accurately as possible since they are necessary for system identification. This paper analyses by experiment the performance of an insulated pilot plant jacketed reactor by heating-up and cooling-down of filled liquid (water) in the vessel. A graph of the change in temperature as a function of time was plotted accordingly after step-change and used to determine the time constant. Upon identification of the system dynamic parameters, the transfer function describing the fundamental dynamics of the plant was utilized to model the process. The mass flow of steam and the rate of the heat transfer were also evaluated based on recorded data. A control scheme was then proposed to predict the process with less delay time via a step-test using simulation. The experimental results showed that the variation in temperature was linear with no oscillations. The results controlling the system with a PI and PID controller demonstrated the PID controller scheme was more suitable for reaching the steady state value fast.

Key words
jacketed-reactor, model, performance, process, step-response, system, time-constant

CONCEPT DEFINITIONS

V (vg): Volume (Specific volume)

H (hg): Enthalpy (Specific enthalpy)

S (sg): Entropy (Specific entropy)

U (ug): Internal energy (specific internal energy)

c_p: Specific heat capacity at constant pressure

c_v: Specific heat capacity at constant volume

u: Velocity of a fluid

μ: Dynamic viscosity of a fluid

v: Kinematic viscosity

ρ: Density of a fluid

$\dot{V}$: Volumetric flowrate

m: Fundamental unit of length (meter)

$\dot{m}$: Mass flowrate

$\dot{m}_s$: Steam mass flowrate

Q: Quantity of heat

W: Unit of energy flow (Watt)

A: Cross sectional area of a conduit (CSA)

g: Acceleration due to gravity

Re_D: Reynolds number in reference to diameter D

D: Diameter of the circular cross section of a conduit

d: Orifice diameter

Pa: Unit of pressure (Pascal)

p: Static pressure of a fluid

ΔP: Differential pressure

s: Fundamental unit of time (second)

σ: Stress

Sr: Strouhal number

Hz: Unit of frequency (number of cycles per second)

J: Joule. The unit of energy

L: Length

M: Molar mass of a fluid

N: Newton. The unit of force

$\dot{Q}$: Heat transfer rate

R: Radius

T_s: Steam temperature

T_L: Liquid (or product) temperature

ΔT: Temperature difference or change

t: Time

q_M: Mass flowrate

q_V: Volume flowrate

Q_L: Liquid flowrate

Q_E: Equivalent water flowrate

P_S: Standard pressure (1,013 bar a)

P_F: Actual flow pressure

T_S: Standard temperature

T_F: Actual flow temperature

CPI: Chemical process industries

MOC: Material of construction

Modelling and Simulation: Art of designing and understanding the insight characteristics or response of a system or parts of a system

Model: Simplified version of a process system at some particular point in time/space to aid understand the real system.

System: Components/elements connected together to facilitate the flow of matter, data and energy

Process Model: Set of mathematical equations that aid in forecasting the dynamic behaviour of a process

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1 INTRODUCTION

In the past decades, global interest has been growing in tackling global warming. Part of the world's greenhouse gas emissions come from industries running energy demanding processes. According to the Centre for Climate and Energy Solutions (C2ES), in 2013 industrial processes contributed 6% metric tons of carbon dioxide equivalent internationally. The EU industrial emissions directive (IED) in 2011 adopted a set of restrictive measures containing mandatory environmental and emission limits requirements on industrial activities within member states. Adopting best available techniques (BAT) is aimed at improving the process plant efficiency and reducing its energy consumption and environmental impact.

By definition, a chemical reactor is a vessel in which chemical reactions are carried out in a controlled way. Jacketed reactors are widely used in process industry for multiple uses such as product mixing, crystallization, polymerization, solid separation and liquid-liquid extraction. They are first choice reactors in laboratories and pharmaceutical industries. A simple jacketed reactor consists of a tank or vessel which varies in size with an agitator for mixing and a build in heating/cooling system. The materials used for the production are in alloys, steel, stainless steel, glass and glass-lined steel. The performance of a typical reactor can be studied using mole balance (Shijie 2017, 172). In heating applications, when the process temperature exceeds 177°C, steam is often used as heating medium of choice. For heat jacketed heating reactor systems, steam moves in an annular space between the jacket and the tank. So, the heat energy is transferred via the solid material separating the composition to be heated. In order to perform cooling, cold water is circulated in the annular space. As a result, the atoms of the hot composition (water) in the vessel move faster, because heat energy molecules migrate from high energy levels to lower energy in order that the process is balanced.

The motivation for this thesis was to analyse and identify the dynamic parameters of a second order system. The process consists of heating/cooling of liquid in the reactor vessel to a set point without oscillation and with less overshoot in a non-flow jacketed reactor. Upon continuously stirring the composition, information gathering of the rise in temperature as a function of time for both processes immediately after a step change is recorded. This was realised by a change in valve position of the steam/cold water flowing along the walls of the vessel. The transfer function was further determined as accurately as possible by correlation and approximation of the step response. The output response of the temperature as a function of time is plotted, analysed and designed. With the art of PID controller, best performance and stability of the system is modelled and simulated in the closed loop control system. In addition, the unknown variables were evaluated, and mass flows of fluid are evaluated by direct measurement using flow metering device techniques.

The lost energy and information relating the steam consumption and heat energy exchange is evaluated as well. The overall reactor energy balance is determined as: Energy accumulation = Energy flow in - energy flow out. However, the issue of performance variation due to steam pressure change of heating medium and due to fouling are not addressed in this paper. Industrially, controlling the reactor temperature is vital in maintaining product (mixture) quality and production cost. The principle connection set-up of the plant with the flow in of either steam for heating of cold water for cooling is shown in figure 1. A fixed motor is connected to the agitator for stirring the composition in the vessel and improving uniform heat transfer.

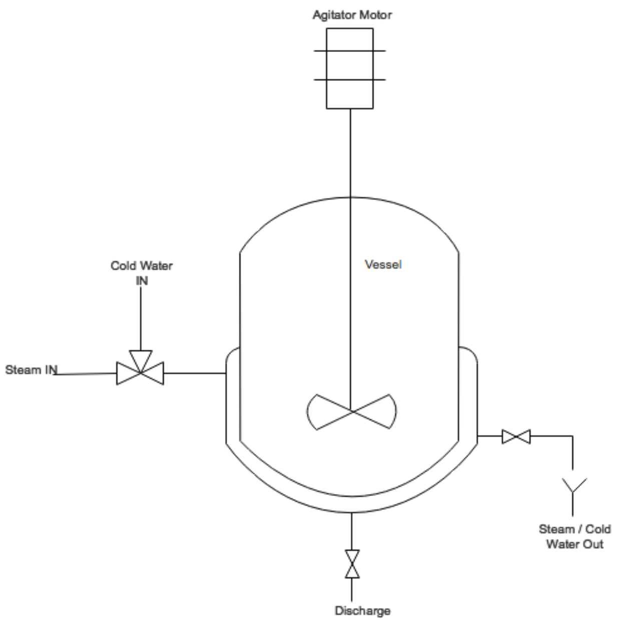

FIGURE 1. Principle diagram of the pilot plant non-flow jacked reactor.

2 PROCESS CONTROLLERS

Most processes are generally operating at steady state conditions to meet the safety, quality, budget and production output objectives. However, in real-life scenarios processes dot not always stay static which could lead to considerable losses and abnormalities due to continuous variation of process variables which could rise beyond limits. In the jacketed-reactor heating and cooling process, in case there is no drainage or discharge, the vessel will unceasingly grow full resulting in overflow and spills. In addition, variations in environmental parameters such as: temperature, flow rate and feed compositions could lead to operations deviating from steady state conditions. Process controlling is a combination of knowledge in the fields of engineering and statistics to design systems, architectures and algorithms for automating processes (University of Michigan 2017, 3). The role of a controller is to affect the controlled system by sending a signal such the controlled element or variable generate an equivalent output value required (Samson Group AG. 2019). This is constituted of a reference and a control variable (Fig. 2). The role of the reference element is to evaluate the error (e) from the reference point (w) with the feedback variable (r), whereas the control element from the error produces the adjustable variable (y).

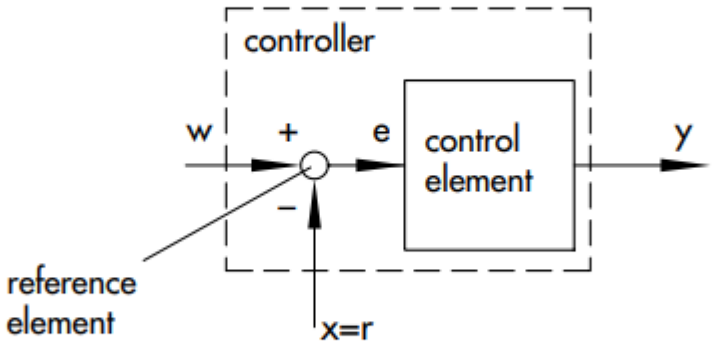

FIGURE 2. Parts of a Controller (Adapted from Samson Group AG. 2019, 23)

In the controlled systems, individual controllers behave dynamically due to step responses. This is better expressed in a closed control loop, where a step change in the reference variable induces an initial step increase in the error signal e (Fig. 2). With the feedback signal control, the error signal gradually reduces. At the end, the variable being controlled will adjust progressively until the control response variable x reaches stable state. The process variables controlled are; pressure, flowrate and temperature. In order to select the type of controller for the process, a look at different kinds of control modes specifically;

the proportional(P), integral (I) and differential (D) and the PID in first and second order systems are discussed in subsequent pages.

2.1 Proportional (P) Control Mode

The proportional control is the simplest type of process controller. P controllers are implemented in easy-to-control systems where steady-state error is tolerable in the event of disturbances. Less manoeuvres are required to attain stable and dynamic responses and the error changes proportionally to the manipulated variable. The output magnitude of the system y = (u(t)) is determined by the product of the proportional-action coefficient K_p or proportional gain and the error e.

$$u(t) = K_p \cdot e(t) \tag{0.0}$$

(Maplesoft 2019, 1)

The Laplace transformation equation of (0.0) is written as;

$$U_p(s) = K_p \cdot E(s) \tag{1.2}$$

(Maplesoft 2019, 1)

Equation (1.2) represents the equation of a straight line with gradient K_p thus, a higher K_p indicates a rise in the gradient and little changes in system changes results in subtle control decisions. The proportional band X_P [%] is given in equation 3.

$$X_p = \frac{[100\%]}{K_p} \tag{1.3}$$

(Samsongroup 1999, 28)

Systems usually undergo deviations, to compensate these effects a reverse equivalent variable is created in the opposite direction. With the P-control mode, a steady-state error cannot be completely eradicated due to the fact that such control mode generates a compensating opposite variable only in case there is system deviation disturbance as shown in Fig. 4 (Samson Group AG. 2019, 29). Moreover, very high K_p leads to unstable control loop. In a zero-error scenario P-controllers solely do not produce control amplitudes. Nevertheless, these amplitudes are necessary in order to maintain the manipulated variable at a set or desired level. To do this, an offset adjustable variable y_0 is added to the adjusted variable.

$$y = K_p . e + y_0 \tag{1.4}$$

(Samsongroup 1999, 29)

2.1.1 First order systems with P Control

In a First Order processed plant the characteristics equation is

$$G_P(s) = \frac{K}{\tau \cdot s + 1} \tag{1.5}$$

(Maplesoft 2019, 2)

where τ is the time constant and K or K_{dc} is the DC gain which stands for the value of transfer function evaluated at $s = 0$. The close loop transfer function of the P control system is

$$G(s) = \frac{K_p \cdot K}{\tau \cdot s + 1 + K_p \cdot K} \tag{1.6}$$

(Maplesoft 2019, 2)

The closed loop time constant is

$$\tau_{closed\ loop} = \frac{\tau}{1 + K_p \cdot K} \tag{1.7}$$

(Maplesoft 2019, 3)

The close loop time constant equation indicates that varying the proportional control gain can be used to make changes in the rising and settling time of a first order system. Assuming a first order system has a step input signal of magnitude A, the steady-state error using the P-control mode is evaluated as

$$e_{ss} = \lim_{s \to 0} \left[s \cdot \left(\frac{A}{s} - \frac{A}{s} \cdot G(s) \right) \right] = A \cdot \frac{1}{1 + K_p \cdot K} \tag{1.8}$$

(Maplesoft 2019, 3)

This illustrates that the steady-state error can be limited by augmenting the gain. Nevertheless, to obtain no steady-state error, the gain will have to rise infinitely. Thus, for a first order system, a P controller cannot be utilized to remove steady state error (Maplesoft 2019, 3).

2.1.2 Second order systems with P Control

For a second order P control, the characteristic equation of the transfer function is given as

$$G_p(s) = \frac{\omega_n^2}{s^2 + 2 \cdot \zeta \cdot \omega_n \cdot s + \omega_n^2} \tag{1.9}$$

(Maplesoft 2019, 4)

where ζ is the damping coefficient and ω_n is the natural frequency. The closed loop transfer function is obtained as

$$G(s) = \frac{K_p \cdot \omega_n^2}{s^2 + 2 \cdot \zeta \cdot \omega_n \cdot s + \left(1 + K_p\right) \cdot \omega_n^2} \tag{1.10}$$

(Maplesoft 2019, 4)

The closed loop natural frequency is described by equation 10 while the closed loop damping ratio is given by equation 11.

$$\omega_{n,closed\ loop} = \omega_n \cdot \sqrt{1 + \mathrm{K_p}} \tag{1.11}$$

$$\zeta_{closed\ loop} = \frac{\zeta}{\sqrt{1 + \mathrm{K_p}}} \tag{1.12}$$

(Maplesoft 2019, 5)

The equations indicate that a rising K_P, the damping coefficient, reduces and the natural frequency rises. This leads to greater and rapid oscillations. By modifying $K_{p,}$ it is possible to alter and change the rising, settling and peak times. The maximum overshoot can also be altered by adjusting the damping ratio (Maplesoft 2019, 5).

Considering a second order system has a step input signal of magnitude A, the steady-state closed loop transfer function error using the P-control mode is evaluated as

$$e_{ss} = \lim_{s \to 0}\left[s \cdot \left(\frac{A}{s} - \frac{A}{s} \cdot G(s)\right)\right] = A \cdot \frac{1}{1 + K_p} \tag{1.13}$$

(Maplesoft 2019, 5)

Unlike the first order P control system, equation 12 indicates that steady state error can be mitigated by an increase in the proportional gain, but this cannot be completely eliminated due to the fact that, the gain will rise to infinity. Practically, this is not achievable. As such, a second order system controlled using the P-mode cannot eradicate steady state error. This type of controller does not also allow the steady state error and maximum overshoot to be reduced at the same time (Maplesoft 2019, 5).

2.2 Integral (I) Control Mode

The integral control mode is utilized to resolve completely the resulting deviations at all operating points. Given that this is not null, the integral controller is used to alter the manipulated variable until it attains its maximum. Mathematically, the integral control mode generates an output signal $u_I(t)$ proportionally linked to the integral of the error signal e(t) (Maplesoft 2019, 6).

$$u_I(t) \cdot \int_0^t e(\tau)\, d\tau \tag{2.1}$$

K_I = integral gain, in the Laplace domain this can be given as

$$U_I(t) = \frac{K_I \cdot E(s)}{s} \tag{2.2}$$

(Maplesoft 2019, 6)

with $K_I = \frac{1}{T_n}$ where T_n is the integral time or reciprocal of the gain K_I

The integral controller helps to control systems when the error reoccurs and last for some time frequently. This is achieved by increasing the control variable over time. This mitigates steady-state error and in some situations removes it completely in a first order process system. The I control mode is more efficient than the P control mode: However, it is not often implemented solely in system control. Utilizing an integral controller for a second order results in a third order system which could turn to generate wobbling undulations (Maplesoft 2019, 7).

2.3 First order systems with I Control

The transfer function of a closed loop integral controller is given by

$$G(s) = \frac{\frac{K_I}{s} \cdot K}{\tau \cdot s + 1 + \frac{K_I}{s} \cdot K} \tag{2.3}$$

(Maplesoft 2019, 7)

The natural frequency is evaluated by equation 16 while the damping ratio is given by equation 17.

$$\omega_n = \sqrt{\frac{K_I \cdot K}{\tau}} \tag{2.4}$$

$$\zeta = \frac{1}{2 \cdot \sqrt{\mathrm{K_I} \cdot K \cdot \tau}} \tag{2.5}$$

(Maplesoft 2019, 8)

Supposing a step-input of magnitude A, then the steady state error is obtained by

$$e_{ss} = \lim_{s \to 0} \left[s \cdot \left(\frac{A}{s} - \frac{A}{s} \cdot G(s) \right) \right] = 0 \tag{2.6}$$

(Maplesoft 2019, 8)

The steady state error equation point that, it is possible to eliminate steady state errors completely using the I control mode thus letting the operator to easily manage the response behaviour: Moreover, given that the response characteristics depend on the gain $K_{I.}$ In practice, this is difficult manipulate the maximum overshot and rise time at the same time. At higher integral time, control action influenced (Samson Group 2019, 35.)

2.4 Derivative (D) Control Mode

The output of the derivative controller produces an output signal designated $u_d(t)$ from the rate of change of the error e. The D-controller generates relatively smaller errors in comparison to the P type and responses are quicker. D control mode also produce greater amplitudes immediately when changes made to the system. Nevertheless, they do not identify steady-state error since no matter how great the error is, the rate of change is null. In principle, they are not often implemented inn stan-alone, but rather in combination with for example the P to make PD controllers.

$$y_d(t) = K_d \cdot \frac{d}{dt} e(t) \tag{2.7}$$

where K_d is the derivative action coefficient defined. The equivalent Laplace domain equation is defined as

$$U_d(s) = s \cdot K_d \cdot E(s) \tag{2.8}$$

(Maplesoft 2019, 9)

The D-controller is implemented in system control to decrease the effect of overshoot. It mitigates the degree of variation of the occurring error to avoid overshoot (Samson group 2019, 10.)

2.5 PID Control Mode

The grouping of the proportional, integral and derivative in parallel produces the PID control (Fig.3). It is often utilized in practice and offer better adjusting control thus obtaining desired y results steady state response faster (Samson group 2019, 42.)

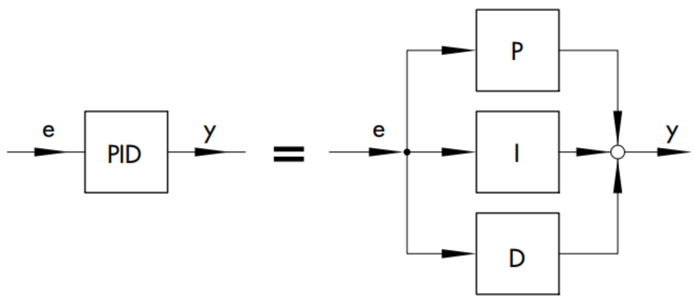

FIGURE 3. Combination of P, I and D to get the PID controller (Adapted from Samson group 2019, 42)

The output generated is pre-tuned by the PI compartment before the D element further rises the control signal in case of any variation in error. The control response is written as

$$y = K_p \cdot e(t) + K_I \cdot \int_0^t (e)\tau \, d\tau + K_d \cdot \frac{d}{dt} e(t) \tag{2.9}$$

(Maplesoft 2019, 10)

from this, the Laplace domain transformation can be obtained as

$$U(s) = \left(K_p + \frac{K_I}{s} + s \cdot K_d\right) \cdot E(s) \tag{2.10}$$

(Maplesoft 2019, 11)

2.5.1 First order systems with PID Control

The first order closed loop transfer function of a PID controller is given as

$$G(s) = \frac{\left(K_p + \frac{K_I}{s} + K_d \cdot s\right) \cdot K}{\tau \cdot s + 1 + \left(K_p + \frac{K_I}{s} + K_d \cdot s\right) \cdot K} \tag{2.11}$$

(Maplesoft 2019, 17)

In case of a system in second order with two-zeros

‘

$$G(s) = \frac{\frac{\left(K_p \cdot s + K_I + K_d \cdot s^2\right) \cdot K}{(\tau + K_d \cdot K)}}{s^2 + \left(\frac{1 + K_p \cdot K}{\tau + K_d \cdot K}\right) \cdot s + \frac{K_I \cdot K}{\tau + K_d \cdot K}} \tag{2.12}$$

(Maplesoft 2019, 18)

2.5.2 Second order systems with PID Control

$$G(s) = \frac{\frac{\left(K_p \cdot s + K_I + K_d \cdot s^2\right) \cdot \omega_n^2}{s(s^2 + 2 \cdot \zeta \cdot \omega_n \cdot s + \omega_n^2)}}{1 + \frac{\left(K_p \cdot s + K_I + K_d \cdot s^2\right) \cdot \omega_n^2}{s(s^2 + 2 \cdot \zeta \cdot \omega_n \cdot s + \omega_n^2)}} \tag{2.13}$$

(Maplesoft 2019, 18)

The closed loop gain for a third order system with two-zeros provides absolute control than the ones previously discussed. The three gains help attain greater response results with minimum effort. The PID controller reaches steady state much faster than the other controllers (Maplesoft 2019, 18). For such as system, the transfer function is given as

$$G(s) = \frac{\left(K_p \cdot s + K_I + K_d \cdot s^2\right) \cdot \omega_n^2}{s^3 + (2 \cdot \zeta \cdot \omega_n + K_d \cdot \omega_n^2) \cdot s^2 + \omega_n^2 \cdot \left(1 + K_p\right) \cdot s + K_I \cdot \omega_n^2} \tag{2.14}$$

(Maplesoft 2019, 18)

Assuming the system has a step input signal of magnitude A, the steady-state closed loop transfer function error using the PID control mode is evaluated as

$$e_{ss} = \lim_{s \to 0} \left[s \cdot \left(\frac{A}{s} - \frac{A}{s} \cdot G(s) \right) \right] = 0 \tag{2.15}$$

(Maplesoft 2019, 18)

3 MODES OF HEAT TRANSFER IN JACKETED-REACTOR

In the jacketed-process heating, steam is generated and supplied to the heat transfer process for heating the process heat transfer surface. Similarly, cold water is readily pumped into the system in the annular space between the jacket and the vessel. There are three modes through which heat can be transferred; conduction, convection and radiation. For the purpose of this experiment, conduction and convection will be described since the reactors in the laboratory use these forms of heat transfer mechanism. The radiation mode will not be discussed. But this is the transfer of heat from one surface to another in the form of electromagnetic waves (Maplesoft 2019, 13.)

3.1 Conduction

Whenever temperature gradient is created by a stationary fluid in a vessel or by solid material separation, this process leads to heat conduction. In other words, heat is transferred from one molecule to another without the displacement molecules from one area to another. The collision of atoms due to heat causes energy to be transferred from higher energy molecules to lesser ones (Spiraxsarco 2019, 5.) As such, heat conduction is produced in the direction of falling temperature. Fourier's Law is used to describe heat transfer phenomenon via conduction in one-dimensional surfaces observing linear temperature distribution in steady-state conditions (Spiraxsarco, 2019.) It is written as:

$$\dot{Q} = kA\frac{\Delta T}{x} \tag{3.1}$$

Where:

$\dot{Q} =$ heat transfer rate per unit of time (W)

k = Thermal conductivity of the material (W/m K or W/m °C)

A = Heat transfer area (m^2)

$\Delta T =$ Temperature difference across the material (K or °C)

x = Material thickness (m)

It can be observed from this equation that the amount of heat (thermal conductivity) depends on the separating wall material properties.

3.2 Convection

In contrast, convection is the displacement of heat energy between a solid material and a moving fluid at different temperatures. An example is the process through which heat is transferred using hot water. The transfer of heat energy due to phase change in the process of boiling water for condensing steam is also described as heat convection (Spiraxsarco 2019, 5.) However, the process of heat transfer via steam does not involve temperature change but rather latent heat to the product as it condenses on the surface of the solid material without the change in temperature. Newton's Law of cooling is utilized to derive the heat convection equation, this is written as:

$$\dot{Q} = h\, A\, \Delta T \tag{3.2}$$

Where

h = Convective heat transfer coefficient of the process (W/m^2 °C)

The thermal conductivity of frequently used wall materials is listed in table 1. The table also illustrates how the thermal conductivity slightly varies as temperature changes.

TABLE 1.Thermal conductivity of common metals (Adapted from www.spiraxsarco.com)

Material	Thermal Conductivity (Wm) °C		
	25 °C	125 °C	225 °C
Iron	80	68	60
Low carbon steel	54	51	47
Stainless steel	16	17,5	19
Tungsten	180	160	150
Platinum	70	71	72
Aluminium	250	255	250
Gold	310	312	310
Silver	420	418	415
Copper	401	400	398

4 NON-FLOW STIRRED JACKETED-REACTOR DESIGN

Process tanks are generally used in the chemical process industries (CPI) to execute chemical processes and storage (Fig.8). Several features and characteristics are required to evaluate the performance of a reactor. These include; the tank geometry which universally are vessels enclosed vertically by standing cylindrical tanks with diameter ratios of 1:1. The type of baffles used for composition agitation. The baffle and agitation speeds are influenced greatly by the performance of stirred-tank reactors. They are often spiral and are welded internally on the walls of the vessel. This facilitates the fluid component maximum contact with the vessel at higher velocities (Garvin John 1999, 62.) Conventionally, detachable type baffles are implemented to improve the performance of the stirred-tank reactor (Kiran Golwalkar 2015, 65). The kind of material of construction (MOC) used for the design and finishing also plays an important role in the stirred tank reactor overall performance. The design consist of tested and approved stainless steels with suitable temperature, anti-corrosive and tensile strength such as; Carbon steel: A-179 and ASTM A 560, chromium–nickel stainless steel, super duplex steel as well as non-ferrous alloys of nickel, copper, aluminium and titanium (Kiran Golwalkar 2015, 80).

In addition, the reactor vessel piping systems include an inlet and outlet streams as well as a nozzle for feed injection and control. The reactor tank controls, and instrumentation devices include level measurement devices, pressure and temperature measurement and control, weighing devices, pH measurement devices, heating / cooling controls and safety devices comprising bursting disks as alarm indicators as well as the heating and cooling system outside the vessel. Generally, cold water for utilized for cooling and hot water or steam for heating are used in process plants. Other factors to be considered are the quantity of heat displacement inside the jacket expressed by the overall heat transfer coefficient and the temperature vs time graph representing different rates of heat transfer in the vessel (Spiraxsarco, 2019).

Figure 4 illustrates the various components of a non-flow jacked-stirred batch reactor.

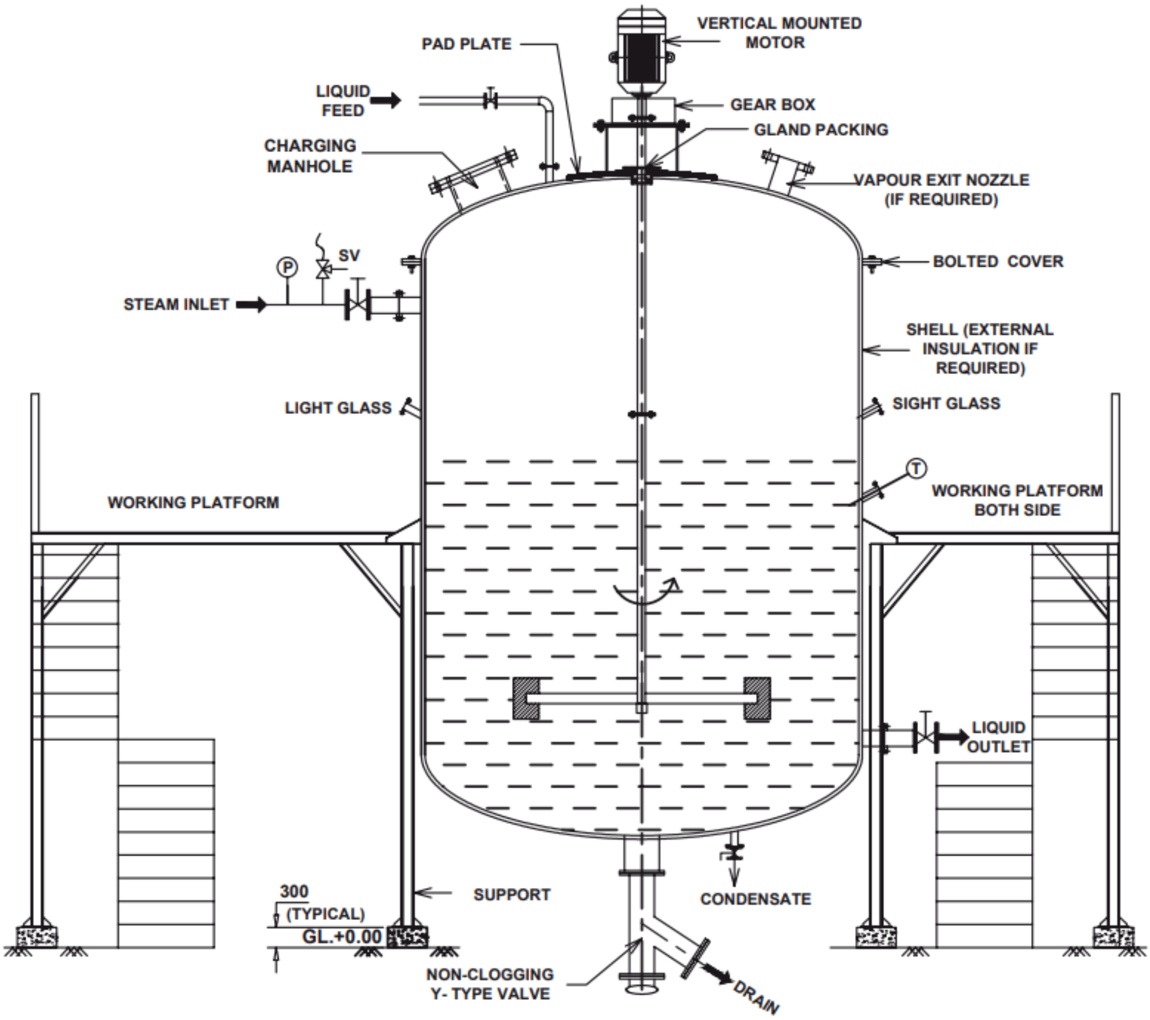

FIGURE 4. Insulated non flow Jacket-stirred reactor with agitator including a steam inlet and condensate outlet (Adapted from Golwalkar 2015, 66)

5 MEASUREMENT OF STEAM CONSUMPTION & RATE OF ENERGY

The amount of steam consumed in a non-flow heating process can be evaluated by collecting the condensate in a container over a period of time (Fig. 9). The results obtained via this method are more reliable since it takes flash steam losses into consideration in comparison to estimation by mathematical computation. In order to do this, the volume (v) of the heating/cooling condensate (water) flowing out of the process is first collected over a period of time (t). Next, by dividing the volume of water used by the time, the mean amount of steam consumption or flow rate can be obtained (Spiraxsarco, 2019). The results from the experiment are presented in table 2.

$$\text{Volumetric flow rate } \dot{V} = \frac{\text{Volume}}{\text{time}}\,(l/s) \tag{3.5}$$

TABLE 2.Flowrate evaluation of condensate (water)

Flow	Volume (mL)	On Stabilization	
		Time (s)	Flowrate (mL/s)
Heating Phase	570	280	2,0
Cooling Phase	500	50	10,0

The density of water $\rho_{\text{water}} = 997\text{kg/m}^3$

The quantity of energy needed to raise the temperature of a subtance can be evaluated as

$$Q = m\, c_p\, \Delta T \tag{3.8}$$

Where

Q = Quantity of heat (kJ)

m_s = Mass of steam (kg)

c_p = Specific heat capacity of the substance (Kj/kg °C)

ΔT = Temperature rise of the substance.

The energy $\dot{Q}$ (kW))required to heat water of mass m(kg) from temperature T_1 to T_2 (°C) over some time t (seconds) is obtained by

$$\dot{Q}_{water} = \frac{m \cdot c_p \cdot \Delta T}{t} \tag{3.9}$$

The quantity of energy provided by the condensing of steam can be determined by

$$Q = m_s \cdot h_{fg} \tag{3.10}$$

Where:

Q = Quantity of heat (kJ)

m_s = Mass of steam (kg)

h_{fg} = Specific enthalpy of evapoaration of steam (kJ/kg)

The expression indicates that steam consumption can be evalauted from heat transfer rate and vice-versa, from

$$\dot{Q} = \dot{m}_s \cdot h_{fg} \tag{3.11}$$

Where:

$\dot{Q}$ = Mean heat transfer rate (kW or kJ/s)

$\dot{m}_s$ = Mean steam consumption (kg/s)

Considering that heat transfer is 100% efficient for example, the energy losses are assumed negligible. This implies, the heat supplied by the steam must be equal to heat needed to increase the fluid temperature to the required level. The energy balance can thus be written as

$$Energy_{primary\ side} = \dot{Q} = Energy_{secondary\ side}$$

$$\dot{m}_s \cdot h_{fg} = \dot{Q} = \frac{m \cdot c_p \cdot \Delta T}{t} \tag{3.12}$$

(Spiraxsarco, 2019)

Where:

m = Mass of secondary side fluid (kg)

c_p = specific heat capacity of the secondary fluid (kJ/kg °C)

ΔT = Temperature rise of the secondary fluid (°C)

t = Time for the heating process (seconds)

The vessel(reactor) was filled with 68 liters of water (approx. 68kg). The approximately 82,2% filled up, with the temperature gradually increased from 38 °C to 89 °C using 5,5 bar supplied steam. The time taken being 29 minutes (1740 seconds). Water has a specific heat capacity of 4,19 kJ/kg °C within this temperature range ((Spiraxsarco, 2019). And the tank was considered to be properly insulated with negligible heat losses. The mean steam consumption is evaluated as

The mean heat transfer rate required in kJ/s is

$$\dot{Q} = \frac{m \cdot c_p \cdot \Delta T}{t}$$

$$\dot{Q} = \frac{68kg \cdot 4{,}19\frac{kJ}{kg}°C \cdot (89-38)°C}{1740} = 8{,}35 \text{ kJ/s}$$

From enthalpy table in appendix , the specific enthalpy of evaporation $h_{fg \text{ of steam}}$ at 5,5 bar is $2075{,}70\,\frac{kJ}{kg}$

From $\dot{m}_s \cdot h_{fg} = \dot{Q}$ => $\dot{m}_s = \frac{\dot{Q}}{h_{fg}}$

Therefore; $\dot{m}_s = \frac{8{,}35\frac{kJ}{s}}{2075{,}70\frac{kJ}{kg}} = 0{,}004\,\frac{kg}{s}$

6 GRAPHICAL FIT PROCESS MODELING

System identification show that, the process is a second order system. In other words, the process consists of two capacitances. The essence of modelling and simulating process systems is to enable the system operator to be able to predict the performance and comprehend the characteristics and behaviour of a process plant. The fundamental essence of this approach is to establish the link between the process plant physical parameters and the transient response. Upon determination by graphically approximating the step response using response data. In order to achieve this, a step input of 1 is assumed for example at the instance when the system inputs change from zero to one in a very short time in order to determine the unknown dynamic parameters of the step response necessary for system identification (Marlin E. 2000, 179).

These parameters are; K = Process gain
ζ = Damping factor
τ_s = Time constant
ω_n = Natural frequency

To is achieved these, the following steps were adopted; first, an approximative step response graph of change in the reactor temperature as a function of time is drawn using experimental data. Secondly, the output and input are determined from the step response curve respectively. Thirdly, from this, the process gains *K* is calculated by dividing the output over the input. Next, the damping factor is computed from the overshoot determined from the step-response graph or via the decay ratio. And finally, the time constant is evaluated from the rise time (tr) and peak time (tp) as well as the natural frequency and the natural period Tn. With the unknown parameters, a control system is established with the P, I and D control modes by computer-generated models from mathematical equations and system transfer functions. The model of the jacketed batch reactors used for heating/cooling of water is developed based on all the information gathered in practice on the plant in the processing laboratory. This is utilized to understand and predict the system behaviour when it is subjected to a step step-input response. In other words, what amount of input will generate the required value or amount of heat necessary to increase or decrease the temperature of water in the vessel to the desired level (set-point) within the time frame? Figure 5 shows the three main stages used to develop the physical pilot plant to developing a mathematical model, executing the simulation and interpreting the results.

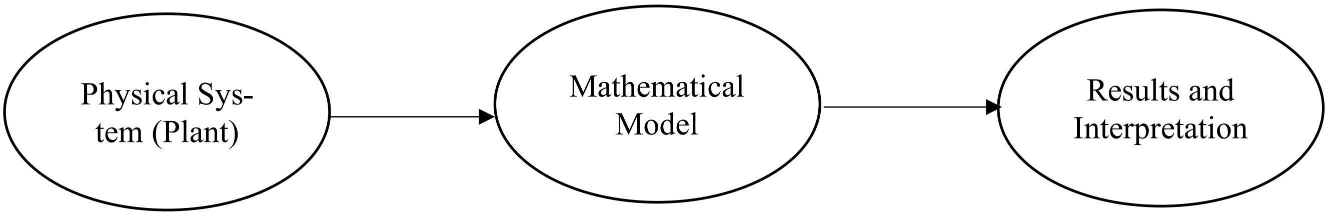

FIGURE 5. Modelling and Simulation Phases (Marlin 2000, 178)

The flowchart in figure 6 below depicts the steps used in establishing the empirical model design. The process consists of making adjustments to the system under normal operating conditions. The proper data is carefully gathered, and the results verified from original model. Based on the dynamic response deducted, a fitting model developed. Attention and close monitoring were also paid during plant operation in order to reduce disturbances during the experiment phase. The process approximation curve consists of the following four steps: First, the process is left to attain steady state. Secondly, it is subjected to a single step input variable. Third, data is gathered from the input and output until the system attains to a new steady state. Lastly, the graphical fitting calculation is performed (Marlin 2000, 179).

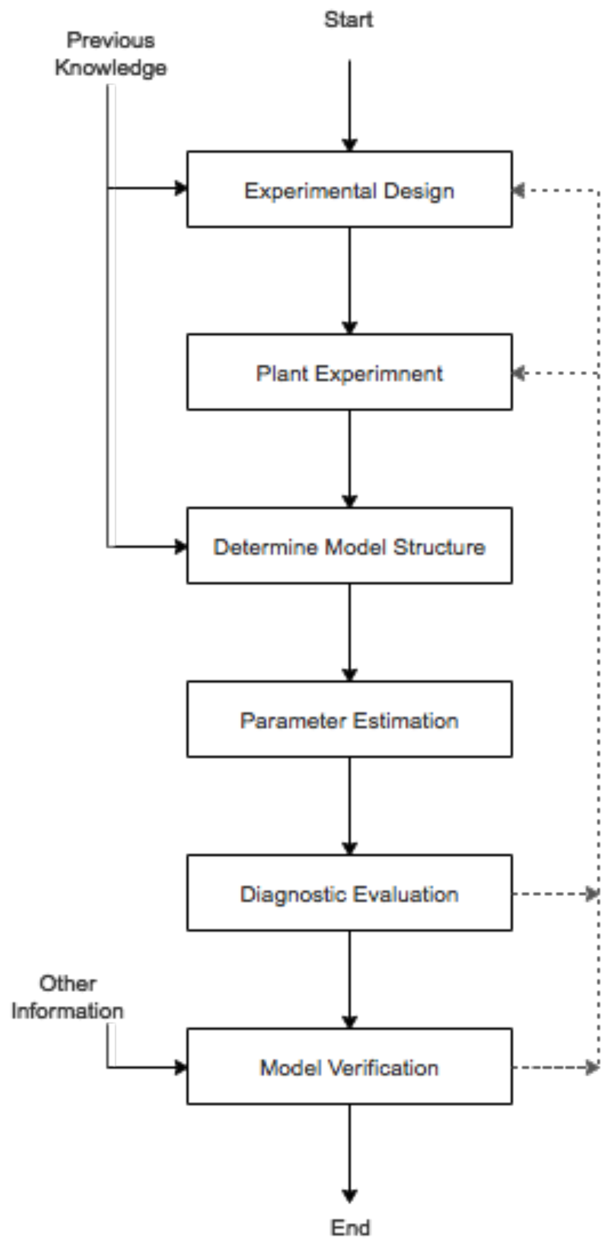

FIGURE 6. Steps for obtaining the transfer function model (Adapted from Marlin. 2000, 176)

6.1 Conservation Principle

The dynamics of the theoritical process system are described on the basis of the general conservation principle. This is written as

$$[Accumulation] = [Input\,] - [Output] + [Internal\, production]$$

or in other words as

$$[Rate\ of\ accumulation\ of\ x]$$
$$= [Rate\ of\ input\ x] - [Rate\ of\ output\ of\ x] + [Rate\ of\ production\ x]$$

The variable x is a corserved element within the limits of the system. From this mathematical modelling equation, the mass/energy balance equation can be expressed in terms of the total mass/energy balance or the system or as individual components of the sytems. The balance expression determined from the total mass balance is referred to as the overall mass balance or total mass balance. The mass balance from individual components is known as partial or component mass balance. When the system is supplied with steam/cooling water within the reactor while the processs of heat transfer occurs, heat energy is lost due to the MOC insulation in the operating environment (Amiya. 2011, 17).

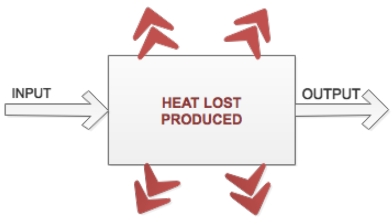

FIGURE 7. An illustration of the general heat balance principle for a system.

6.2 Approximation of Heat Losses

Throughout the process of heating or cooling of water using steam and cold water, heat energy is lost and escapes to the environment as illustrated in figure 7 expressed as

$$\dot{Q} = kA\frac{\Delta T}{x} = UA \cdot \Delta T \qquad (6.1)$$

Where:

$\dot{Q}$ = Heat escaped to the environment per unit of time (W)
k = Thermal conductivity of the material (W/m °C)
A= Heat transfer area
ΔT = Temperature difference across the material °C
x = Material thickness
U = Overall Heat Transfer Coefficient

The aforemention method is straightforward in computing the overall heat transfer coefficient U. Since the material used in conbtructing is unspecified, the thermal conductivity k is unknown as well.

$$\dot{Q} = U \cdot A \cdot (T_{in} - T_{out}) \qquad (6.2)$$

Where

U = The overall heat transfer coefficient
A = Heat transfer area of vessel
T_{in} = The temperature water in the vessel at any point in time
T_{out} = Outside temperature (room temperature)

The mean heat coefficient $\dot{Q}$ is calculated in equation (3.12), using the heat lost $\dot{Q}$ and assuming ideal heat transfer inside the reactor between the jacket and inner tank. The quantity of heat contained by the fluid (water) per unit of time is given as

$$\frac{dQ}{dt} = \rho \cdot C_p \cdot V \cdot \frac{dT}{dt} \qquad (6.3)$$

By making U the subject of the formula in equation 6.2 the following equation is obtained:

$$U = \frac{\dot{Q}}{A \cdot (T_{in} - T_{out})} \qquad (6.4)$$

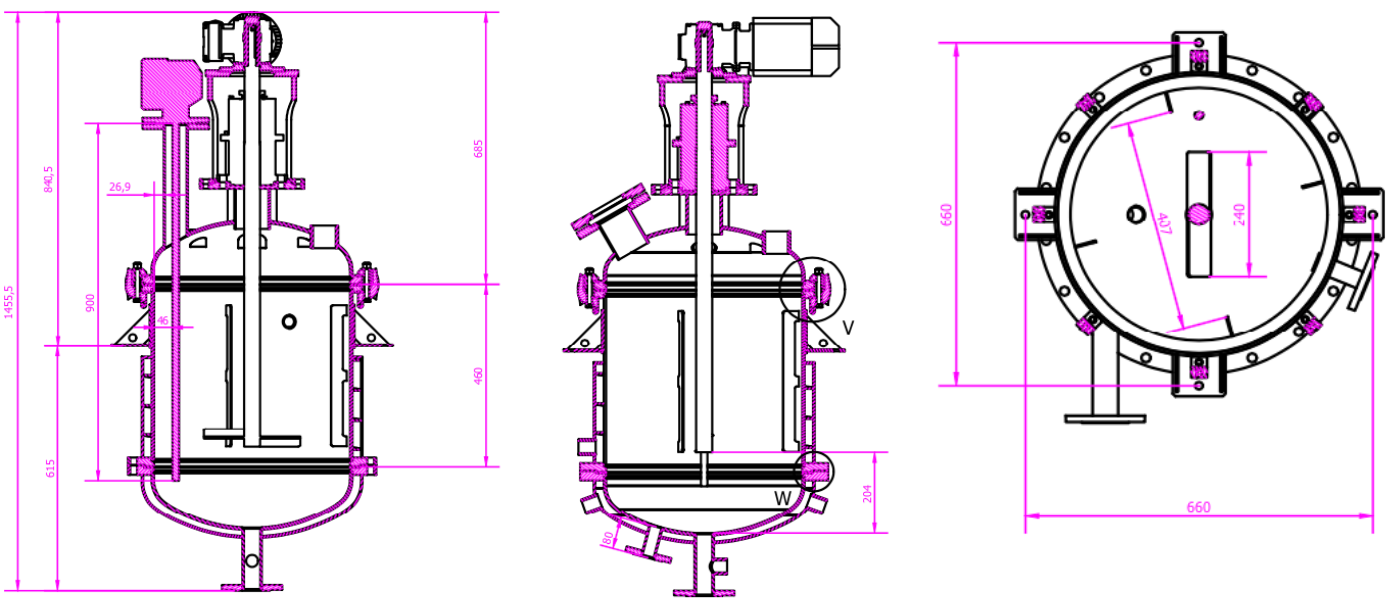

FIGURE 8. Illustration of the reactor cross-sections with dimensions in mm.(Puskala. 2007, 1)

Figure 8 shows the difference of cross-sectional areas of the reactor casing and internal structure. The area and volume of the tank is calculated as

A = Surface Area (half-sphere): $A = 2\pi r^2$ (6.5)

V =Volume (half-sphere) V = $\frac{2}{3}\ \pi r^3$ (6.6)

V = Volume (Cylinder) $V = \pi r^2 h$ (6.7)

A = Surface Area (Cylinder): $A = 2\pi r(r + h)$ (6.8)

A = Surface Area (half-sphere): $\mathrm{A} = 2 \cdot \pi \cdot 0{,}2035^2 = 0{,}26\mathrm{m}^2 = 2 \cdot 0{,}26\mathrm{m}^2 = 0{,}52\mathrm{m}^2$

V = Volume (half-sphere) V = $\frac{2}{3}\ \pi \cdot 0{,}2035^3 = 0{,}018\mathrm{m}^3 = 2 \cdot 0{,}018\mathrm{m}^3 = 0{,}036\mathrm{m}^3$

V = Volume (Cylinder) $\mathrm{V} = \pi \cdot 0{,}2035^2 \cdot 0{,}46 = 0{,}06\mathrm{m}^3$

A = Surface Area (Cylinder): $\mathrm{A} = 2 \cdot \pi \cdot 0{,}2035(0{,}2035 + 0{,}46) = 0{,}85\ \mathrm{m}^2$

From which the total surface area and volume of the rector tank is

$A = 0{,}52\mathrm{m}^2 + 0{,}85\ \mathrm{m}^2 = 1{,}37\ \mathrm{m}^2$

$\mathrm{V} = 0{,}036\mathrm{m}^3 + 0{,}06\mathrm{m}^3 = 0{,}096\mathrm{m}^3$

Substituting the value of the area determined including respective temperatures in equation 6.4 yields

$$U = \frac{8{,}35\,\frac{kJ}{s}}{1{,}37\ \mathrm{m}^2 \cdot (89 - 25)°\mathrm{C}}$$

Hence, $U = 0{,}092\ (\mathrm{W/m^2\ °C})$

6.3 Closed Loop Feedback System and Process variables

A mathematical model is used to describe the system with defined set of variables. The plant is supplied with steam/cold water at a certain pressure and temperature. It is assumed that the wetness of the steam is minimal. That is, it is dry enough with very little amount of water and thus negligible. The system variables consist of the state variables (input); pressure and temperature while the output variable is temperature. The closed loop feedback control is modelled to control these variables to obtained optimum performance.

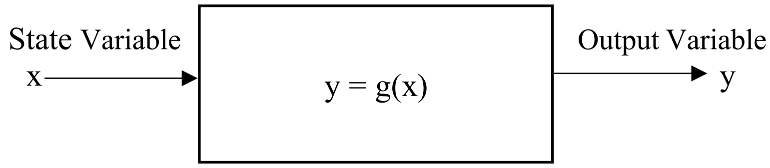

FIGURE 9. Illustration of system state- output variables

A close loop control system illustrating various elements used is given in figure 10. The signal at the process variable point is the same as the feedback signal.

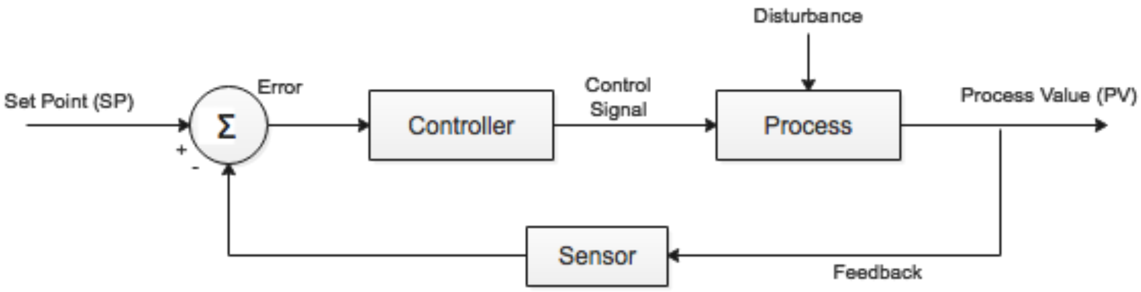

FIGURE 10. Closed-loop system block diagram with feedback control

6.4 Experiment Results & Plant Approximation

For a first/second order system, the fit parameters are determined by correlation using the step response curve (Fig. 11). The steady state analysis of the graph can help to find the overshoot, the decay ratio and the period. From this, the time constant and the damping factor can be determined mathematically. In order to determine the time constant τ, the jacketed reactor, the system is considered as two first order systems operating together. Both the jacket temperature (steam) and the inner vessel temperature (water) are taken as one capacitance process. The time constant for heating is the time it takes a first order system to reach 63,2 % of full raised value. On the other hand, the time constant for cooling is the time it takes the first order system decreased 36,8% of its final value. The temperature time variation graph for heating and cooling upon stabilization of the plant is given in figure 12. It shows that initially for heating, on powering the plant with steam the vessel temperature was adjusted and stabilized around 38°C by letting the steam flow valve at approximately 10% open. Then, a step change was made by opening the steam valve to 100% allowing an increase in steam flow. As a result, the temperature of the system gradually raised to approximately 89 °C when at steady state. Since water becomes vapor at temperature above 100°C, steam flowing to the system was cut off at this point and the system was allowed to gradually stabilize around 86°C. For cooling, another step change was made with cold water by opening the cold-water valve fully at 100%. This supplied the jacket with cooling water which caused the vessel temperature to gradually decrease until somewhere around 34 °C. While this was achieved, the water in the vessel was constantly stirred with the agitator at 900rpm corresponding to 60% of motor output performance.

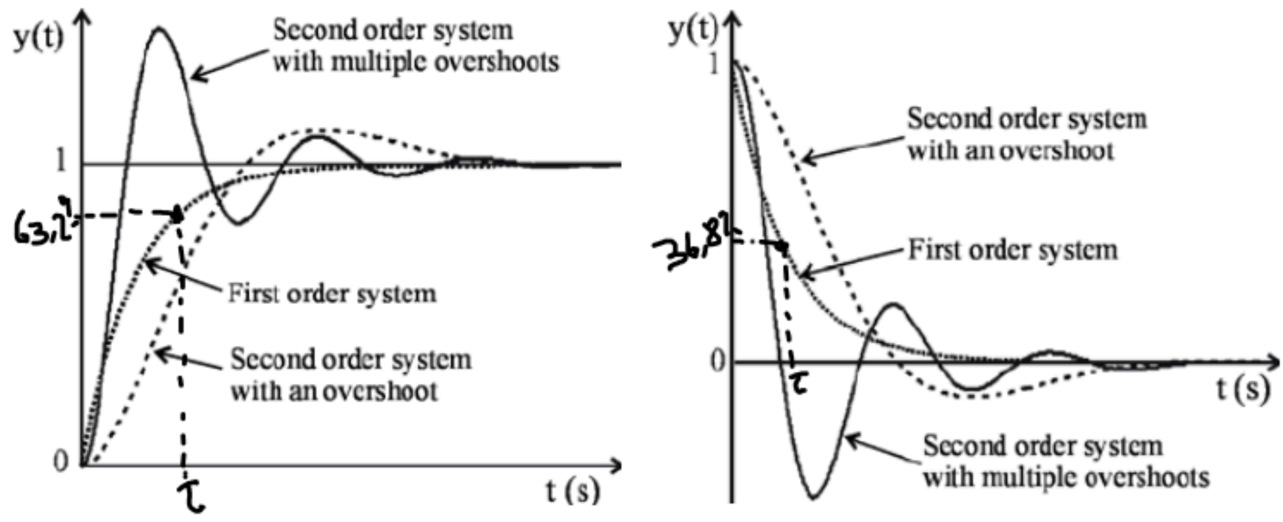

FIGURE 11 Illustration of step-responses of the rising and falling outputs of first and second order systems (İsmail H. Atlas & A.M. Sharaf 2007).

The time constants for the rising curve (heating phase) and falling curve (cooling) is estimated from the experiment graph as illustrated on the corresponding graph (figure 12) below.

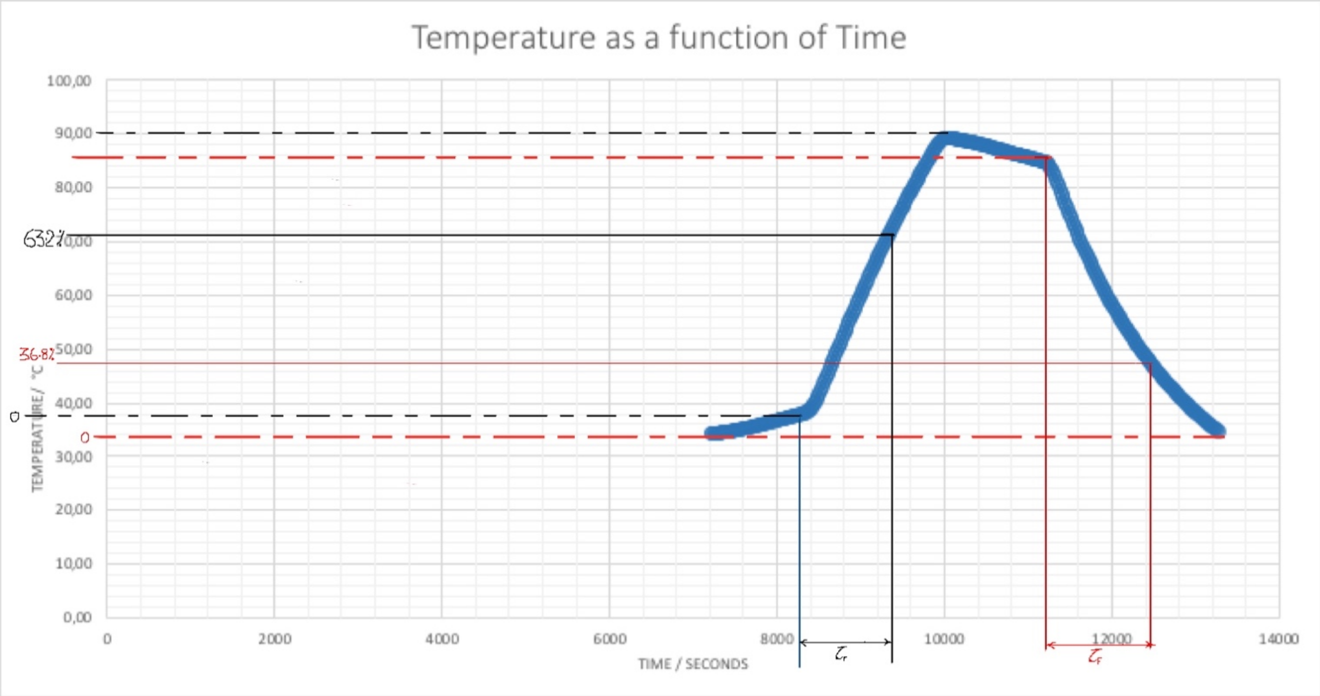

FIGURE 12. Illustration of rising and falling time constants for heating and cooling from experiment curve

Graphically, the time constant for heating (τ_r) and the time constant for cooling (τ_f) were deducted to be approximately; $\tau_r = 1100$ seconds and $\tau_f = 1100$ seconds.

These values were further verified precisely using the equation that describes the experimetal results based on exponential rise of the temperature.

$$Temp = T_{initial} + \Delta T(1 - e^{-t/t}) \qquad (3.13)$$

Where t = time taken to reach final value.

The closest match for the rising time constant is thus,

$$89 = 38 + 51(1 - e^{-1800/t_r})$$

$$\tau_r = 50 \text{ seconds}$$

The time constant is the time taken to observe the first output changes due to a step change at the input. The value of t_r = 50 seconds clearly indicates longer time to observe the initial change in the output response immediately after the step-input is induced graphically. On the other hand, the closest approximation value for the falling or cooling time constant is

$$34 = 86 - 52(1 - e^{-2200/t_f})$$

τ_f = 1 seconds

7 CONTROLLER DESIGN AND SIMULATION OF THE SYSTEM

The steps indicated on the chart in figure 13 were adopted in the process of determining the optimized parameters of the plant. The PID controller is selected to control the proposed plant, as previously discussed in earlier chapters, the PID controllers are more convenient for controlling such plants. In the simulation, the controllers are implemented in a continuous-time domain.

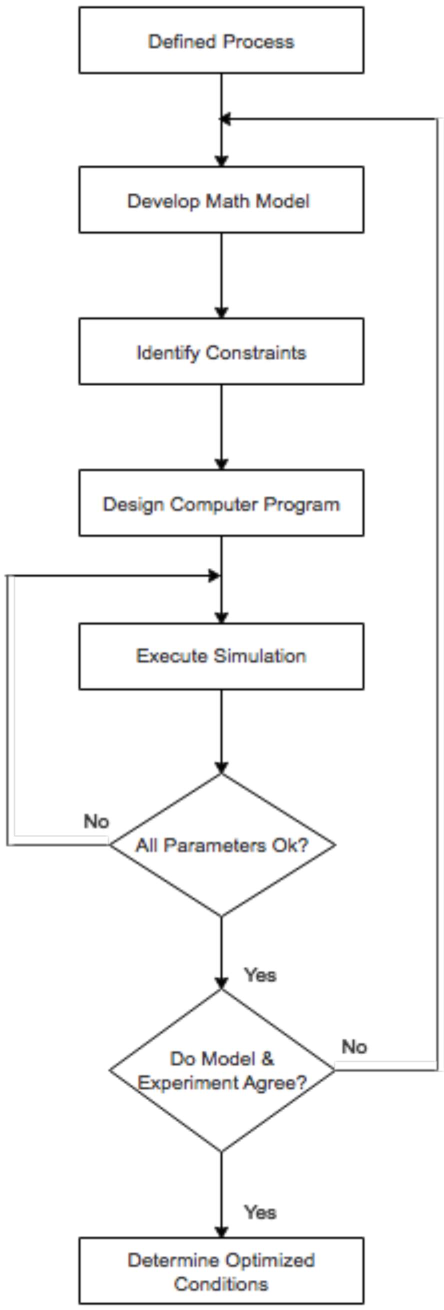

FIGURE 13. Flow chart of steps used to simulate and determine the optimized conditions.

The general parameters of a second order system and the system transfer function is written as

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K}{s^2 + 2\zeta s + 1} \quad (3.14)$$

The system is said to be underdamped in case. $0 \leq \zeta < 1$, critically damped if $\zeta = 1$ and overdamped if $\zeta > 1$. When $\zeta < 0$ the system is unstable. Assuming the same has a natural frequency $\omega_n = 1$, and a damping coefficient $\zeta = 1$

The gain K for the heating and cooling phases is computed as

$$K = \frac{y(t)}{u(t)} = \frac{Output\ Response}{Step\ Response}$$

For heating, $K_h = \frac{89{,}01}{100} = 0{,}89$

For cooling, $K_c = \frac{34}{100} = 0{,}34$

TABLE 3.Process Dynamic Parameters

Parameters	Heating	Cooling
K	0,89	0,34
ζ	1	1
τ_s	50	1
ω_n	1	1

A summary of the deduced process dynamic parameters is presented in table 2.

7.1 PID Controller Tuning

Manual tuning of the PID controller consist of setting K_I and K_d values to zero. Then, increasing proportional gain (*Kp*) until system exhibits oscillations. Next, K_I *is* fine-tuned to limit oscillations are eliminated and finally D is varied to achieve faster response. However, with the aid of computer simulation software MATLAB Simulink, the PID controller was auto tuned to reduce overshoot and determine the appropriate controller parameters.

The block diagram from SIMULINK, tuned parameters and response of the heating process is represented in figures below.

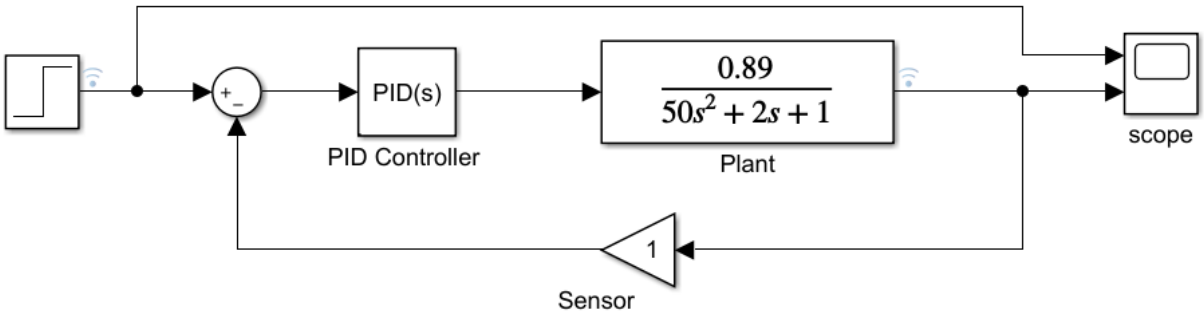

FIGURE 14. Heating Block Diagram

Figure 15 illustrate the settings of proportional, integral and derivative determined automatically by Matlab Simulink is shown on the screenshot.

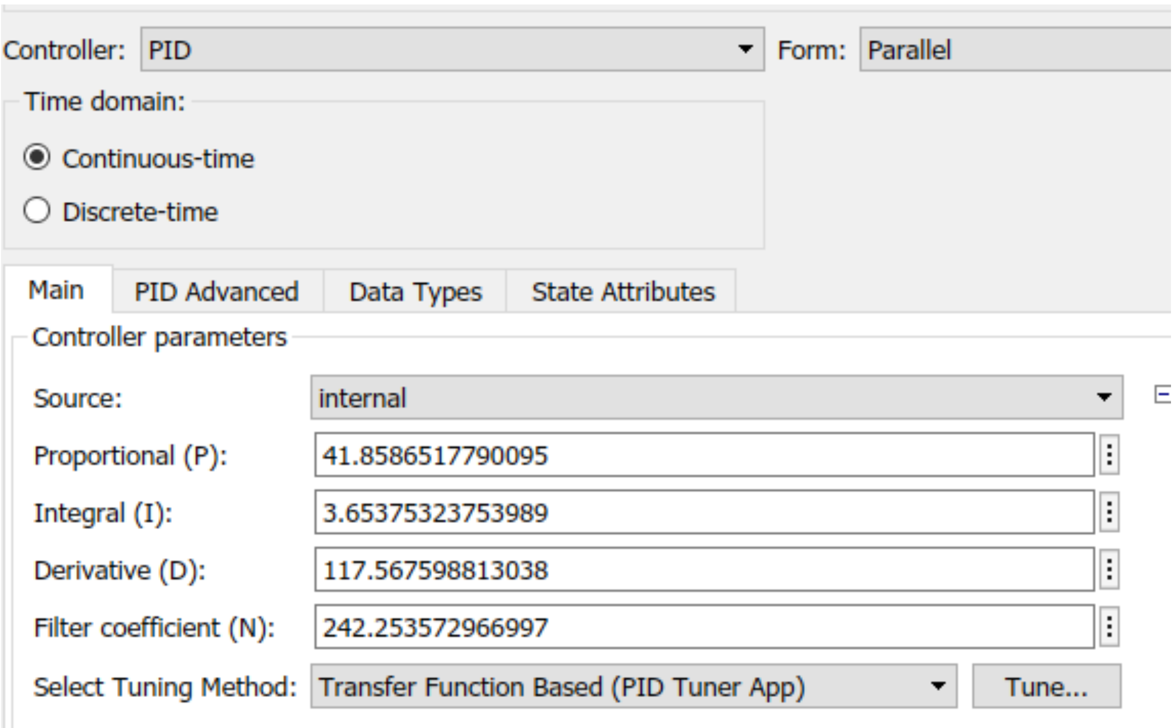

FIGURE 15. Heating PID Controller -Tuned Parameters

As predicted, the derivative element placed at the end of the controller had a higher value. Overtime, the rate of change of the error of the final value at the output is continuously mitigated. The response curve (figure 16) indicates the time taken to reach steady state was approximately 28 seconds with an overshoot of about 18% at the beginning.

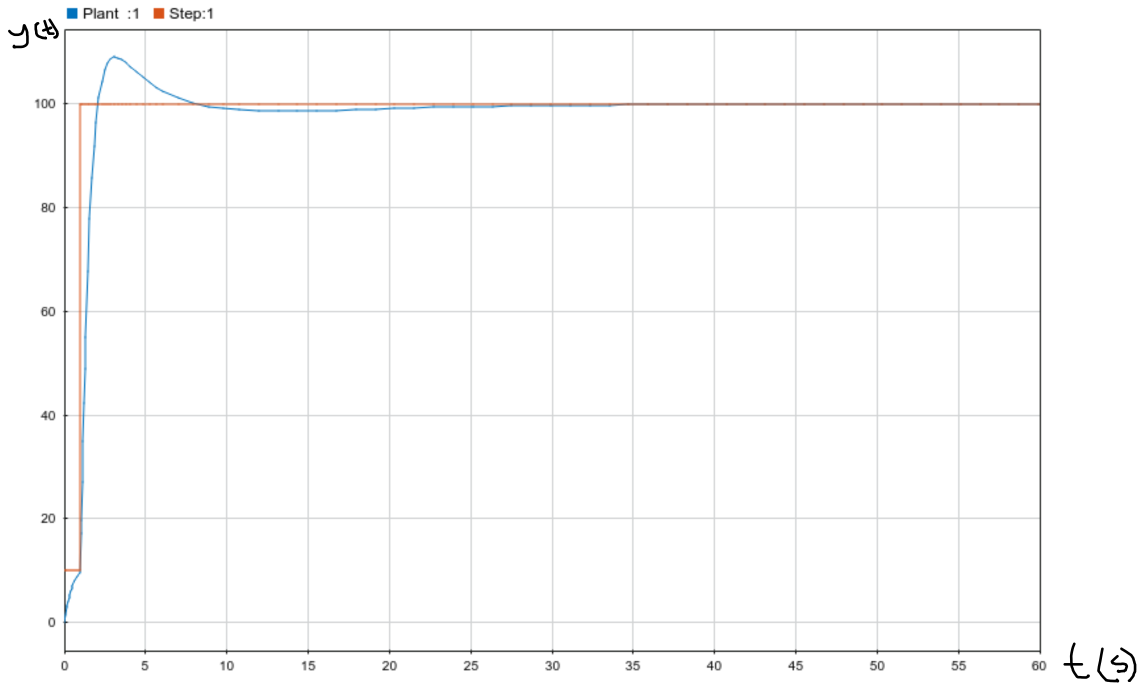

FIGURE 16. Heating Simulation Response from Matlab Simulink

The response curve shown in figure 17 illustrates the results after simulation obtained from heating process in the pilot plant test. Th x-axis represent the time in seconds.

The block diagram and tuned parameters and response of the cooling process is represented in figures below.

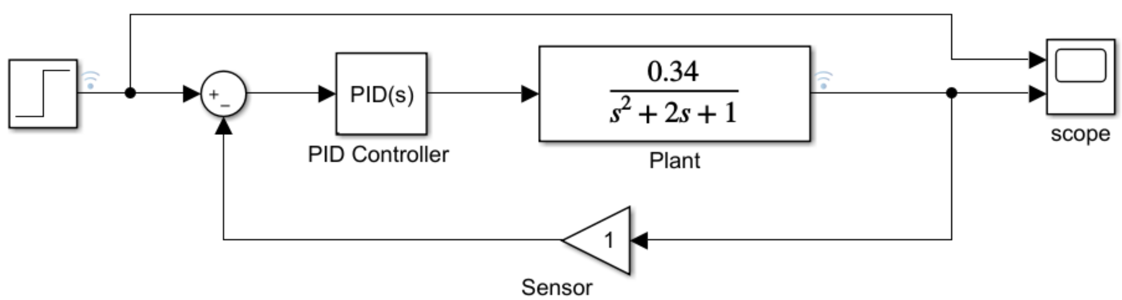

FIGURE 17. Cooling Block Diagram from Matlab Simulink

Figure 18 illustrate the settings of proportional, integral and derivative determined automatically by Matlab Simulink for cooling.

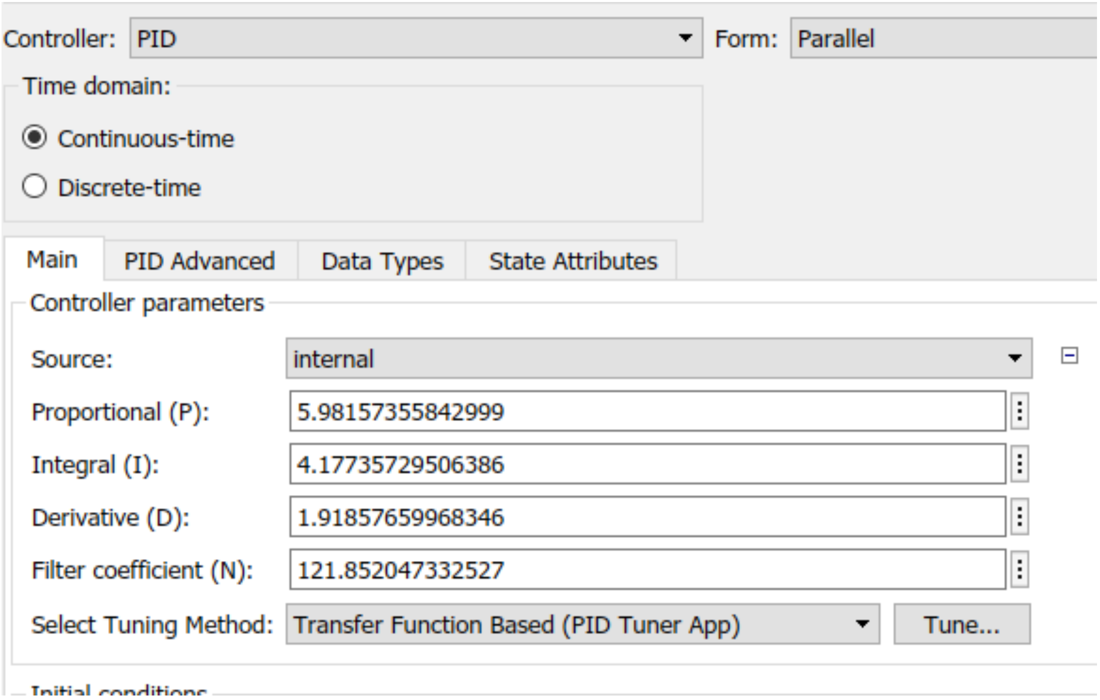

FIGURE 18. Cooling PID Controller -Tuned Parameters from Matlab Simulink

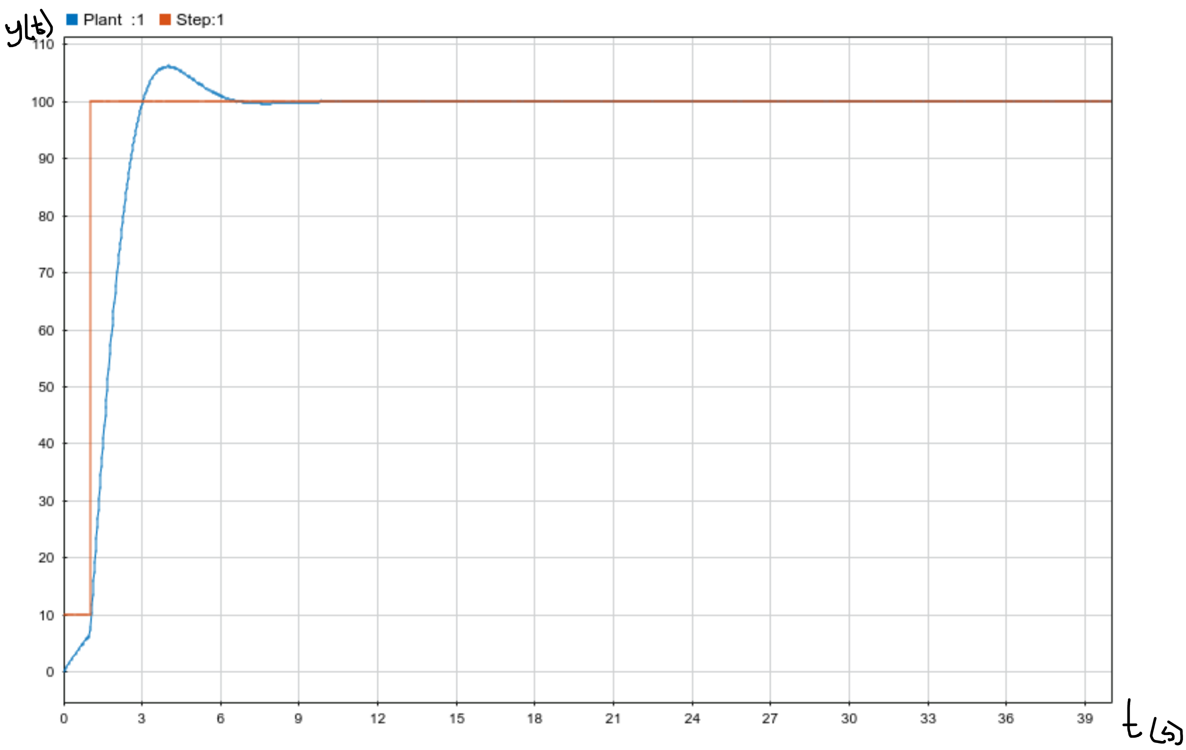

FIGURE 19. Matlab Simulink Cooling Simulation Response from Matlab Simulink

On the contrary, the derivative element placed at the end of the controller for cooling had a smaller value. Overtime, the rate of change of the error of the final value at the output resulted in reduced errors as the temperature was decreasing. The response curve (figure 18) indicates the time taken to reach steady state was approximately 9 seconds with an overshoot of about 7% at the beginning.

The step response obtained after running the simulation and tuning the PID controller for best performance is given in figure 20. The x-axis represents the time in seconds. With the step responses of equivalent transfer functions of both the heating and cooling phases, the tuned system settling to its final value has zero or minimal oscillations after step-input. The dead time is almost inexistence and inconsiderable from observation as shown in figure 16 and figure 19.

7.2 PI Controller Tuning

The PI controller is similar to the PID the differential element zeroed. The model was simulated and tuned with the PI controller configured in parallel and using the PID tuner in Matlab Simulink. This was auto tuned to best performance. The response curve for the heating and cooling of the vessel composition are presented in figure 22 and figure 25 respectively.

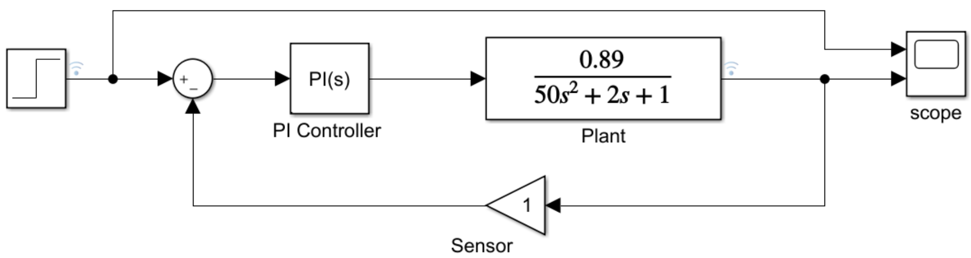

FIGURE 20. Matlab Simulink Heating Block Diagram PI controller

The parameters for heating process obtained from the PI simulation are shown on the screenshot in figure 21. The is no derivative controller and the auto tuned value determined by Simulink for the proportional controller is zero. Similarly, the value determined for the integral is 0.004498 which is approximately null.

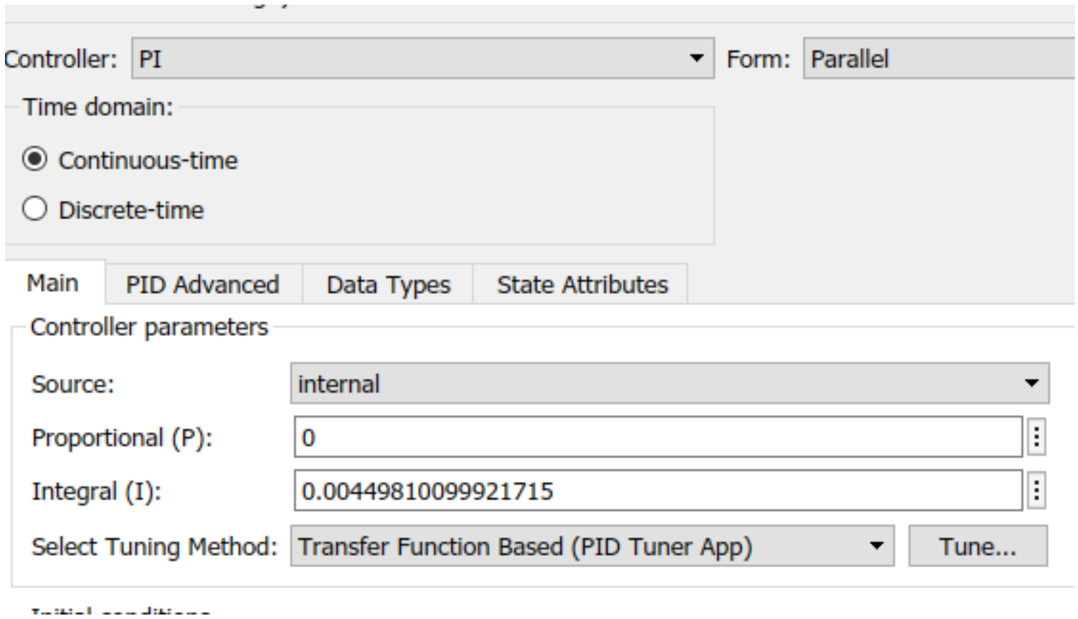

FIGURE 21. Matlab Simulink Heating Tuned PI controller tuned parameters obtained for optimum performance

Figure 22 shows the response curve of the PI controller optimized for efficient heating. The graph rises steadily but takes longer time (about 1300seconds) to reach steady state.

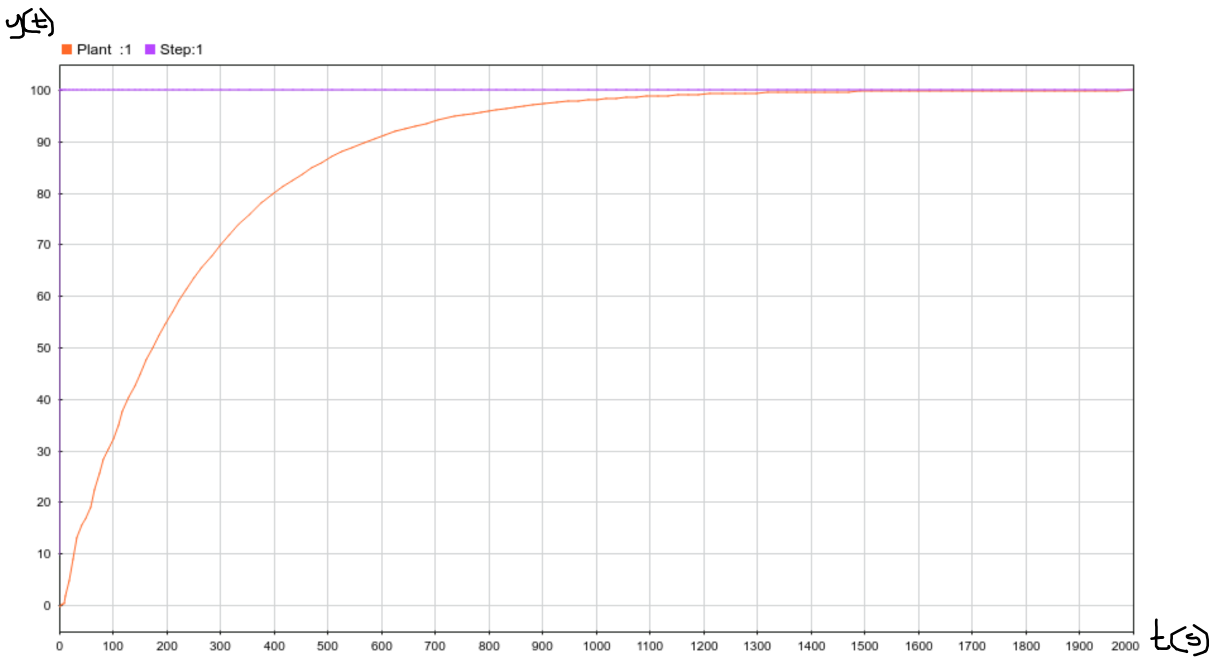

FIGURE 22. The Matlab Simulink Response curve for the heating process using the PI controller mode

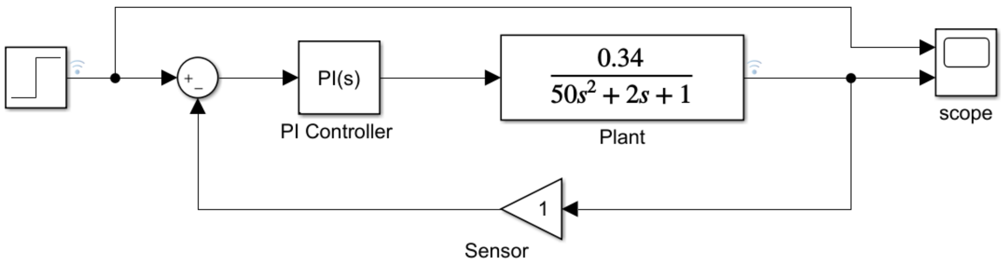

FIGURE 23. Matlab Simulink Cooling Block Diagram PI controller

Similarly, figure 24 which indicates the optimized parameters for the cooling process are almost the same as for heating. The P parameter is set to zero and the I parameter set to 0.00469.

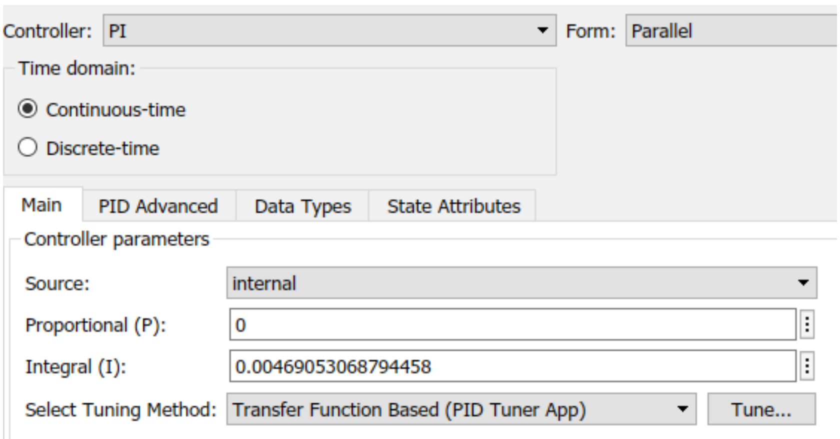

FIGURE 24.Matlab Simulink Cooling Tuned PI controller tuned parameters obtained for optimum performance

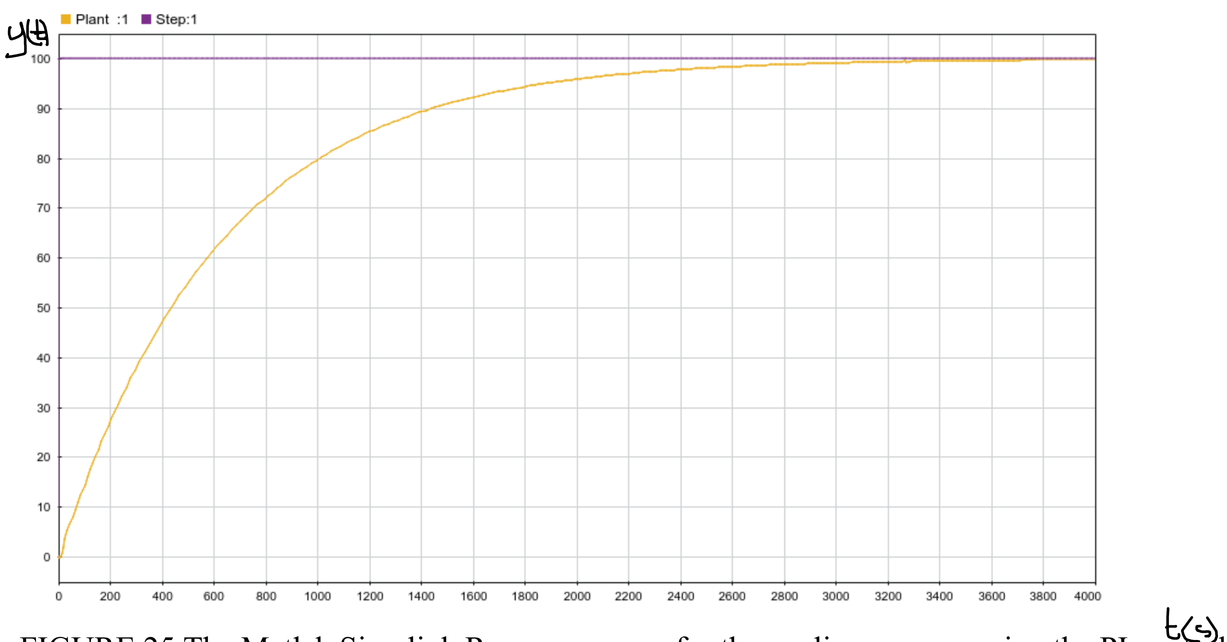

FIGURE 25.The Matlab Simulink Response curve for the cooling process using the PI controller mode

The response curve for cooling is illustrated on figure 25. The graph rises steadily and takes approximately 3200 seconds before attaining steady state.

8 CONCLUSION

An experimental approximation of parameters in a second order system was studied. It showed that it is possible to determine approximate parameters based on experiment result curve from real system which does not always give the full picture of the dynamics of the process from data. The step response curves from simulation were auto tuned to attain stability in minimal time. However, from the response time obtained using the PID and PI control mode, the graph confirmed that the PID has better response time that the PI controller. This can be observed from both response curves. By adjusting controls automatically, the desired y results reach steady state response faster with the PID than the PID. For example, comparing the cooling process step response curve in figure 25 and figure 19. The experiment demonstrated that, cooling using the PI control mode will take close to 4000s (33minutes). The process in 7s after step change reached steady state.

Nevertheless, tuning the PI controller was easier than the PID since the differential D element was suppressed and the proportional element P set to zero. In addition, the slight overshoot observed in the heating step response using the PID controller in processed industries can led to some issues since some products during processing are very temperature sensitive meaning slight increase or decrease in temperature could possibly alter the final product characteristics. However, some results did not meet expectation. The overall heat transfer coefficient U which gave approximately $U = 0{,}092$ (W/m^2 °C) from every indication shows that is very small. This could be caused because, the mean heat transfer rat $\dot{Q} =$ 8,35kJ/s from equation 3.12 could be linked to heat escape and variation on the the area of the vessel as well as the temperature change of the composition. The discrepancy between the cooling time constant can be explained by the fact that, steam is used for heating vessel content at high tamperature. As a result, when the process was stopped, the cooling water had a temperature that rose steady at start. Cooling from 10,5 °C to about 95,7°C when the initial temperature of composition was observed.

Overall, the thesis objectives were attained. In this study, the temperature of water was raised from around 40°C to approximately 90 °C using steam in a non-flow Jacketed reactor. The experiment demonstrated how to a second order plant mathematically and determine its corresponding transfer function. Based on the mean heat transfer rate required evaluated by calculations, the mean steam mass flow flowing into the system, or in other words the required steam consumption rate could be estimated. Furthermore, the flow rate of the exiting steam and cold water of the plant was calculated as well. Steam application is easy and enables fast heating.

The experiment also showed that utilizing steam as heating fluid in jacked vessel could have challenges when it comes to stabilizing the inner vessel temperature. According to Philip Sutter at Pick Heaters Inc., uniform heat transfer and precise temperature control is not often guaranteed by steam and typically hot spot areas are formed over time in the reactor due to the nozzles supplying steam. In addition, the drastic temperature change between steam and cooling water increased process load and thermal shock must be avoided. The system was also influenced by the amount of steam which could still possibly be present in the jacket prior to injecting cold water. The process dynamic parameters upon evaluation were substituted in the transfer function and simulated. The responses determined from heating after careful tuning indicated a slight overshoot, no dead time or oscillations. Both were fine-tuned using the PID controller which is more versatile. Finally, in future study switching from steam to hot water for jacketed system could be considered as alternative. This method could offer uniform and more accurate temperature control. Finally, conducting an investigation and validation of the pilot plant fitted parameters used in the closed-loop simulation by comparing the actual and simulated jacket reactor response findings will enhance the understanding of the process and develop or improve a novel approach.

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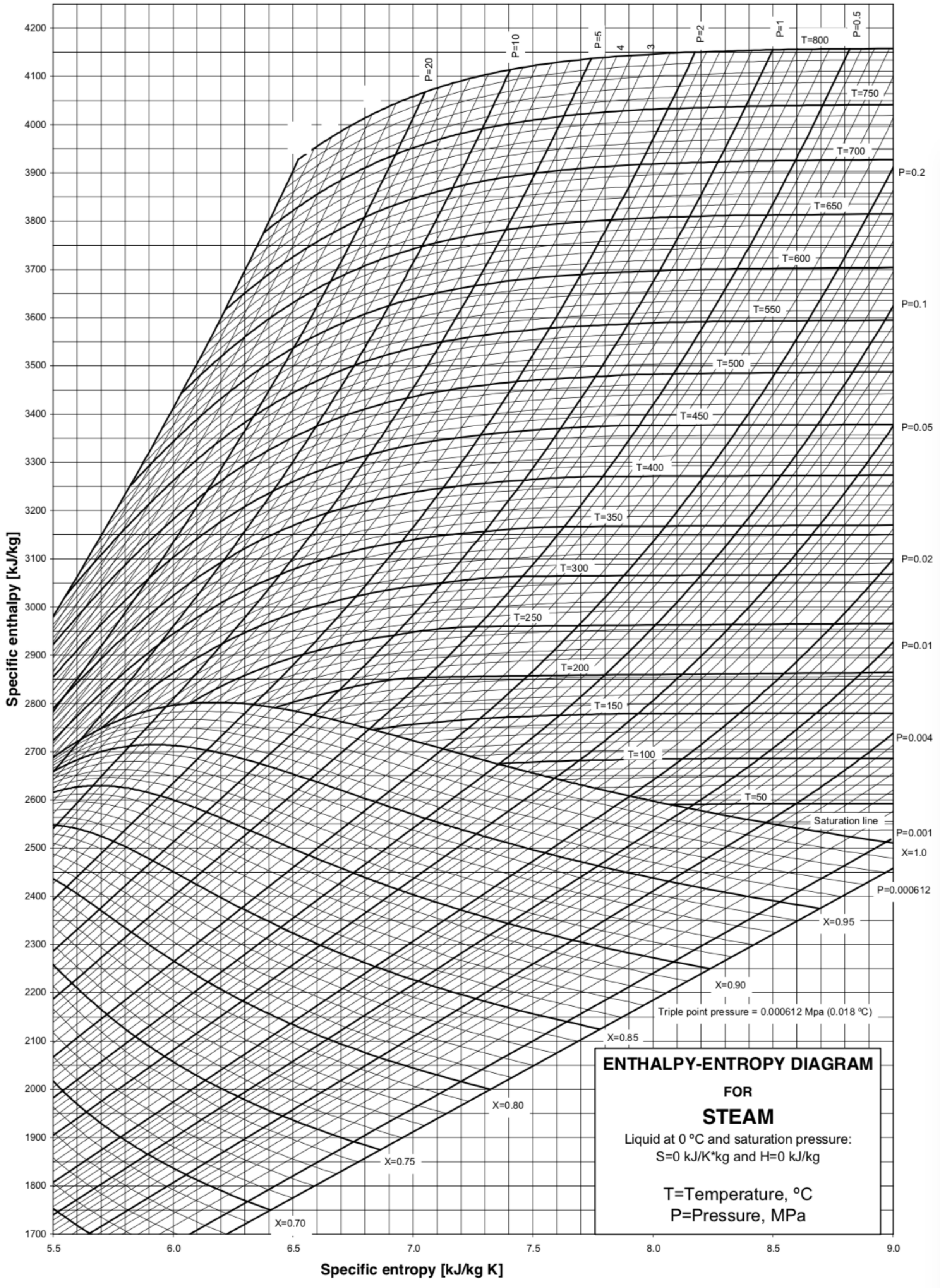
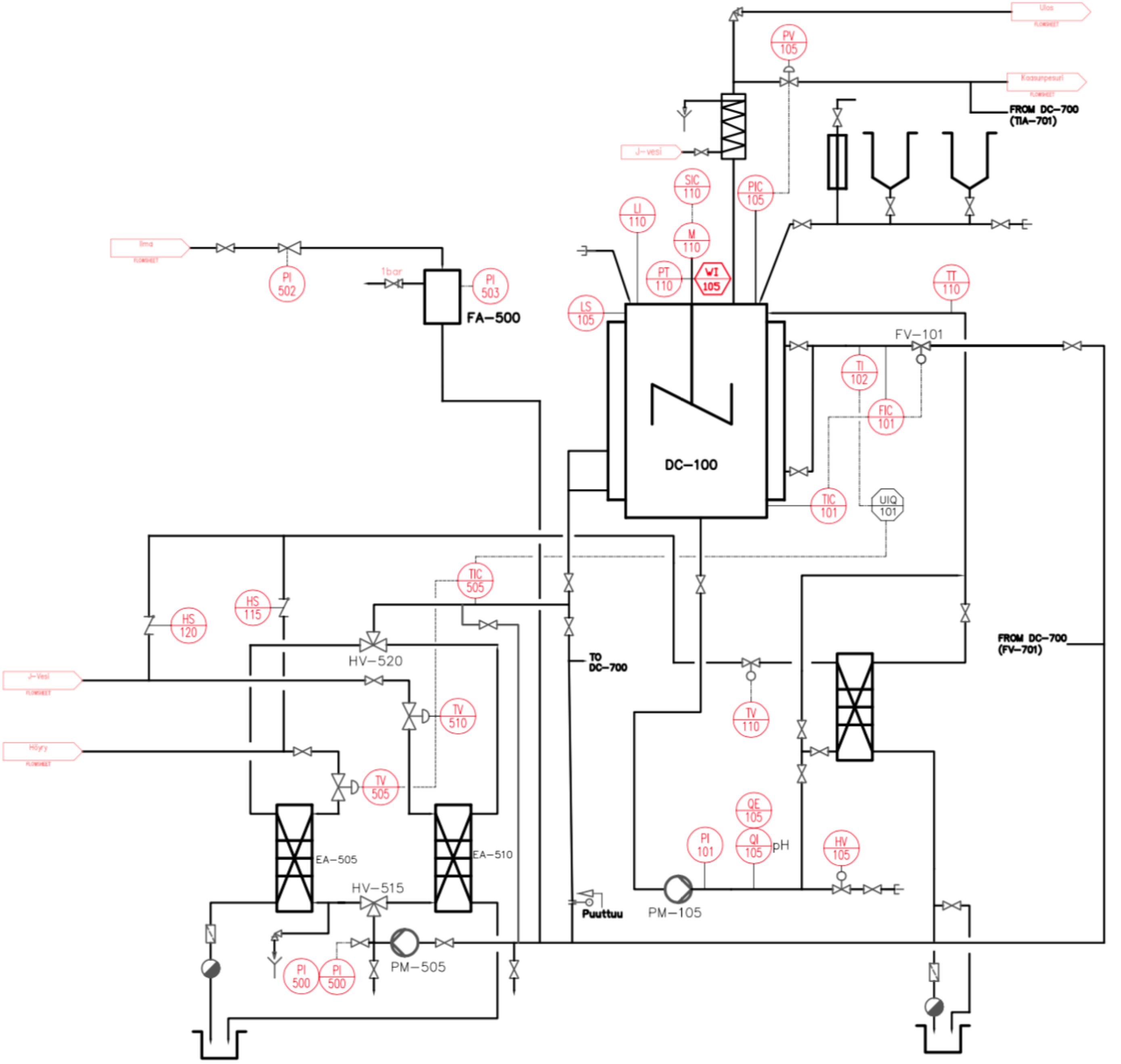


Enthalpy-Entropy Diagram (Aartun I. 2001)

APPENDIX 2.



Process Diagram of Plant (Risto Puskala 2007)

APPENDIX 3.

Saturated Steam Tables

Pressure			Temperature	Specific Enthalpy			Specific Volume Steam
				Water (hf)	Evaporation (hfg)	Steam (hg)	
bar		kPa	°C	kJ/kg	kJ/kg	kJ/kg	m³/kg
0.30		30	69.10	289.23	2,336.10	2,625.30	5.2290
0.50	absolute	50	81.33	340.49	2,305.40	2,645.90	3.2400
0.75		75	91.78	384.39	2,278.60	2,663.00	2.2170
0.95		95	98.20	411.43	2,261.80	2,673.20	1.7770
0	gauge	0	100.00	419.04	2,257.00	2,676.00	1.6730
0.1		10	102.66	430.20	2,250.20	2,680.40	1.5330
0.2		20	105.10	440.80	2,243.40	2,684.20	1.4140
0.3		30	107.39	450.40	2,237.20	2,687.60	1.3120
0.4		40	109.55	459.70	2,231.30	2,691.00	1.2250
0.5		50	111.61	468.30	2,225.60	2,693.90	1.1490
0.7		70	115.40	484.10	2,215.40	2,699.50	1.0240
0.9		90	118.80	498.90	2,205.60	2,704.50	0.9230
1.1		110	121.96	512.20	2,197.00	2,709.20	0.8410
1.3		130	124.90	524.60	2,188.70	2,713.30	0.7730
1.5		150	127.62	536.10	2,181.00	2,717.10	0.7140
1.7		170	130.13	547.10	2,173.70	2,720.80	0.6650
1.9		190	132.54	557.30	2,166.70	2,724.00	0.6220
2.2		220	135.88	571.70	2,156.90	2,728.60	0.5680
2.6		260	140.00	589.20	2,144.70	2,733.90	0.5090
3		300	143.75	605.30	2,133.40	2,738.70	0.4610
3.4		340	147.20	620.00	2,122.90	2,742.90	0.4220
3.8		380	150.44	634.00	2,112.90	2,746.90	0.3890
4.5		450	155.55	656.30	2,096.70	2,753.00	0.3420
5.5		550	162.08	684.60	2,075.70	2,760.30	0.2920
6.5		650	167.83	709.70	2,056.80	2,766.50	0.2550
7.5		750	173.02	732.50	2,039.20	2,771.70	0.2270
8.5		850	177.75	753.30	2,022.90	2,776.20	0.2040
11		1100	188.02	798.80	1,986.00	2,784.80	0.1630
13.5		1350	196.62	837.90	1,953.20	2,791.10	0.1360
16		1600	204.38	872.30	1,923.40	2,795.70	0.1170
18.5		1850	211.25	903.10	1,895.80	2,799.00	0.1020
21		2100	217.35	931.30	1,870.10	2,801.40	0.0906
24		2400	224.02	962.20	1,840.90	2,803.10	0.0797
27		2700	230.14	990.70	1,813.30	2,804.00	0.0714
30		3000	235.78	1017.00	1,787.00	2,804.10	0.0645
35		3500	244.26	1057.70	1,745.50	2,803.20	0.0554
40		4000	251.94	1094.60	1,706.30	2,800.90	0.0485
46		4600	260.13	1135.30	1,661.60	2,796.90	0.0421
50		5000	265.26	1160.80	1,632.80	2,793.60	0.0386

Heat Emission from Pipes (W/m)

Heat emission from bare horizontal pipes with ambient temperatures between 10°C and 21°C and still air conditions.

Temp. Diff. Steam to Air	Pipe Size									
	15mm	20mm	25mm	32mm	40mm	50mm	65mm	80mm	100mm	150mm
°C	W/m									
56	54	65	79	103	108	132	155	188	233	324
67	68	82	100	122	136	168	198	236	296	410
78	83	100	122	149	166	203	241	298	360	500
89	99	120	146	179	205	246	289	346	434	601
100	116	140	169	208	234	285	337	400	501	696
111	134	164	198	241	271	334	392	469	598	816
125	159	191	233	285	321	394	464	555	698	969
139	184	224	272	333	373	458	540	622	815	1133
153	210	255	312	382	429	528	623	747	939	1305
167	241	292	357	437	489	602	713	838	1093	1492
180	274	329	408	494	556	676	808	959	1190	1660
194	309	372	461	566	634	758	909	1080	1303	1852

Steam Tables/ Data (Spiraxsarco 2019)