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Comparison of Cascade and Feedforward-Feedback Controllers for Temperature Control on Stirred Tank Heater Systems

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Abstract— The temperature control in stirred tank heater (STH) systems is important, especially since the equipment is utilized in a wide variety of industries such as oil and gas. However, within the current STH control process there is often a small disturbance which adversely affects the overall process and it is quite difficult to solve with a regular feedback configuration. Many researchers have applied cascade and feedforward control configurations to solve this problem. Therefore, this paper discusses a comparison of cascade and feedforward-feedback control configurations in maintaining and regulating temperature in the STH. The results show that a cascade controller configuration performs better in various test conditions than a feedforward-feedback controller.

Keywords—cascade; control; feedforward-feedback; PID; stirred tank heater

I. INTRODUCTION

The stirred tank heater (STH) is one of the most widely used types of equipment in the industrial today. The chemical, oil, and gas industries are particularly dependent on STH technology. At the most basic level, the STH is a tank that mixes materials and applies heat to produce a new product. The use of heat is key to the reactions taking place within the STH. Therefore, temperature control becomes an important factor and must be considered when studying ways to produce a good product or otherwise improve the process. Temperature control is usually achieved by controlling a valve which releases fuel; opening the fuel release valve results in higher temperatures while closing the valve has the opposite effect. Temperature control can also be regulated by controlling the flow of heated materials such as gas or steam into or around the STH. Temperature control for STH equipment has been extensively studied including using Proportional Integral Derivative (PID)[1], Proportional Integral (PI)[2], dan fuzzy PID[3] controllers. Other studies reported using a combination of computational intelligent methods to optimize PID control parameters [4]. This controller has been able to solve general problems of temperature control. However, in the process of controlling the temperature, there is often a coincide change in pressure of gas or steam. This change in pressure will interfere

with the attempts to control temperature, although the effect does not directly interfere with the system. As a result of this pressure change, the temperature will also change. To solve this problem, the controller configuration is modified by adding a secondary controller which compensates for the initial pressure changes then maintain the correct temperature. In this configuration, the addition of a secondary controller system will also add a secondary sensor to determine the disturbance condition faster than the controlled variable. This approach is called the cascade control system [5]. The advantages of this cascade controller configuration, i.e. the ability to increase the response speed of the primary controller by increasing the response from the secondary controller. If there is a disturbance then the secondary controller will overcome the interference directly.[5][6].

Other disturbances that need to be compensated for during the process within the STH include an error in the modeling and the existence of unmeasurable disturbance. To overcome any modeling error a feedback controller can be used, while to overcome the immeasurable disturbance on the sensor a feedforward controller can be used. Feedforward and feedback controllers can be combined in different ways. In the controller configuration, the feedforward and feedback outputs are summed, where the summed signal will be sent to the controller. Such control is commonly called the feedforward-feedback system[5]. The advantages of the feedforward-feedback controller configuration are: the controlled variable does not have to be measurable; the error correction is immediate when there is a disturbance, and any actions and changes in this configuration do not affect the stability of the process[5][7][8].

Both controller configurations also have the disadvantage i.e. adding to the cost of the equipment, due to the addition of controllers and sensors. However, this addition is proportional to the performance shown by these two control configurations in overcoming the disturbance. This paper compares both types of control configurations in STH temperature control. Both types of control configurations will be seen their response of

control to handle undesirable temperature changes as well as tracking disturbance.

This paper is structured as follows: Section 1—Introduction, explaining the problem, current research, and objectives of this paper; Section 2—Stirred Tank Heater modeling; Section 3—Research Method, describing the controller configuration method used in this paper; Section 4—Results, including an Analysis of the experiment that has been done; and Section 5—Conclusion.

II. Stirred Tank Heater Modelling

STH is a common type of industrial equipment that is designed to mix certain materials at a specific temperature. The contents of the STH must be stirred so that the mixture is evenly distributed in order to consistently produce a particular, high-quality product. In addition to blending the ingredients as they mix, the stirrer also serves to prevent the mixed material from being frozen or becoming too thick. Heat is obtained from heaters, or from steam or gas. The heat conductively moves to the substances contained in the STH tank through the coil wall. The STH work process can be seen in Fig. 1, where temperature (T_i) and flow (F_i) at the input are assumed to be constant. The output is the new product, which is also at a specific flow and temperature. The temperature of the tank is maintained at a setpoint. Heat (Q) is used to keep the temperature constant. Temperature control is performed to regulate the heat by adjusting the valve controlling the flow of steam or gas.

Based on Fig. 1 it is assumed that the heater has been worked and the liquid temperature is kept constant (T_S). The fluid volume must also be maintained at a constant state, a value V. The mathematical equation model pertaining to the STH can be defined using the law of total energy balance in the process tank by the equation:

$$0 = F\rho C\,(T_{I,S} - T_S) + Q_S \qquad (1)$$

Or

$$0 = WC\,(T_{I,S} - T_S) + Q_S \qquad (2)$$

Where C is the heat of type (KJ/Kg°C), T_S is the steady state of the output temperature (°C), T_{IS} is the steady state of the input temperature (°C), ρ is the liquid type density (Kg/m³), F is the fluid flow rate (m³/s), and W is the mass flow rate (W=F. ρ) (Kg/s).
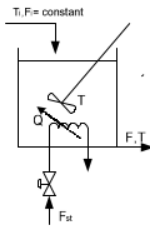

Fig. 1. Stirred Tank Heater Work Diagram

If T_I suddenly increases and if Q_S (energy in steady state condition) has no change, then the energy balance around the tank is::[4][5]

$$V_\rho C\frac{dT}{dt} = F_\rho C(T_1 - T) + Q \qquad (3)$$

$$MC\frac{dT}{dt} = WC(T_1 - T) + Q \qquad (4)$$

Where M = V. ρ and M are the tank mass (Kg), ρ is the density of the species (Kg / m³), and V is the volume of the vessel (m³). The design of this heating system uses the same working principle as a steam-heat modeling process, where input pressure is controlled. In this modeling process, the heater uses gas, which is sent to the stove to burn. So the main factor on the heater is the gas pressure output. The pressure of the gas is then set as the temperature of fire (T_A) through the adjustment of the thermodynamic relationship.

$$T_A = f(P_G) \qquad (5)$$

So the energy balance is [4]

$$MC\frac{dT}{dt} = WC(T_I - T) + h_P A_P(T_D - T) \qquad (6)$$

$$M_D C_D\frac{dT_D}{dt} = K_A A_A\frac{(T_A - T_D)}{X} - h_P A_P(T_D - T) \qquad (7)$$

Where:

- K_A is the Aluminum Conductivity (W / m°C)
- C_D is the Hearth type of wall (KJ / Kg°C)
- $A_P = A_A$ is the cross-sectional area (m2),
- T_A is the temperature in gas (Fire) (°C),
- h_P is the heat transfer coefficient W / m2°C), MD is wall mass (Kg),
- T_D is Tank wall temperature (°C),
- X is reactor tank thickness (m).

Based on the law of energy equilibrium, which stated that the energy change in a system is equal to the amount of energy entering the system minus the amount of energy going out of the system, then equation (8), as follows[4]

$$\frac{d[\rho A h C (T - T_{ref})]}{dt} = \rho FC(T_I - T_{ref}) - \rho FC(T - T_{ref}) + Q \qquad (8)$$

or

$$\frac{d[MC\,(T - T_{ref})]}{dt} = WC(T_I - T_{ref}) - WC(T - T_{ref}) + Q \qquad (9)$$

The mathematical equation (3) can be developed from the dynamic model equations of the STH heating system, i.e. (8) and (9)[4].

$$MC\frac{dT}{dt} = WC(T_I - T) + h_P A_P (T_D - T) \qquad (10)$$

$$M_D C_D\frac{dT_D}{dt} = K_A A_A\frac{T_A - T_D}{X} - h_P A_P(T_D - T) \qquad (11)$$

Assuming the dynamic conditions in equation (11) can be ignored, it is assumed that the tank wall value of temperature or temperature (T_D) equals the temperature or temperature of the burning gas (T_A). So equation (11) becomes: [4]

$$T_D = \frac{\frac{K_A A_A}{X}T_A + h_P A_p T}{\frac{K_A A_A}{X} + h_p A_P} \qquad (12)$$

Substituting into equation (3) will produce,

$$V \rho C \frac{dT}{dt} = WC(T_I) - WC(T) + UA (T_A - T) \qquad (13)$$

Since the T output variables, UA is a multiplication of heat transfer coefficient (h) to the cross-sectional area (A), and the T_I and P_G input variables are still nonlinear, the variables are converted into a linear form by deviation of variables, resulting in [4]

$$WCT_{I,S} = f(WCT_{I,S}) + WC(T_I - T_{I,S}) \qquad (14)$$

$$UA(P_G - T) = f(UA(P_{G,S} - T_S)) + UA(P_G - P_{G,S}) - (T - T_S) \qquad (15)$$

$$-WCT = -f(WCTS) - WC(T - T_S) \qquad (16)$$

The steady state value is

$$0 = WCT_{I,S} - WCT_S + UA(P_{G,S} - T_S) \qquad (17)$$

After the linearization values are known, the linear equations (14), (15), and (16) are fed into (13). Substitution with (17) then obtains the deviation equation of the variable below.[4]

$$V \rho C \frac{d(T - T_S)}{dt} = WC(T_I - T_{I,S}) - WC(T - T_S) + UA((P_G - P_{G,S}) - (T - T_S)) \qquad (18)$$

or

$$V \rho C \frac{dT'}{dt} = WCT_I' - WCT' + UA(P_G' - T') \qquad (19)$$

By doing a Laplace transform, generates:

$$V \rho C \; sT'(s) = WCT_I'(s) - WCT'(s) + UA(P_G'(s) - T'(s)) \qquad (20)$$

Changing into the transfer function obtains:[4]

$$T'(s) = \frac{K_I}{\tau s + 1} T_I'(s) + \frac{K_C}{\tau s + 1} P_S'(s) \qquad (21)$$

The transfer function of the control valve can be seen in the following equation:[4]

$$\frac{P_g(s)}{P(s)} = \frac{K_{CV}}{\tau_{cv}s + 1} \qquad (22)$$

Where K_{CV} represents the total gain of the control valve, cv denotes the constant time of the control valve (s), P_S represents the output signal from the controller (mA), P_{GS} represents the flow of LPG gas flowing through the valve (psi).

Based on the transfer function equation, the temperature control block diagram of the STH is seen in Fig.2. where the actuator is a control valve that will allow gas or steam to flow in the STH model. The setpoint is the standard temperature to be maintained and kept constant. The stirring speed of the stirrer's driving motor is also made constant. This control is a closed loop. However, an issue arises if there is any disturbance in the pressure of gas or steam, which directly affects the temperature. Resolving this required proper controller configuration.
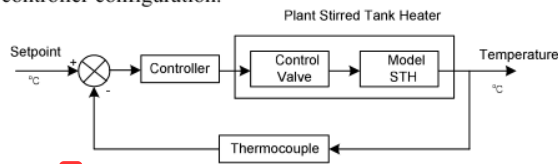
Fig. 2. Block Diagram of Temperatur Control of The Stirred Tank Heater

III. CONTROLLER CONFIGURATION

The controller which was used in this paper is the Proportional Integral Derivative (PID) controller because it is reliable, simple, and widely used throughout various industries. However, the configuration will compare the performances between cascade and feedforward.
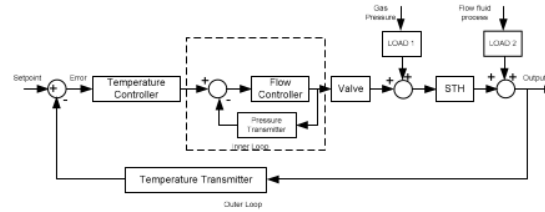
Fig. 3. Block Diagram of Cascade Control

A. Cascade

The block diagram of the controller with this cascade configuration can be seen in Fig. 3. In this controller, there are two feedback paths in the cascade control system, thus forming two loop controls, namely the outer loop which is the primary loop (or master), and the inner loop which is the secondary loop (or slave). The master or primary loop controls the primary variable process (fluid temperature process), while the slave or secondary loop controls the process of secondary variables (vapor or gas pressure).

The cascade controller is chosen because there are several reasons such as the output response of the single control is not as expected, there is the addition of a secondary variable in the control of the plant, which is added as a plant control, can overcome the disturbance.

B. Feedforward-feedback

In this STH control system, if there is change of load from the plant while the flow of steam or gas is constant, so it will be used a feedback control system. But if the load changes happen too quickly, then another type of control system becomes necessary. Because conventional feedback paths need to "see" errors before performing corrective actions, a standard feedback system will not be able to handle the load well if the load change frequency is too fast. Therefore, the design of the feedforward system as shown in Fig. 4 is based on process requirements, reducing the large loads that can disrupt the output process. The ultimate design of the system is left up to the designer because it is expected that a holistic, streamlined design will be able to reduce the interaction between feedforward and feedback (FFFB).
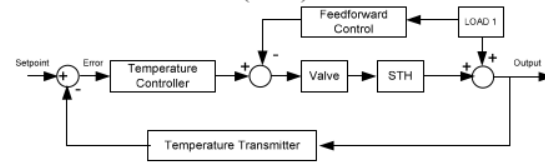
Fig. 4. Block Diagram of the Feedforward-feedback Control

IV. EXPERIMENT RESULT

The purpose of this paper is to compare the configurations of the cascade and feedforward-feedback controllers. Both of these configurations use PID controllers as both primary and secondary controllers. The cascade controller has a response when given setpoint temperature of 90°C. As shown in Fig. 5, the resulting overshoot value is 12.1%, the rise time is 1.075 seconds. The settling time value is 25.45 seconds, and the steady state error is 0% and the resulting offset value is 0.
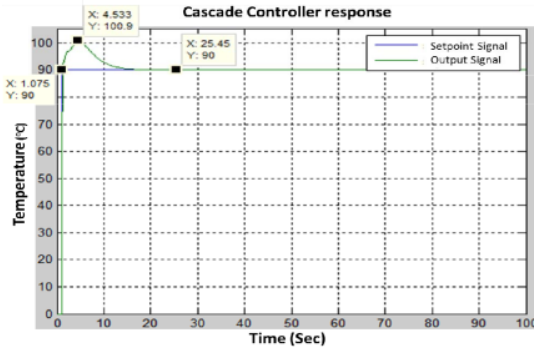

Fig. 5. The response of Cascade Control with setpoint

Then it tested the disturbance in the form of a changing setpoint as seen in Fig. 6. This test obtained the results of overshoot values of 12.1%, 4.64%, 3.83%, 3.24% and 0.2%. The average overshoot generated is 4.8%. The time rise results are 0.2836 seconds, 0.28 seconds, 0.3 seconds, 0.3 seconds and 0.3 seconds. This results in an average rise time of 0.292 seconds. The settling time value results are 24.4 seconds, 21.73 seconds, 22.1 seconds, 21.1 seconds and 20.6 seconds. This yields an average required settling time of 21.98 seconds. The steady state error is 0% and the offset value is 0. These results indicate the cascade control system on the stirred tank heater can work well when used with changing set-point conditions. This is evidenced by low overshoot value, fast rise time and settling time and 0% steady state error. This proves an STH will work well under these conditions.
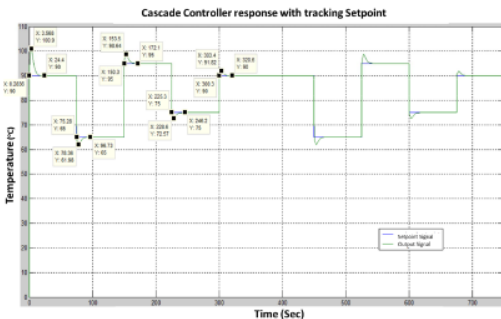

Fig. 6. The response of Temperature Control of STH using Cascade Control with Tracking Set-point
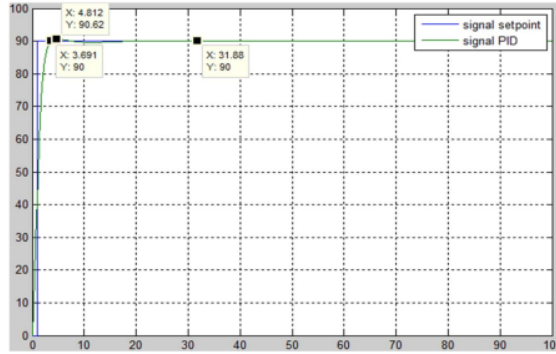

Fig. 7. The response of Temperature Control of STH using FFFB with setpoint

Then, comparison tests were run using the FFFB controller, again with both a single setpoint and tracking setpoint. Based on the output response generated in Fig 7, it can be seen that the FFFB controller was effective for single-setpoint conditions. The resulting overshoot value is 0.68%, the rise time is 3.691 seconds, the settling time is 31.88 seconds, the steady state error is 0% and the offset value result is 0. This response is very good, the overshoot is very small, almost 0%, the rise time is fast, the settling time is also quite good and the steady state error is 0%. This proves that the FFFB control system is good enough to overcome the existing issues.
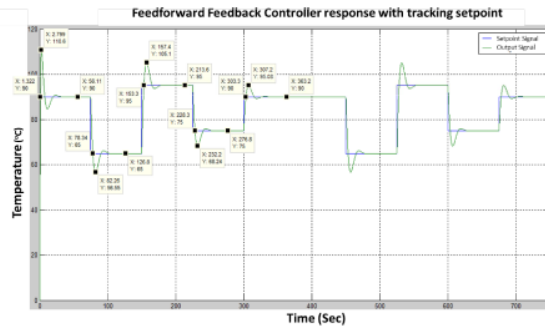

Fig. 8. The response of Temperature Control of STH using FFFB with Tracking Set-point

However, in Fig.8, the results of the FFFB configuration with a changing setpoint were not as promising. The resulting overshoot value is 22.8%, 13%, 10.6%, 9.01% and 5.6%, so the average overshoot generated is 12.2%. the time rise results were 1.322 seconds, 3.34 seconds, 3.3 seconds, 3.3 seconds and 3.3 seconds, which yields an average rise time equal to 2.91 seconds. Settling time values were 56.11 seconds, 51.8 seconds, 63.6 seconds, 51.8 seconds and 63.2 seconds, so the average settling time required is 57.3 seconds. The steady state error is 0% and the resulting offset value is 0. The resulting response is good enough, the overshoot is low, the rise time is fast and the steady state error is 0%, but the settling time is not very fast since the average was 39.81 seconds.

Based on the response generated by these two configurations, it can be seen that for conditions where the temperature setpoint is desired to be kept constant, the cascade controller has a smaller rise time and faster settling time than the FFFB controller. Therefore, the cascade is better than FFFB even though the overshoot generated is quite high. The comparison of response both of this controller can be seen in table 1. Although better, the cascade has its drawbacks; with its high overshoot, equipment may be adversely affected. In the cascade configuration, responses are accelerated due to the direct influence of the secondary controller. Anticipating the influence of pressure changes on steam or gas in the heater results in a high overshoot in an attempt to reach the new setpoint temperature. In the FFFB controller tests, under fixed setpoint conditions, the results indicate that the controller tries simply to approach the setpoint. Therefore, adding FFFB controllers is quite effective in minimizing overshoot. This ensures the safety of the equipment, but the time to reach a stable temperature exceeds the amount of time needed by the cascade. Similarly, when comparing the results of the test with changing setpoints, the cascade configuration proved to be the better choice because the rise time, overshoot and settling time all were lower than the FFFB. The only advantage to FFFB in the conditions introducing disorder by testing setpoint changes is that FFFB can eliminate the overshoot and thereby reduce the risk of equipment damage compared to the cascade.

TABLE I. COMPARISON OF CASCADE AND FEEDFORWARD-FEEDBACK CONTROLLER RESPONSE WITH SETPOINT

Controller	Rise time (second)	Overshoot (%)	Settling time (second)	Error Steady state (%)
Cascade with setpoint	1.575	12.1	25.45	0
FFFB with Setpoint	3.691	0.68	31.88	0

V. CONCLUSIONS

Based on the experiments and the tests that have been conducted, the cascade is better than the feedforward-feedback control system for a stirred tank heater (STH). The biggest advantage is that the cascade system generates the lowest rise time and settling time values. The cascade also has better results than the feedforward-feedback under changing setpoint conditions, based on the following factors: overshoot situations, rise time, and lower settling time. Future jobs will test other types of controllers such as PI and fuzzy logic, to develop more and better controllers for STH systems.

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