Understanding Heat Exchanger & Furnace Operations and Controls

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Abstract **– A paper on understanding unit operations for process control aims to discuss some of the individual unit operations and related equipments working on common scientific techniques and based on certain physical laws and principles, from their principles of operation and control point of view. Such unit operations when brought together in a specified sequence form a complete process in chemical, pharmaceutical and other manufacturing and processing industries. Discussion on understanding the need, development and practical implementation of various automatic control strategies to establish control over a unit operation is relevant only after understanding the need and behaviour of a unit operation and related equipments.**

I. INTRODUCTION

Although the number of individual processes in chemical or pharmaceutical industries is great, each one can be broken down into a series of steps called individual operations, which in turn appears process after process. These individual operations have common scientific techniques and follow universal physical principles like conservation of mass and energy, physical equilibrium, kinetics and certain properties of material. We can see almost all the chemical manufacturing and processing industries have to practise some of the common primarily physical steps like:

- Preparing the reactants
- Separating and purifying the products
- Recycling unconverted reactants
- Controlling the energy and mass transfer into or out of the chemical reactor etc

Irrespective of the manufacturing process being reactive like cracking of petroleum or nonreactive like manufacturing common salt, every process shares certain operations in common like heat transfer, distillation, crystallization, evaporation, separation, absorption, drying etc each of which can be called a unit operation in chemical process. Very easily we can categorize this unit operation on the basis of heat and mass transfer operation. We aim to study the heat transfer unit operation and related equipments in particular to build our understanding on the control system for the same.

Some of the heat transfer unit operation equipments whose principle of operation and control we are going to discuss here are:

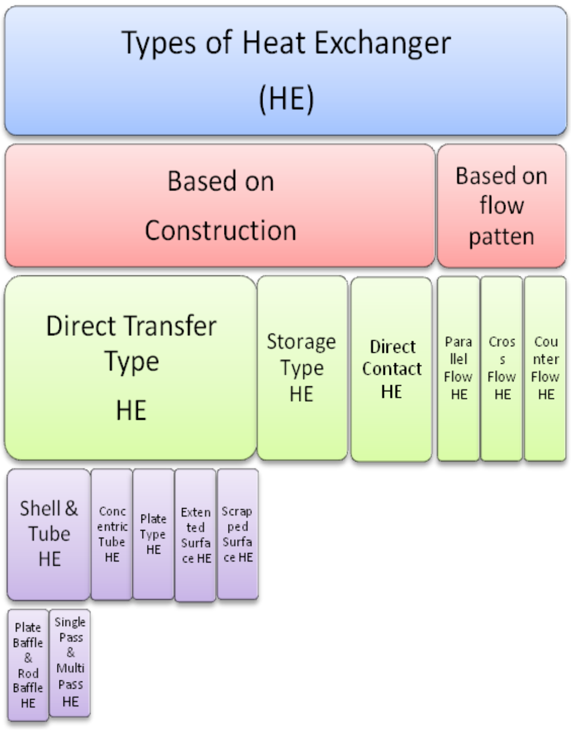
- Heat exchangers
- Furnaces

Although the complexity and variation in design of all heat transfer equipments may be appreciable however the mechanism of heat transfer or flow of heat in all such unit operations in governed by law of conduction, convection and radiation. Understanding these laws governing the transfer of heat and the type of apparatus can be very crucial in control of heat transfer.

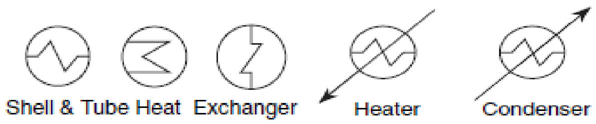
II. HEAT EXCHANGERS

Heat exchangers are the devices in which heat is transferred between the two fluids at different temperature without any mixing of the fluids. While the fundamental operation is heat transfer, the primary purpose of heat exchangers in the process is controlling the temperature of system or substance by adding or removing thermal energy.

Heat exchangers are found in very wide range of processes and industries including chemical and petrochemical plants, petroleum refineries, natural gas processing, power plants, sewage treatment etc. Due to such wide spread use and application of heat exchangers they can be classified on variety of categories including construction, flow pattern, application, principle of working etc. We will try to evaluate the control and working of shell and tube type heat exchangers which forms a very important part of many of chemical and pharmaceutical processes. Shell and tube type of heat exchangers are commonly seen in many phase change operations (condensation) where vapours are condensed down due to heat transfer, such shell and tube type of heat exchangers are called condensers which are very widely used.



A. Principle of operation of shell and tube heat exchanger



_Flow sheet Symbols Of Heat Exchangers

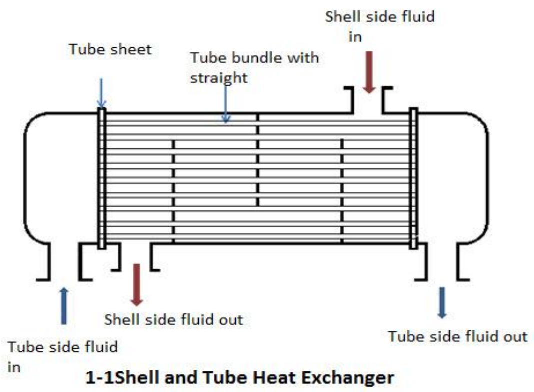
The diagram shows 1-1 shell and tube type heat exchangers consist of a shell side and a tube side flowing fluid between which heat transfer takes place through conduction and convection. Generally the fluid flowing through the tube side is the process fluid which is heated till certain desired temperature is achieved, while flowing through shell side is the heating fluid like hot steam, hot oil etc which is at relatively higher temperature. While the two fluids flow in the heat exchanger either in parallel or cross flow path the heat transfer operation takes place heating the process fluid to the desired temperature. Here the capacity of a heat exchanger depends on many factors like the relative flow rate and temperature of fluids, heat transfer area etc. Hence generally the number of tubes in a heat exchangers is increased which ultimately increases the capacity by increasing heat transfer area.

B. Heat exchanger control system

Heat transfer operation in a heat exchanger is controlled to maintain the desired temperature of the process fluid by normally controlling the flow rate and temperature of the heating fluid or utility. The degree of accuracy and promptness i.e. the quality of control desired to maintain the process value depends on the process type, requirement and other related factors. The nature of heat exchanger and the quality of control desired plays very important role in determining the proper instrumentation in a unit. While the nature of heat exchanger can be evaluated as liquid- liquid HE, steam heaters, condensers etc quality control on the heat exchanger unit can be established by implementing sophisticated control systems like cascade, bypass and feed forward control system. Some commonly established control schemes for heat exchangers are:

- Feedback control of HE
- Feed forward (anticipatory) control of HE
- Feedback + Feed forward control of HE
- Bypass control of HE using 3-way or 2-way valve
- Cascade control of HE
- Model based control of HE

Feedback control of heat exchanger involves the detection of the controlled variable i.e. temperature of the process fluid and counteracting the changes in its value related to the set point by adjusting the manipulated variable i.e. the steam flow rate. Here the control action is taken only after the disturbance affects the PV.

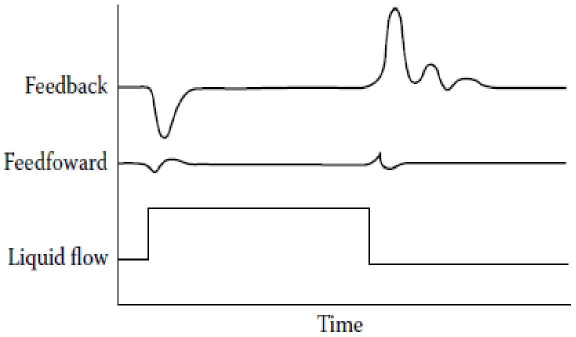


1-1Shell and Tube Heat Exchanger

Feed forward control is an anticipatory control as the control action is taken before the disturbance such as the change in flow rate or temperature of process fluid etc could affect the PV. Feed forward control is based on steady state process it contribute a stable and damped response to load changes however the cost and difficulty involved in implementation of feed forward control is considerable.

Feedback + Feed forward control can significantly improve performance over simple feedback control whenever there is a major disturbance that can be measured before it affects the process output. In the most ideal situation, feed forward control can entirely eliminate the effect of the measured disturbance on the process output. Feedforward control is always used along with feedback control because a feedback control system is required to track set point changes while the feedforward control suppresses unmeasured disturbances that are always present in any real world process. Hence we say that feedback and feedforward portions of the loop complement each other.

The feedforward portion is responsive, fast, and sophisticated, but inaccurate. The feedback portion is slower, but is capable of correcting the upsets caused by unknown or poorly understood load variations, and it is accurate.

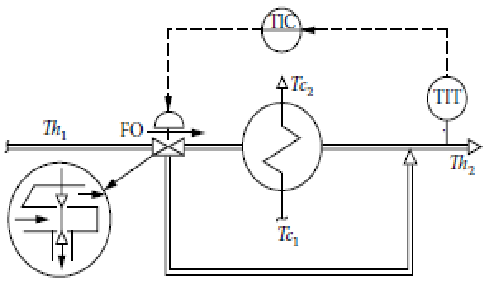


The plot shows how the feedforward control is capable of reducing both the area and duration of load response transient.

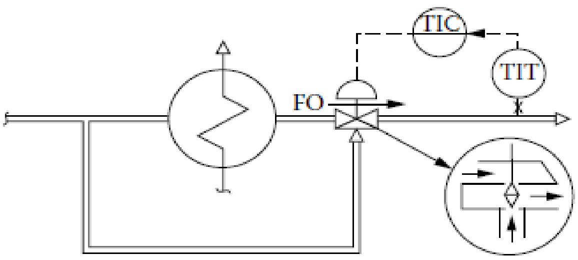
Bypass control of heat exchanger is implemented when the flow rate of both streams are set by process requirement. A portion of one of the streams (either hot or cold) is sent through the HE, and the remainder is bypassed around the exchanger. The temperature of the mixed steam is controlled by the valve in each path. The system provides very tight temperature control, since the dynamics of blending a hot stream and a cold stream are very fast. Such control is possible to be implemented by throttling a 3-way valve or two 2-way valves. Following table gives the comparison between the two techniques on the basic of certain important process considerations.

Merits of Two-Way vs. Three-Way Valves in Exchanger Bypass Installations

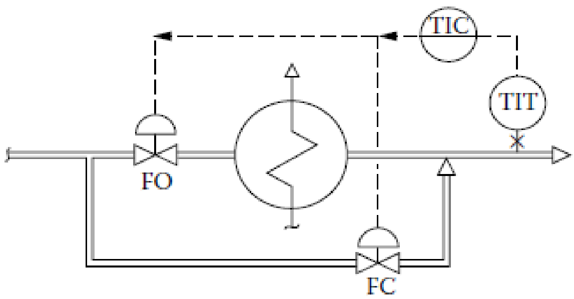
	One Three-Way Valve	*Two Single-Seated Two-Way Valves*	*Two Double-Ported Two-Way Valves*
Most economical	Yes		
Provides tight shut-off	Yes	Yes	
Applicable to service above 500°F (260°C)		Yes	Yes
Applicable to differential temperature service above 300°F (167°C)		Yes	Yes
Applicable to operation at high pressure and pressure differentials		Yes	Yes
Highest capacity for same valve size			Yes



3-Way Diverting Valve Bypass Control

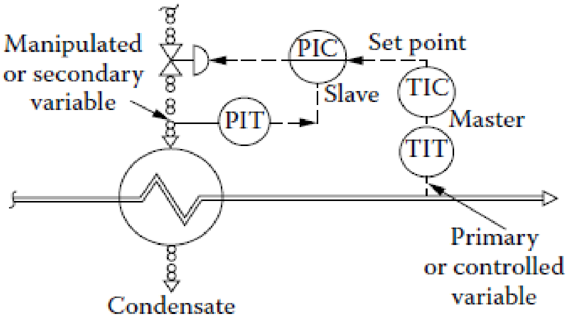


3-Way Mixing Valve Bypass Control



2-Way Valve Bypass Control

Cascade control is implemented through a cascade loops which consist of two controllers in series, the output of the primary controller to manipulate the set point of the secondary controller as if it were the final control element. In heat exchanger applications, the master detects the process temperature and the slave detects a variable that may upset the process temperature. The improvement in control quality is a function of relative speeds and time lags of the two loops. A slow primary (master) variable and a quickly responding secondary (slave) variable is a desirable combination for this type of control. If the slave can quickly correct the fast disturbances, they will not be allowed to enter the process and, therefore, will not upset the primary (master) variable.



Cascade Control Of Heat Exchanger

Model-Based Control systems today are used to facilitate optimization; such systems are called expert systems as they carry certain features and capabilities. From the point of view of use of methods of optimization we categorize control in model-based control methods and model-free control methods. The model-based control (MBC), model predictive control (MPC), or internal model control (IMC) methods are all suited for the optimization of such unit processes that are well understood, such as heat transfer. Their performance is superior to that of the model-free systems, because they are capable of anticipation and, thereby, can respond to new situations. In this sense, their performance is similar to that of feedforward control systems, while the model-free systems behave in a feedback manner only.

C. *Conclusion on heat exchanger control*

Looking at various control systems for control of heat exchangers it is very easy to list the feature they carry; however choosing among these control systems while practically implementing the control should not be a tough choice, as it can be directly related to the process requirement from the quality, productivity and safety point of view. The temperature upsets resulting from the sudden change of the load can be reduced by an order of magnitude through the use of feedforward control. Such a reduction in temperature error can make a great contribution to both safety and quality of production. Therefore, optimized or dynamically compensated feedforward heat exchanger controls are usually justified not on the basis of increased production or reduced energy costs, but on the basis of more stable, accurate, and responsive control.

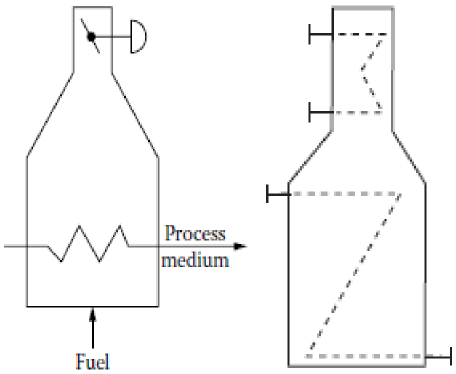
The significance of properly choosing and installing instruments including the sensors, controllers and final control elements cannot be denied. From the mode of operation of the controller like P, PI, PD and PID to the inherent valve characteristic like quick opening, linear and equal percentage. The control valve actions when properly selected like FO or FC ensures the safety of the process. Every detail considered by the designer along with the proper choice of control system is a key for establishment of a quality control over the unit operation like heat exchanger. In addition, it is always wise to consider the use of equal percentage control valves furnished with positioners and to evaluate the adversity of using the advanced control schemes like cascade, feedforward and model based control system.

III. FURNACE

Furnace is a device used in heat transfer unit operation in many processes where the charge (feed) or process fluid entering the furnace is heated to a desired temperature in a controlled manner. The major difference in furnace and heat exchanger is that in heat exchangers the heat is transferred between two fluids one being the process and other being utility such as hot stem, hot oil etc while in the furnace the source of heat is combustion of the fuel gas; used to transfer the heat energy to the process fluid to heat it to the desired temperature. Furnaces are generally available in many designs depending on their area of application and function. Furnaces are used in industries for many major heat transfer operations and their functions can be broken down in following three categories:

- To heat or vaporize the charge.
- To provide heat of reaction to the reacting feeds
- To provide and evaluate the controlled temperature for the physical change of charge material.

Some of the commonly used furnaces in industries are Start up Heater, Fired Reboilers, Reformer Furnace, Cracking (Pyrolysis) Furnaces etc which can be easily distinguished on the basis of their functionality and application; while the operation they all perform remain same i.e. heat transfer.



Flow sheet Symbols Of Furnace

A. *Principle of operation of furnace*

A typical furnace used in industries look like a metallic housing lined with a heat conserving refractory. The major components of the furnace system consist of air blower, burner, combustion chamber, heated coils and air vent path with adjustable damper. The charge can enter the furnace and flow in to the heated coils or tubes as solid, liquid or gas and may or may not be converted to a different state by the heat energy supplied.

The charge is carried through the furnace in to the metal coils where it can be heated continuously or batch heated by remaining stationary after entering. This depends on the function that the furnace is employed for i.e. vaporization of charge, provide heat of reaction etc. Now from the process point of view the furnace can be required in two phase of the process, one while the process is being initialized or start up and second while the process have already been initialized i.e. to maintain the sustainability of the process. The basic operation of furnace in both the phases remain same however the requirement by the process varies widely, this gives rise to two different categories of the furnace called Start-up Heaters which are required to start up a process unit and are normally functional till certain hours to few weeks and reboilers which are functional till the process last. It is necessary to be noted that no matter what category of the furnace we are looking at the basic operation remains almost same which is to heat the process fluid to the desired temperature.

B. *Furnace control system*

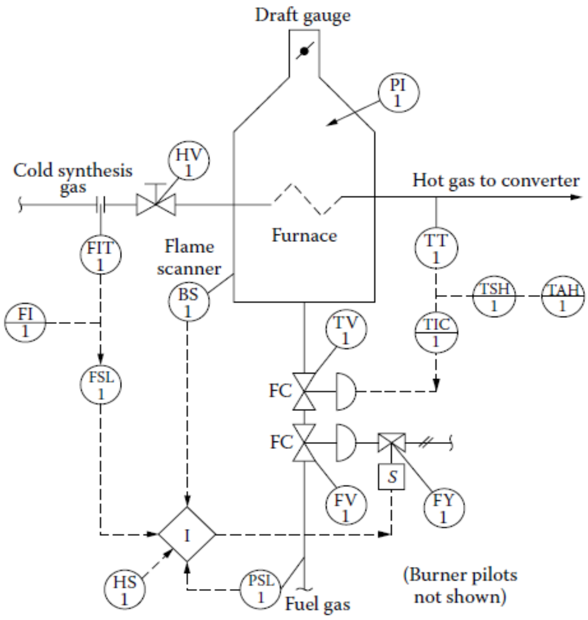
In a furnace control system along with establishment of effective control over the major control variable i.e. the temperature of the process fluid, certain other control strategies need to be implemented to ensure overall control of furnace system. The primary functions of furnace control systems can be hence listed as following:

- To ensure that the charge receives the heat energy at the proper rate, the controlled variable is the exit temperature of the charge.
- To maintain efficient combustion of the fuel. Proper combustion of the fuel requires the regulation of the air-fuel ratio.
- To maintain the safety during all phases of furnace operation so as to prevent explosions or fires.

The recommended control strategies can be thus broken down into the following three categories:

1. Process controls.
2. Fuel firing controls.
3. Safety controls.

Let us try to study and evaluate the significance and establishment of these control strategies in a ammonia process that require a start-up heaters usually heats an intermediate stream, such as air or natural gas, which in turn heats another fluid or solid, such as a reactor catalyst. The following P&ID shows the control of a start-up heater used in ammonia unit to start-up the process.



The Control of a Start-up Heater

Process control ensure that the charge receives the heat energy at the proper rate, here the controlled variable is the exit temperature of the charge which is monitored and controlled by manipulating the burner flame; which is made possible by controlling the fuel gas inlet to the burner through a fail-close temperature control valve.

Safety control is implemented to ensure the safety in furnace operations. The potential sources of hazards include

- Fire or explosion caused by tube rupture. Such rupture can occur because of tube overheating due to feed flow loss or because of flame impingement
- Explosion in the firebox caused by the loss of flame or by improper ignition or purge procedures

The standard ANSI/ISA-84.01–1996, "Application of Safety Instrumented Systems (SIS) for the Process Industries," is implemented to ensure the safety of a furnace operation. The SIS safety and shutdown system is usually located on a PLC that is separate from the control equipment that directs the normal operation of the furnace. Such safety systems usually include a flame scanner. The reliability of PLC-based SIS systems is increased by implementing them in redundant or triple-redundant (voting system) configurations, as far as their processors and power supplies are concerned.

Here the safety control is ensured by implementing logic that works on the inputs of flame scanner, flow safety low switch for inlet charge flow and pressure safety low switch for inlet fuel gas, to cut-off the fuel gas inlet flow into the burner ensuring the safety of the furnace operation.

Fuel firing controls of a start up heater operation plays a very important role in both the process and safety control. Here the fuel gas firing rate is set by process temperature controller (TIC-1). The heater draft (i.e., negative pressure in the firebox) is produced by the stack; the operator sets it by observing the draft gauge (PI-1) and by manually adjusting the position of the stack damper. Once initially set, the damper is rarely adjusted again, unless the furnace conditions or loads change drastically.

C. Conclusion on furnace control

The furnaces and related control systems we discussed are representative of a wide spectrum of furnaces used throughout the process industry. The control strategies including Process controls, Fuel firing controls, Safety controls are valid whether implemented by older analogue instrumentation or by more sophisticated DCS or PLC systems. With the expansion of industrial facilities and with the use of larger furnace units on the one hand and with the increased availability of advanced process control (APC) on the other hand, the use of more advanced and model-based controls should be considered, while taking full advantage of the basic controls we described, to obtain more efficient and more economical furnace operation.

IV. CONCLUSION

Through this review paper I have made an attempt to give the reader a quick understanding and overview of perhaps most commonly used equipments in process industries like heat exchangers and furnaces pertaining to their operation and control strategies. I hope this will help my student colleagues and working professionals to brush up the fundamentals of unit operations and process control schemes.

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