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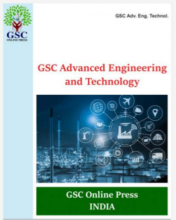

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(Research Article)

Steady state modeling of steam condensate cooler

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Abstract

Mathematical models for steam condensate cooler were developed. The models were deduced by applying the principle of conservation of energy and yielded an ordinary differential equation, which were solved by using MatLab ODE45 solver and validated using industrial data of a fertilizer company. The result gives minimum percentage absolute error or deviation between model predictions and industrial plant of 0.09% and 0.10% respectively for hot and cold fluid outlet temperature. These shows that the developed model predicted the fluid outlet temperature of the steam condensate cooler closely and the models were used to study the effects of process parameters such as fluid inlet flow rate and heat transfer coefficient on the performance of the steam condensate cooler.

Keywords: Condensate Cooler; Hot Fluid; Cold Fluid; Polisher; Steady State

1. Introduction

A heat exchanger is a device built for efficient heat transfer from one fluid to another, whether the fluids are separated by a wall to prevent mixing, or fluids are directly contacted. They are widely used in petroleum refineries, chemical plants, petrochemical plants, natural gas processing, refrigeration, power plants, air conditioning and space heating. One common example of a heat exchanger is car radiator, in which a hot engine cooling fluid like antifreeze, transfers heat to air flowing through the radiator. The general function of an exchanger is to transfer heat from one fluid to another and its basic component can be viewed as a tube with one fluid running through it and another fluid flowing by on the outside. Heat exchanging unit can be classified as parallel, counter current, cross current, condenser and evaporator based on exchanger flow arrangement or as regenerator and recuperator due to design or construction basis [1]. The heat exchanger was introduced in the early 1900s to execute the needs in power plants for large heat exchanger surfaces as condensers and feed water heaters capable of operating under relatively high pressures. Both of these original applications of shell and tube heat exchangers continued to be used, but the design have become highly sophisticated and specialized subject to various specific codes and practices. The steadily increasing use of shell and tube heat exchangers and greater demands on accuracy of performance prediction for a growing variety of process conditions resulted in the explosion of research activities [2].

Heat exchangers simulated studies were carried out by using a complete distributed parameters method by treating the two phase flow as a homogeneous flow and this led to an inaccurate prediction of mass flow rate distribution [3,4]. A dynamic model that described the transient phenomena of a two phase heat exchanger by solving a set of one dimensional ordinary differential equations (ODE) over three different zones (liquid, two phase and vapor) was performed [5]. Rossi and Braun (1999) developed a fast yet large model of a roof-to pair conditioning unit, and the heat exchanger model uses the Finite difference method to solve mass and energy balance equations [6], while Jakobsen et al, 1999 compared a homogeneous flow model and a slip-flow model in an evaporator with experimental data. The validation showed that the slip-flow model agreed very well with experimental data on dynamic response and is more

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accurate than the homogeneous flow model on charge calculation. They recommend the use of the slip-flow model when investigating the dynamic behavior of heat exchangers [7]. In addition, Bendapudi et al, 2004 used both finite difference and moving boundary approaches to develop a shell and tube heat exchanger model. The comparison showed that the moving boundary approach was at least two times faster than the finite volume method based on the execution speed, but the accuracy of both models were not represented. Hence, in order to shorten the computing time and maintain accuracy, it is felt that the moving boundary approach is a better choice when a large segment size applied on heat exchanger simulations [8].

Besides, a condensate polisher is a device used to filter water condensed from steam as part of the steam cycle and it is important in systems using the boiling and condensing of water to transport or transform thermal energy. Using technology similar to a water softener, trace amounts of minerals or other contaminants are removed from the system before such contaminants becomes concentrated enough to cause problems by depositing minerals inside pipes, or within precision engineered devices such as boilers, steam generators, heat exchangers, steam turbines, cooling towers, and condensers [9]. The removal of minerals has the secondary effect of maintaining the pH balance of the water at or near neutral (a pH of 7.0) by removing ions that would tend to make the water more acidic. This reduces the rate of corrosion where water comes in contact with metal. Thus, condensate polishing typically involves ion exchange technology for the removal of trace dissolved minerals and suspended matter, and it is used as part of a power plant's condensate system, which prevents premature chemical failure and deposition within the power cycle that would have resulted in loss of unit efficiency and possible mechanical damage to key generating equipment [10]. Furthermore, the temperature of steam condensate entering the polishing unit of the fertilizer plant should not be above $45^{O}C$ to prevent operational inefficiency of the polisher thereby causing the breaking and gluing of anion and cation resins in the polisher. Therefore, this research study will develop model equations that predicts the outlet temperature of the steam condensate cooler, which acts as inlet stream to the polisher. This will be achieved by developing an appropriate mathematical model for the steam condensate cooler through the application of the principle of conservation of energy, simulation of the developed model equations with both empirical and industrial plant data by using MatLab ODE45 solver and analysis of the developed model results with industrial fertilizer plant data to check for deviations and predicted models' effectiveness.

2. Material and methods

In describing the operation of the steam condensate cooler, models of the cooler were developed by applying the principle of conservation of energy based on the following assumptions: the cooler operates at steady state, flow into the cooler equals out flow from the cooler, heat is provided by condensing steam and all steam condenses (no steam loss), no reaction taking place in the cooler. Thus, these developed models were solved by using both empirical and industrial data of a fertilizer plant.

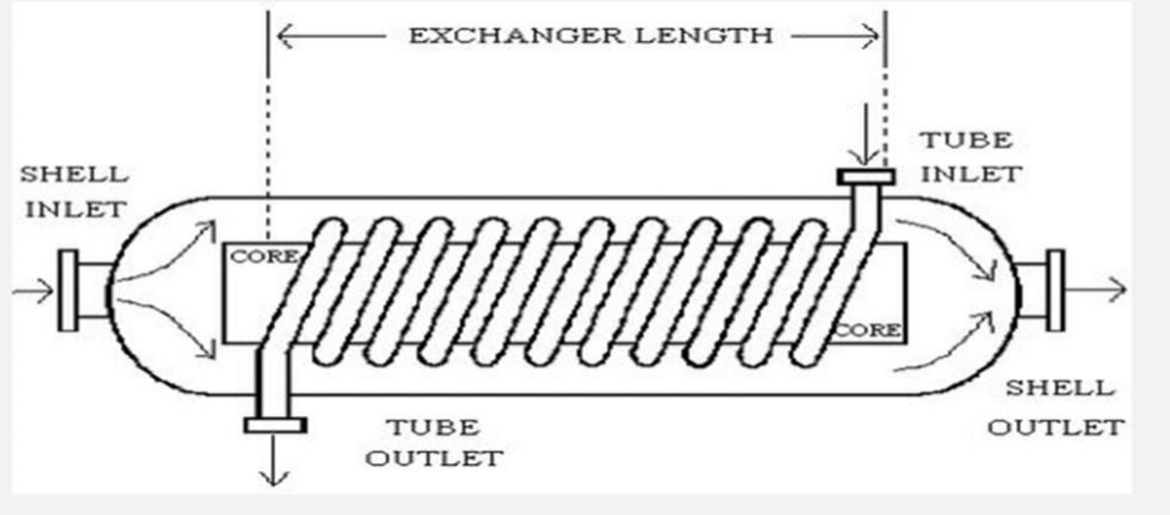

Figure 1 Helical Coil Steam Condensate Cooler

2.1. Model Equation

Temperature change along the length of the steam condensate cooler was developed for hot and cold steam by applying the principle of conservation of energy at steady state. Thus, the developed model equation is applied in predicting temperature change for hot and cold steam along the length of the steam condensate cooler as:

Hot Fluid:

$$\frac{dT_h}{dL} = \frac{-US}{\rho_h F_h C_{ph}} (T_h - T_c) \tag{1}$$

Cold Fluid:

$$\frac{dT_c}{dL} = \frac{US(T_h - T_c)}{\rho_c F_c C_{pc}} \tag{2}$$

3. Results and discussion

The results deduced from the solution of the developed model equations are discussed thus.

3.1. Temperature Profile

The model predicted temperature profiles for hot and cold fluid along the length of the cooler as shown in Figure 2.

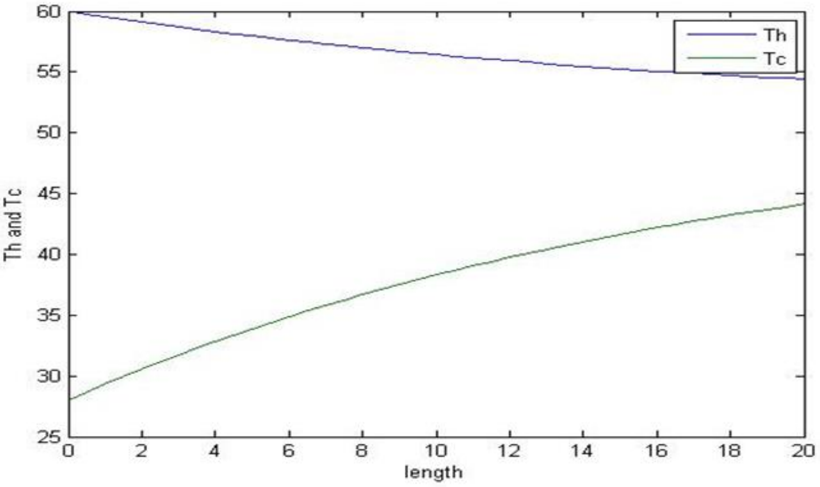

Figure 2 Variation of Hot and Cold Fluid Temperature against Length

It can be deduced from Figure 2 that as the temperature of the hot fluid declines, there is increase in the temperature of the cold fluid along the length of the steam condensate cooler. Hence, heat exchange is achieved.

3.2. Model Validation

The developed model results were compared with an industrial fertilizer plant data as shown in Table 1.

Table 1 Comparisons of model results and industrial data.

Parameters	Industrial Data	Developed Model Data	Absolute Error (%)
Hot Fluid Outlet Temperature	49.90	54.51	0.09
Cold Fluid Outlet Temperature	40.00	44.15	0.10

The maximum percentage absolute error also known as deviation between the developed model and output from industrial fertilizer plant data for hot and cold fluid outlet temperatures are 0.09 and 0.10 respectively. Thus, the developed model can be applied for simulation studies of steam condensate cooler.

3.3. Process Simulation

The steam condensate cooler was simulated to study the effect and performance of process variables on the condenser.

3.4. Effect of Fluid Inlet Flow Rate

The effects of variation of fluid inlet flow rate on the performance of steam condensate cooler is shown in Figure 3.

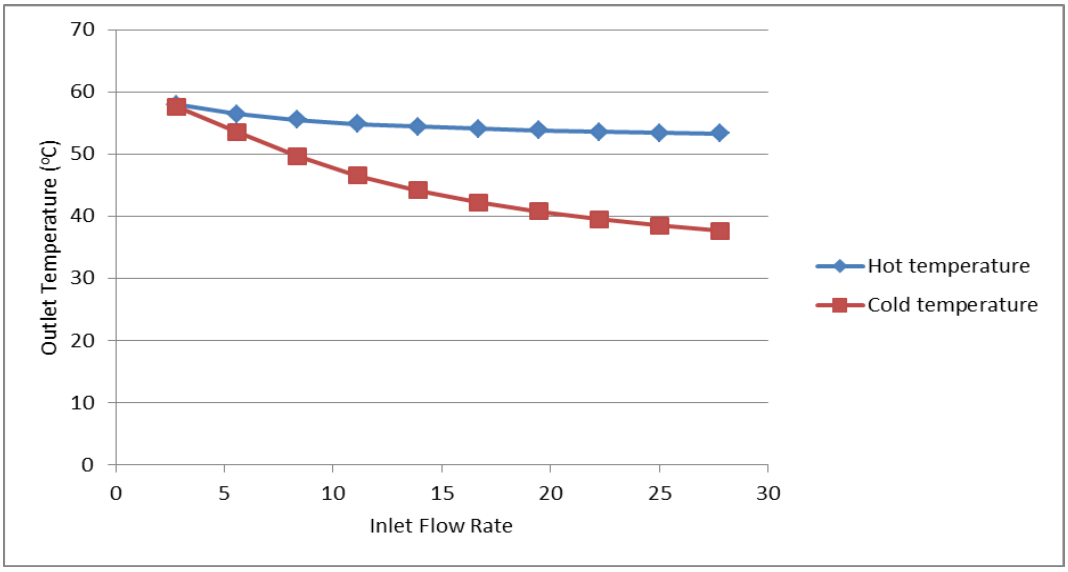

Figure 3 Variation of Inlet Flow Rate on Outlet Temperature

Increase in the fluid inlet flow rates yields a decrease in hot fluid outlet temperature and also, a corresponding decline in the outlet temperature of the cold fluid. Thus, increase in inlet fluid flow rate increases the overall heat transfer coefficient as a result of increase in Reynolds number, which subsequently increases the Stanton number thereby leading to decrease in the tube outlet temperature(11). Therefore as shown in Figure 3, decrease in outlet temperature is due to increase in the volumetric flow rate which increases mass flow rate faster than the overall heat transfer coefficient (heat energy transferred). Also, since the specific heat capacity remains almost constant, outlet temperature should decrease in order to conform with the principle of conservation of energy.

3.5. Effect of Heat Transfer Coefficient

The effects of variation in heat transfer coefficient on the performance of the steam condensate cooler was also studied as shown in Figure 4.

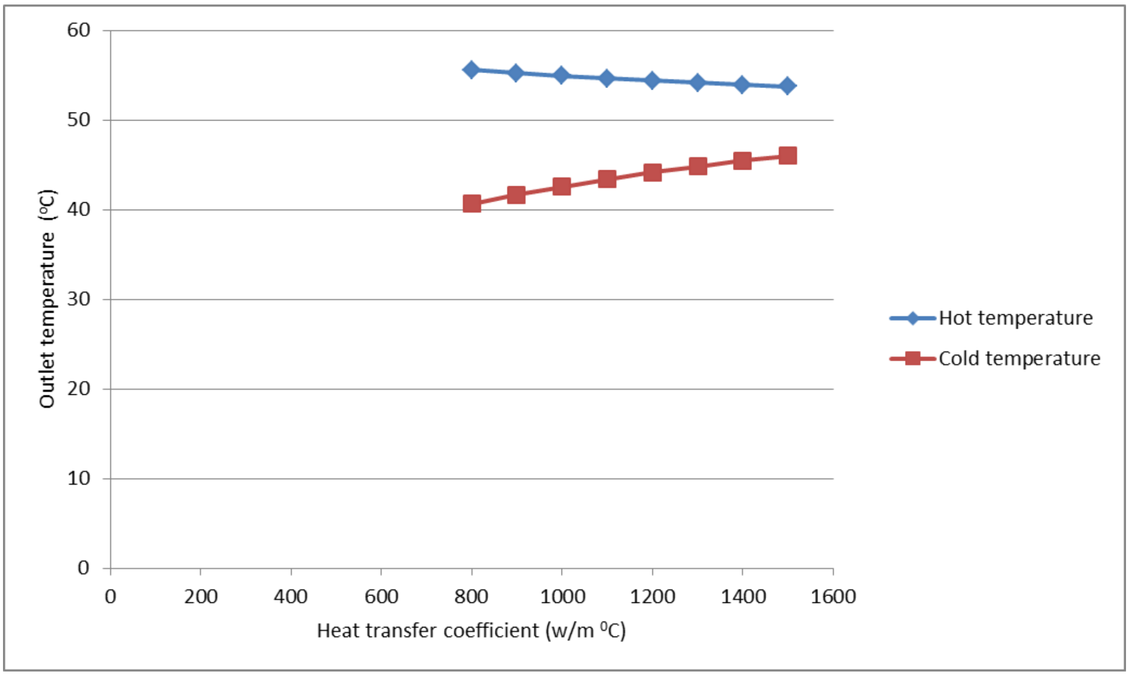

Figure 4 Variation of Heat Transfer Coefficient on Outlet Temperature

It can be deduced from Figure 4 that as the heat transfer coefficient increases, there is a decrease in the hot fluid outlet temperature and the cold fluid outlet temperature increases slightly. As the volumetric flow rate increases, the overall heat transfer coefficient increases and there is reduction in the tube outlet temperature with a slight increase in cold fluid temperature. This also conforms with other previous study(11). Thus, it can deduced that the developed models predicts appropriately the performance of steam condensate cooler.

4. Nomenclature

T_{ref}	Reference Temperature	°C
T	Temperature of the Liquid in the exchanger	°C
T_{so}	Temperature of Liquid out of the Shell	°C
T_{si}	Temperature of Liquid into the Shell	°C
P	Density of Liquid in the Shell	Kg/m^3
V	Volume of liquid in the shell	m^3
C_p	Specific heat capacity of liquid in the shell	J/KgK
F_{si}	Volumetric Flow Rate of Liquid into the Shell	Kg/hr
F_{so}	Volumetric Flow Rate of Liquid out of the Shell	Kg/hr
ρ	Density of Flow	Kg/m^3
A	Heat Transfer Area	m^2
T	Fluid Temperature	K
U	Overall Heat Transfer Coefficient	W/m^2K
S	Heat Transfer Perimeter	m
L	Tube Length	m

5. Conclusion

Models for the simulation of steam condensate cooler were developed. The model predicts the outlet temperature of the steam condensate cooler and its temperature change along the length of the cooler. In evaluating this model, developed model results were compared against industrial plant data of a fertilizer company and the percentage absolute error or deviation of hot and cold fluid outlet temperatures are 0.09% and 0.10% respectively. These results yield a close mapping between the developed model prediction and industrial data, thus developed model can be applied in simulating steam condensate cooler. Furthermore, the effects of change or variation in fluid inlet flow rate and heat transfer coefficient were also deduced.

Compliance with ethical standards

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Disclosure of conflict of interest

There is no conflict of interest in this research study

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