Design Procedure of Heat Recovery Unit for Combined Heat and Power System

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ABSTRACT

The purpose of this research is to put together a combined heat and power (CHP) system for the College of Engineering at the University of Louisiana at Lafayette by integrating the solar turbine unit with the Thermax absorption chiller. To achieve this, a heat exchanger is designed using a theoretical methodology called the Bell-Delaware method. This method helped obtain the basic dimensions of the heat exchanger. A general design procedure is developed and some of the design decisions are discussed. Future scope of the work includes constructing the heat exchanger designed in this work and the practical integration of the equipment, to finally setting up a CHP system that would meet the chilling needs of the university.

INTRODUCTION

The basis of a combined heat and power (CHP) system lies in efficiently capturing thermal energy and using it effectively. Generally in CHP systems, the exhaust gas from the prime mover is ducted to a heat exchanger to recover the thermal energy in the gas. The commonly used heat recovery systems are heat exchangers and heat recovery steam generators (HRSG) depending on whether hot water or steam is required. The heat exchanger is typically an air-to-water kind, where the exhaust gas flows over some form of tube-and-fin heat exchange surface and the heat from the exhaust gas is transferred to make hot water. Sometimes, a diverter or a flapper damper is used to maintain a specific design temperature of the hot water or steam generation rate by regulating the exhaust flow through the heat exchanger. The HRSG is essentially a boiler that captures the heat from the exhaust of a prime mover such as a combustion turbine, gas or diesel engine to make steam. Water is pumped and circulated through the tubes, which are heated by exhaust gases at temperatures ranging from 800°F to 1200°F. The water can then be held under high pressure to temperatures of 370°F or higher to produce high pressure steam.

There are many different factors in the design procedures of a combined heat and power (CHP) system. To meet specific needs of the CHP system, configurations can be altered to affect different factors of the design. Before the design process can begin, product specifications, such as steam or water pressures and temperatures, and equipment, such as absorption chillers and heat exchangers, need to be identified and defined. The Mechanical Engineering Department of the University of Louisiana at Lafayette received a donated 800-kW diesel turbine from Solar Turbines and a 100-ton Thermax absorption chiller from Coastal Engines. This equipment needs to be connected with a heat recovery unit to work as a CHP system, which can supplement the chilled water supply and electricity. The general specification needed for a CHP in university environment has been discussed in Reynolds et al. [1]. This objective of this article is to report on the design of the heat recovery unit to be integrated with the turbine and the chiller.

SYSTEM INTEGRATION AND HEAT RECOVERY DESIGN

Integration of a CHP system is generally at two levels—at the system level and at component level. Certain trade-offs between the component level metrics and system level metrics are required to achieve optimal integrated cooling, heating and power performance [2]. All CHP systems are mainly comprised of three components, power generating equipment or a turbine, a heat recovery unit, and a cooling device such as an absorption chiller. There are various parameters that need to be considered at the design stage of a CHP project. For instance, the chiller efficiency together with the plant size and the electric consumption of cooling towers and condenser water pumps are analyzed to achieve the overall system design [3]. Absorption chillers work great with micro turbines. A good example is the Rolex Reality building in New York, where a 150-kW unit is hooked up with an absorption chiller that provides chilled water. An advantage of absorption chillers is that they don't require any permits or emission treatment [4].

The HRSG is primarily a boiler that generates steam from the waste heat of a turbine to drive a steam turbine. The heat recovery boiler design for cogeneration process applications covers many parameters. The boiler could be designed as a fire-tube, water-tube or combination type. Further for each of these parameters, there is a variety of tube sizes and fin configurations. For a given boiler, a simplified method that determines the boiler performance has been developed [5]. The shell-and-tube heat exchanger is the most common and widely used heat exchanger in different industrial applications [6]. It is compared to a classic instrument in a concert playing all the important notes in different complex system set-ups and can be improved by using helical baffles. There are other ways to augment the heat transfer in a shell-and-tube exchanger such as through the use of wall-radiation [7].

The design of a shell-and-tube heat exchanger for a combined heat and power system basically involves determining its size or geometry by predicting the overall heat transfer coefficient (U). The process of obtaining the heat transfer coefficient values is obtained from literature by correlating results from previous findings in the determination of heat exchanger designs. This involves listing assumptions at the beginning of the procedure, obtaining fluid properties, calculation of Reynolds number and the flow area to obtain the shell-and-tube sizes. Once U is calculated, the heat balances are calculated. This study also compares the theoretical U values with the actual experimental ones to prove the theoretical assumptions and to obtain the optimum design model [8]. A mathematical simulation for the transient heat exchange of a shell-and-tube heat exchanger based on energy conservation and mass balance can be used to measure the performance.

Design of the heat exchanger is optimized with the objective function being the total entropy generation rate considering the heat transfer and the flow resistance [9]. Once a heat exchanger is designed, a total cost equation for the heat exchanger operation is deduced. Based on this, a program is developed for the optimal selection of shell-and-tube heat exchanger [10]. The heat exchanger to be used in the CHP system in the end needs to be tested for its performance. A heat recovery module for cogeneration is tested before use for CHP application through a microprocessor based control system to present the system design and performance data [11].

DESIGN PROCEDURE AND DECISIONS

A heat recovery unit in this CHP system is primarily a heat exchanger connected at the end of a turbine. This equipment is designed to reduce exhaust gas temperature of the solar turbine and provide the absorption chiller with water at the required temperature. The designing of any heat exchanger follows a basic design procedure, as shown in Figure 1. First of all the problem is identified by defining the flow rates, pressures, temperatures and physical properties of the two fluids. At this point, the basic configuration of the heat exchanger is decided. After that, a tentative set of parameters are set for the exchanger such as the tube type, layout, and shell diameter, etc. These tentative parameters are then used to determine the thermal performance by calculating the overall heat transfer coefficient. This leads to the determination of the total heat exchanger area required, which is compared to the area available that was initially chosen for the design. If the calculated area is close to the available area, the heat exchanger design is acceptable and then pressure drop calculations are performed. The pressure drops

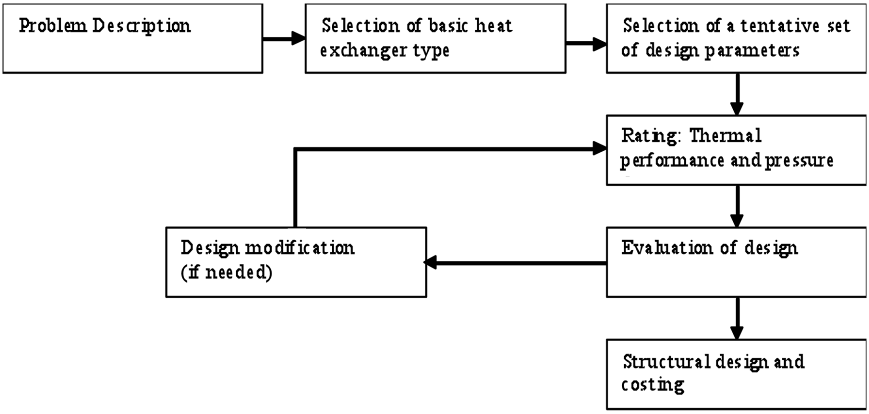

Figure 1. Heat Exchanger Design Procedure

should be within the permissible values preset beforehand.

In this research, a shell-and-tube heat exchanger is selected because it is the most widespread and commonly used heat exchanger configuration in industrial applications. The method we used to size the heat exchanger is the Bell-Delaware method [12].

Before the heat exchanger rating, there are some design decisions that have to be made. These included which stream goes into the tubes and which one goes into the shell, selection of the shell type and what kind of shell arrangement to use. Each of these decisions is approached as follows.

Allocations of Streams

Certain rules of thumb were used to determine where to put the water and where to let the exhaust gas flow. The first rule of thumb states that the fluid with the lower heat transfer coefficient is allocated to the shell side. This implied putting the exhaust gas in the shell side because it had a lower coefficient, as will be shown below. The second rule stated that the corrosive fluid should be placed in the tubes so that the shell doesn't have to be made of an anti-corrosive alloy, which means that the water goes in the tubes. Also as per the first rule, because the low coefficient fluid is in the shell, extended surface tubes aid in transferring the heat to the fluid to be heated.

Selection of Shell Type

The most important factor that governs the selection of a shell type is thermal stress. Thermal stress problem arises because the average temperature of the shell differs from that of the tubes resulting in the shell contracting or expanding relative to the tubes. The thermal stress problem involves a lot of complex calculations so again a few rules of thumb are used to determine the shell type. As per the first rule of thumb, a fixed tube heat exchanger is used only when the differences in the inlet temperatures of the two fluids is within a 100°F. Because the difference in this case is much higher (800°F – 175°F = 625°F), this eliminates the possibility of using a fixed tube heat exchanger. This is where a U-tube bundle comes into the picture. The U-tube design allows independent expansion of the tubes and shell. It solves the thermal expansion problem, but the problem of serviceability remains, i.e., how to clean or replace tubes. A pull through floating head is chosen in this design because of ease of maintenance.

Shell Arrangement

The best way to determine the number of shells needed is by plotting the inlet and exit temperatures of both the shell and the tube side fluid. A horizontal line is drawn from the hot fluid exit temperature on to the cold fluid line. From there a vertical line straight up to the hot fluid line is drawn. This process keeps on repeating until the inlet temperature of the cold fluid is reached. Then the number of horizontal lines represents the number of shells in series that are needed. Sample graphs can be found in [13]. No horizontal lines can be drawn between the two fluid lines, implying that only one shell is needed in this case. For a 1 shell configuration, there are n tube passes where n is an even number. So the heat exchanger designed so far is a 1-n configuration.

Extended Surfaces

Use of extended surfaces helps reduce the total length of the tubing required and therefore the size of the heat exchanger. A good example of extended surfaces is fins on tubes. Many heat recovery units use extended surfaces. When one of the film heat transfer coefficients is significantly smaller than the other, extended surfaces are used. The lower heat transfer coefficient dominates in the calculation of the overall heat transfer coefficient of the heat exchanger. As will be seen in the calculations, one heat transfer coefficient is much lower than the other, so this is an ideal case to use extended surfaces in the form of radial fins on tubes.

According to the Tubular Exchanger Manufacturers Association (TEMA) standards, a heat exchanger with one shell pass and n tube passes is called the TEMA E shell. It is the most common type of shell used because it is inexpensive, simple and easy to manufacture [12]. The shell fluid has entry and exit nozzles attached at opposite ends while the tubes are supported by transverse baffles.

Design Summary

A 21¼-in. shell diameter with 8 ft effective tube length and eight baffles spaced 11 in. apart has been designed for the CHP system as shown in Figure 2. The figure follows TEMA C class standards, which determine the mechanical standards for manufacturing of commercial and general process applications of moderate requirements. The heat exchanger, shown in Figure 2, is a TEMA-BET type, where B signifies that the front end is an integral bonnet cover, E means that there one shell

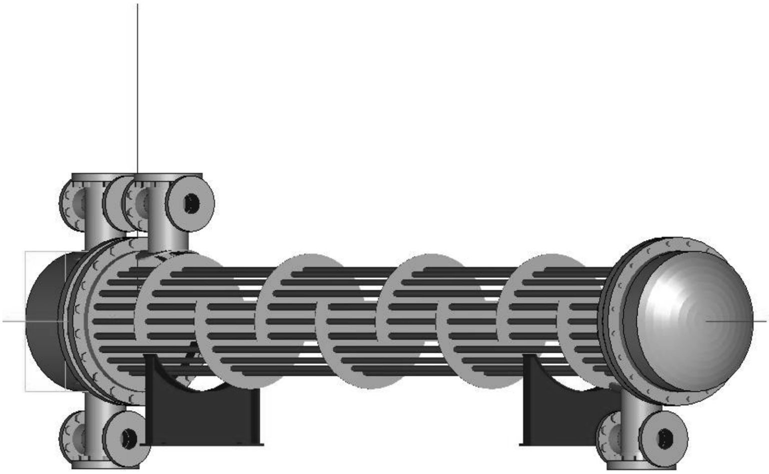

Figure 2. Design of the CHP Heat Exchanger

passes (as explained previously) and T represents that the rear end has a pull through floating head (also discussed earlier). This design solves the problem of expansion, where one tube sheet is fixed and the other is floating to accommodate the thermal expansion of the tube bundle. Software, called Pressure Vessel and Heat Exchanger Mechanical Design and Modeling, developed by Heat Transfer Consultants, Inc. has been used to generate the drawing of the final sized heat exchanger.

CONCLUSIONS

Integrating equipment to form a CHP system generally does not always present the best solution. In our case, the absorption chiller is not able to utilize all of the waste heat from the turbine exhaust. Approximately 65% of the waste heat goes out the stack. This is because the capacity of the chiller is too small compared to the turbine capacity. However, the need for extra space conditioning in the buildings considered remains an issue that can be resolved through the use of this CHP system.

The heat exchanger designed can either be constructed following the TEMA standards or it can be built and purchased from an industrial facility. The design that is used is based on the methodology of the Bell-Delaware method and the approach is purely theoretical. So the sizing may be slightly different in industrial design. Also the manufacturing feasibility needs to be checked. After the heat exchanger is constructed, the CHP equipment can be hooked together. Because the available equipment is integrated to work as a system, the efficiency of the CHP system needs to be calculated. A control module needs to be developed that can monitor the performance of the entire system. Finally, the cost of running the set-up needs to be determined along with the air-conditioning requirements.

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