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Thermal design and analysis of a shell and tube heat exchanger integrating a geothermal based organic Rankine cycle and parabolic trough solar collectors

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ABSTRACT

In this paper, the design and analysis of a shell and tube heat exchanger used to combine parabolic trough solar collectors (PTSCs) and an organic Rankine cycle (ORC) based geothermal power plant is presented. A thermal model for the PTSC was first used to find the temperature of the thermal oil entering the heat exchanger under different solar irradiation intensity. Then, a detailed thermal model for the shell and tube heat exchanger based on logarithmic mean temperature difference method was formed. A computer code was developed using Engineering Equation Solver to study the effect of some key design parameters on the heat transfer surface area of the heat exchanger and the pumping power. Furthermore, a two-stage Taguchi method was applied to find the design parameters that give the minimum heat transfer surface area and pumping power. In addition, the effect of the solar irradiation intensity on the optimum design parameters was assessed. The results show that the baffle spacing is the most dominant design parameter; and Therminol VP1 or Dowtherm A as the PTSC side fluid and R245fa or R600 as the ORC side fluid should be selected. In addition, it was found that when the solar irradiation intensity increases from 450 W/m^2 to 1000 W/m^2, the minimum heat transfer surface area increases from 2.644 m^2 to 8.681 m^2.

1. Introduction

Solar collectors absorb the incoming solar radiation and transfer the heat into a fluid (e.g. air, water, or thermal oil) that circulates through the tubes of the collector [1]. This fluid is then directly used or transfers its heat to another fluid for the desired purpose (e.g. production of power, hot water or steam). In order to reach higher temperatures at the collector outlet (also higher rate of useful heat transferred to the heat transfer fluid) with high thermodynamic efficiency, parabolic trough solar collectors (PTSCs) are generally preferred as compared to flat plate collectors [2]. PTSCs are light structures, have low cost, and are used for process heat applications between 50 °C and 400 °C [2,3]. These collectors are made of a reflective material sheet, which has a form of parabolic shape. The schematic of a PTSC and its layers are given in Fig. 1. As can be seen in this figure, the receiver (the tube shown in black color in Fig. 1b) is surrounded by a glass cover, which is used to reduce the undesirable heat losses. Collector performance, which depends on the design conditions and the type of materials used, is significantly affected by factors such as reflectivity and absorptivity of the receiver, the type and operating conditions of the heat transfer fluid, and the tracking mechanism [4,5].

Heat exchangers are typically classified according to the flow arrangement (e.g. parallel flow, counter-flow and cross-flow), number of fluids (one fluid or two fluids), and construction type (e.g. shell and tube, plate, and compact) [6–9]. Among the different types of heat exchangers, shell and tube heat exchangers are preferred for space heating, power production, and chemical processing applications. The main advantages of this heat exchanger type over other types can be listed as follows. There is substantial flexibility regarding their materials to accommodate corrosion and other concerns; they can be used in systems with higher operating temperatures and pressures; and tube leaks are easily located and plugged since pressure test is comparatively easy [10–12]. However, this heat exchanger requires more space; and cleaning and

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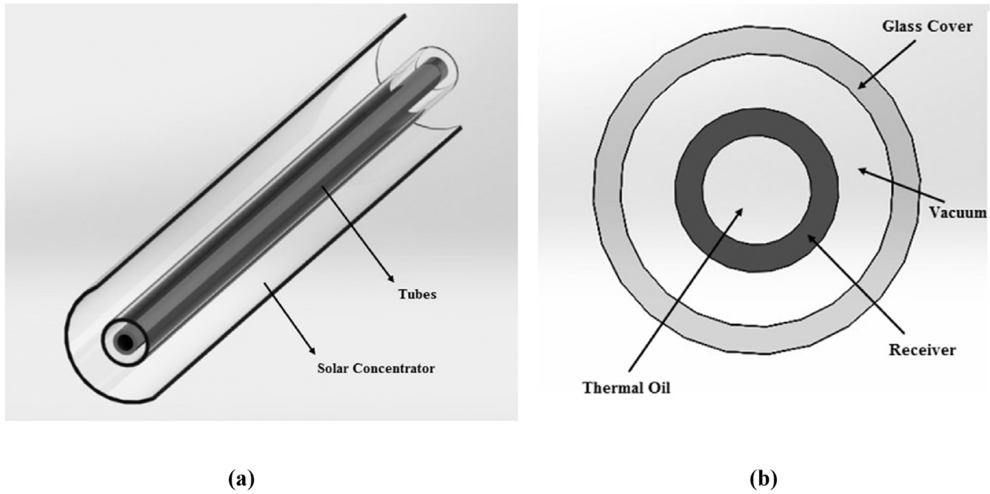

Fig. 1. Schematic of (a) the main components of the PTSC and (b) the cross section of the PTSC tubes.

maintenance are difficult since a tube requires sufficient amount of clearance at one end to remove the tube nest. Shell and tube heat exchangers are classified and built according to the widely used Tubular Exchange Manufactured Association (TEMA) standards [13]. This type of heat exchangers can be categorized according to the number of tube passes. The simplest form is one tube pass as shown in Fig. 2a. Two tube passes and three tube passes configurations are shown in Fig. 2b and c, respectively. Baffles are often installed to increase heat transfer coefficient of the shell side fluid. In addition, they are fixed to the tubes to reduce tube vibration.

The thermal design of shell and tube heat exchangers is done according to the principles of thermodynamics, heat transfer, and fluid dynamics. As a result of the design process, shell types, flow arrangement, geometry of the heat exchanger, and tube and shell materials are determined for the specified heat transfer. The mass flow rate of shell and tube side fluids, inlet temperatures, and outlet temperature of one of the fluids are generally used as input parameters in this type of design problem. There are some studies on the design, modeling, and optimization of the shell and tube heat exchangers in the literature. For example, Kara et al. [14] created 240 alternative exchanger configurations and the computer program that they developed selects the optimum configuration among the all possible exchanger configurations. The shell diameter, baffle spacing, number of pass are the parameters that can be changed in this program. The program then determines the overall dimensions of the shell and the optimum heat transfer surface area required to meet the specified heat transfer duty by calculating minimum or allowable shell-side pressure drop. The results of their study showed that triangular tube pitch layout with one or two tube pass yields the best performance. Reppich et al. [15] developed a computer based design model to determine the optimum dimensions of segmentally baffled shell and tube heat exchangers by calculating optimum shell side and tube side pressure drops using the equations provided in their work. The optimized design parameters were selected as number of tubes, tube length, shell diameter, number of baffles, baffle spacing, and baffle cut. The proposed model also includes a cost analysis. Selbas et al. [16] created a mathematical model of the heat exchanger, which was

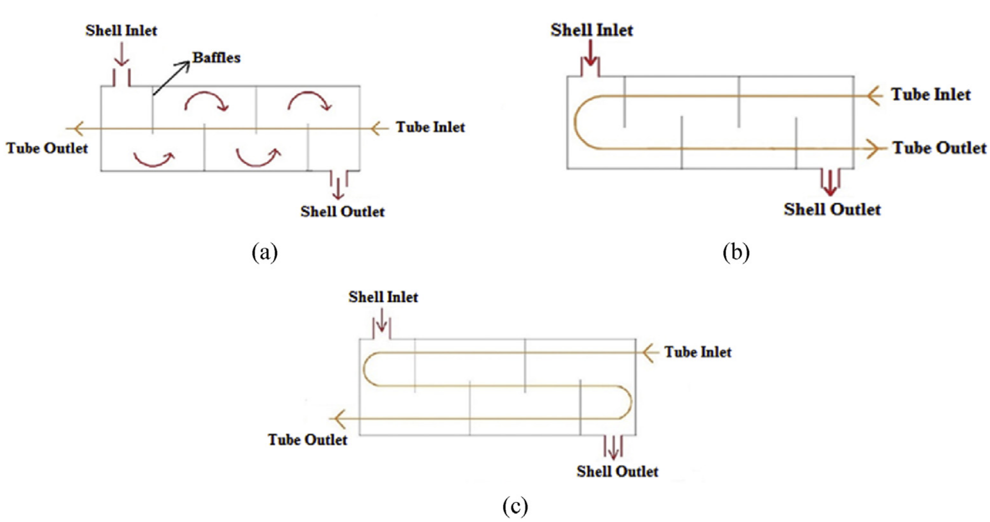

Fig. 2. Types of shell and tube heat exchangers: (a) one tube pass, (b) two tube passes, and (c) three tube passes.