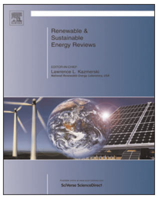
Renewable and Sustainable Energy Reviews 53 (2016) 500–514

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Layer pattern thermal design and optimization for multistream plate-fin heat exchangers—A review

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ARTICLE INFO

Article history:
Received 9 June 2015
Received in revised form
12 August 2015
Accepted 2 September 2015

Keywords:
Layer pattern
Multistream plate-fin heat exchangers
Design criterion and evaluation
Optimization design
Intelligent algorithm

ABSTRACT

Cryogenic processes involve air separation and liquefaction. To reduce energy consumption in these processes, many compact and efficient equipments that can handle fluid heat transfer have been developed. Of these, a multistream plate-fin heat exchanger is one of the best solutions. Studies of plate-fin heat exchangers are currently focusing on four areas: heat transfer calculation, surface analysis, flow resistance and design optimization. It is also important to optimize the layer patterns design of multi-stream plate-fin heat exchangers. Several techniques have been proposed for this purpose thus far; however, most of these are based on qualitative or trial-and-error approaches. Therefore, no universally accepted methodology exists designing for the layer pattern of multistream plate-fin heat exchangers. This article starts by reviewing traditional design approaches for multistream plate-fin heat exchangers and then focuses on the development of layer pattern design methods. It highlights three types of thermal design and evaluation criteria. It then discusses some suggestions and new methods for the optimization of the layer pattern design that have emerged in recent years. Further, newly emerging intelligent heuristic algorithms for optimizing the layer pattern thermal design are discussed. In addition to these basic design methodologies, the "layer pattern ring model" and "dual objective function" optimization methods developed by the author's research team are discussed. Finally, the status of this research area is summarized, and emerging trends are noted.

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http://dx.doi.org/10.1016/j.rser.2015.09.003
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1. Introduction

Cryogenic processes usually involve air liquefaction and separation. A large amount of energy is required to achieve cooling below 120 K in these processes [1,2]. Therefore, it is necessary to improve the thermal efficiency of cryogenic processes to avoid unnecessary energy consumption. Toward this end, improved technology and high-performance equipment are required. A multi-stream plate fin heat exchanger (MPFHE) is widely used in cryogenic processes [3,4], including those in the aerospace, petrochemical and industrial gas production industries [5,6], owing to its compact structure, high efficiency, low cost, and ease of handling multiple streams [7–9]. In air separation units and natural gas liquefaction plants, they represent 20–30% of the investment costs [10,11]. An MPFHE serves as an important hub connection between cryogenic processes and distillation compartments. Therefore, its performance directly affects the proper operation and performance of the entire cryogenic process. As a result, designers are strongly focusing on exploiting the advantages of MPFHE. Conventionally, a two-stream heat exchanger design can be divided into two categories: rating design and sizing design. In the rating simulation, the exit conditions of the fluid streams are estimated for a given heat exchanger geometry and known inlet conditions. On the other hand, in the sizing calculation, the geometrical details of the heat exchanger are determined for specified inlet and outlet stream temperatures. For multistream heat exchangers, mainly rating simulations have been tried thus far. The sizing design of multistream heat exchangers can be performed only under a limited scope. Obviously, for a multistream plate-fin heat exchanger, if the inlet and outlet temperatures of different fluid streams are specified, fixing the core dimensions and fin geometry becomes very difficult, and its success often depends on the experience and intuition of the designer. Compared with a two-stream heat exchanger, the combination of multiple streams in an MPFHE is similar to that in a heat exchanger network; furthermore, its structure is more compact and process is more complex. Many problems faced in a two-stream heat exchanger have not yet been explored, and many new features in the design optimization of an MPFHE are presented. For example, the quality of the layer pattern directly influences the overall MPFHE performance. When the layer arrangement deviates from the ideal layout, local heat load causes a large imbalance. The resulting temperature crossover and internal heat loss reduce the efficiency of the MPFHE. In severe cases, we cannot use sufficient backup heat transfer areas to compensate for the loss of efficiency [3]; in addition, local heat stress affects the structural strength and span life.

The layer pattern problem has proved difficult to solve because the many types of hot and cold fluids involved in the heat exchange lead to combinatorial explosion. It is impractical for a designer to analyze all permutations exhaustively. Moreover, the nonuniformity of the temperature field and the pressure field between the layers is coupled to each other, making it difficult to derive a theoretical general solution formula to design the layer pattern. In fact, designing the layer pattern of an MPFHE is an integer nonlinear optimization problem, and the conventional continuous variable optimization method cannot be employed. To optimize noncontinuous variables, it is necessary to perform many different layer pattern simulations. However, the number of simulations required to obtain optimized results increases with the number of layers. The traditional gradient-based optimization method is also not effective because direct contact cannot be established between different layer patterns and random layers [4]. This produces the nonuniform distribution phenomenon, making it impossible to avoid local optimal solution trap in the optimization process. Thus far, the layer pattern problem has remained the key difficulty to overcome in the design and optimization of an MPFHE.

To highlight the importance of layer pattern design, the general design flow of the MPFHE is briefly introduced. The present review mainly focuses on studies conducted on the means and methods for layer pattern design and optimization. The novel genetic-algorithm (GA)-based modeling and optimization approaches developed by the author's research group are also highlighted.

2. Brief overview of MPFHE design methodologies

An MPFHE can simultaneously handle many different streams for heat exchange owing to its structure. As shown in Fig. 1, the core of the MPFHE includes fins, headers and sheets. The interlayer between two adjacent parting sheets consists of heat transfer fins, distribution fins and a side bar. The manufacturer suitably stacks an arrangement of such layers based on different flow modes for each heat transfer stream and conducts vacuum brazing of the necessary headers, nozzles and structural support.

Cryogenic heat exchangers have traditionally been designed and rated using three models: lumped parameter, distributed parameter and stream evolution. Lumped parameter models represent the basic design theory for heat exchangers. They are based on the following energy balances for two single-phase streams and include the logarithmic mean temperature difference (LMTD) method, effectiveness-number of transfer units (ε-NTU) method, and so on [13]. Distributed parameter models are based on dividing the heat exchangers into elements of variable size and applying a lumped parameter model to each of them; they are widely used for applications with cryogenic heat exchangers, such as complex geometries and two-phase stream systems [14]. Stream evolution models are based on steady-state one-dimensional mass, momentum and energy balance equations for each individual stream. These models are usually implemented in proprietary software [15], and their key features are related to the correlations used for fluid properties and heat transfer and pressure drop characteristics.

2.1. Heat transfer design

The heat transfer design of a plate-fin heat exchanger mainly includes thermal property matching, determining the heat transfer temperature difference, heat load checking, reasonable reconstruction of temperature field in heat exchanger and model engineering considerations. Conventionally, the heat exchanger design can be of two types [13]: rating design and sizing design using LMTD and ε-NTU. Fig. 2 shows the common heat transfer design flow of heat exchangers. However, as the multistream thermal

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