Applied Thermal Engineering 73 (2014) 963–974

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Passage arrangement optimization of multi-stream plate-fin heat exchangers

Qiqi Tian [a], Guogeng He [a, *], Linshan Zhao [a], Dehua Cai [a], Liping Chen [b]

[a] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan, China
[b] CAD Center, Huazhong University of Science and Technology, Wuhan, China

HIGHLIGHTS

- A passage arrangement method by minimizing cumulative heat load is presented.
- Mean square error of cumulative heat load is reduced by 2.9% than previous research.
- A further improvement scheme is proposed based on heat transfer simulation.
- Outlet temperature distribution becomes more uniform after improvement.

ARTICLE INFO

Article history:
Received 22 April 2014
Accepted 25 August 2014
Available online 3 September 2014

Keywords:
Passage arrangement
Multi-stream plate-fin heat exchanger
Cumulative heat load
Parameter-distributed model

ABSTRACT

Passage arrangement quality is of great significance for the heat transfer performance of multi-stream plate-fin heat exchangers. In the present paper, a passage arrangement method is presented on the basis of minimizing the cumulative heat load to bring convenience for passage arrangements and to improve the heat transfer performance. The passage arrangement results are compared with that of the previous research, indicating 2.9% reduction of the mean square error of the cumulative heat load. For further improvement of the passage arrangement quality, the temperature profiles of the heat exchangers are obtained by applying the distributed-parameter model, based on which a further scheme for optimization is proposed. By carrying out the optimization, the outlet temperature inhomogeneity of the air stream, the waste nitrogen stream and the nitrogen stream are reduced by 7.8%, 4.1% and 82.0% respectively, indicating better heat transfer performance.

1. Introduction

Plate-fin heat exchangers are widely used in industry due to the high heat transfer efficiency, high compactness, light weight and wide range of applications. For the air separation unit (ASU), the plate-fin heat exchanger is the key equipment for heat transfer in order to save energy, and several streams are involved in the heat exchange of ASUs, including the air stream, the cryogenic nitrogen stream, the cryogenic oxygen stream and the cryogenic waste nitrogen stream. Each stream is divided and assigned to a number of passages of the heat exchangers. The passage arrangement is important for the heat exchange performance among the streams of air, nitrogen, oxygen and waste nitrogen, since a bad arrangement may result in the unbalance of local heat load and even temperature crossover [1] among passages, reducing the heat transfer efficiency.

Much research has been devoted to the plate-fin heat exchangers on the heat transfer [2–4], flow distribution of the header [5–8], fin efficiency and correlations [9–11], new algorithms and methods for design [12–20].

The optimal design, which is important for structure improvement and performance enhancement, is extensively researched in general thermal systems. These research covers conductive systems [21–24], convective systems [13–15,25–28] and radiative systems [29]. For example, Hajmohammadi et al. [21,28] proposed fork-shaped highly conductive pathways that effectively reduce the hot spot temperature, and conducted the optimization on unequal heat flux elements in a rectangular duct that remarkably minimize the maximum temperature. Najafi et al. [13] used multi-objective optimization with genetic algorithm to successfully achieve a set of optimal solutions. Kotcioglu et al. [14] investigated the effects of

* Corresponding author. Tel.: +86 2787542718x601; fax: +86 2787540724.
E-mail addresses: tianqiqi@hust.edu.cn, tianqiqihust@gmail.com (Q. Tian), gghe@hust.edu.cn (G. He).

http://dx.doi.org/10.1016/j.applthermaleng.2014.08.055
1359-4311/

six parameters on plate-fin heat exchangers by using Taguchi method, and achieved minimum pressure drop and maximum heat transfer.

However, at present, the studies conducted on the optimal design on passage arrangement of plate-fin heat exchangers are only a few. Suessmann et al. [30] proposed the basic principles of passage arrangement from the perspective of local heat load balance, which indicate that for a good quality of passage arrangements the cumulative heat load should be in a zigzag pattern, i.e., fluctuating above and below zero alternately, and the zigzag pattern is also demonstrated by Ghosh [31] by using a genetic algorithm and Yan [32] by using a two-step method. Prasad [33] discussed the advantages of symmetric passage over the segregated arrangement, and presented a method for assessing the relative merits of passage arrangements.

For the passage arrangement of multi-stream plate-fin heat exchanger, it still remains at semi-empirical, empirical or trial-and-error stage, lacking efficient approaches to obtain the optimum [19]. To solve the problem, a detailed scheme for passage arrangement of multi-stream plate-fin heat exchanger is proposed in the present paper, which may bring convenience and simplify the process of passage arrangements. By using the method, a relatively small mean square error of cumulative heat load can be obtained. Moreover, a distributed-parameter heat transfer model is built to obtain the simulation results, based on which an approach is proposed to further improve the passage arrangement quality.

2. Methodology

2.1. Main methods for passage arrangement

Two different methods are generally used in the passage arrangement of multi-stream plate-fin heat exchangers. One is the passage-segregated method [1], of which the main principles of the method can be drawn as follows:

(1) The cold passage and the hot passage are arranged alternatively, which means that a cold passage is segregated by two hot passages and a hot passage is also segregated by two cold passages.
(2) The passages of the same stream are suggested to be arranged relatively together.

Compared with the method of balance of the local heat load, the passage-segregated method is beneficial to reduce the internal dissipation of heat and to avoid temperature crossover. For the passage-segregated method, the hot streams and cold streams are required to have the same quantity of passages, and the hot stream and cold stream can thus be arranged segregated, i.e., each hot passage is followed by a cold passage.

However, for the plate-fin heat exchangers in the air separation units, the hot stream (air stream from the molecular sieve adsorber) and the cold streams (oxygen stream, nitrogen stream and waste nitrogen stream from the cryogenic distillation columns) have different quantity of passages in most cases. For example, in the literature [34] validated in the present paper, the plate-fin heat exchanger have a total passage number of 93, of which 34 is assigned to the hot stream (air stream), and 59 is assigned to the cold streams (waste nitrogen: 34; oxygen: 11; nitrogen: 14). In this case, the passage-segregated method is inappropriate, since a number of $59 - 34 = 25$ passages will become redundant. If the hot passage quantity is increased forcibly to meet the quantity requirement, the mass flow rate in hot passages will decrease, reducing the heat transfer coefficient. Therefore, in the present paper, the method of balance of local heat load is employed.

The balance of local heat load proposed by Suessmann et al. [30], of which the main idea can be drawn as follows:

(1) The calculation of the plate-fin heat exchanger is based on the assumption that the walls in the same cross section have nearly the same temperature.
(2) The cross section can be divided to a number of basic units. In each basic unit the heat load balance can be achieved, which means that the heat exchange only occurs inside the basic unit instead of occurring among different units.
(3) In the basic unit, the algebraic sum of the heat load in each passage is called the excess heat load, and the integral mean value of it is the mean value of the excess heat load. A half length of the basic unit is the transferring distance. Larger excess heat loads and transferring distance correspond to more obvious effects on stream temperature and wall temperature. The excess heat load and transferring distance should be minimized.

The second method is mainly based on qualitative and semi-empirical analysis, and detailed schemes for practical design are not presented. This method only provides a general principle that the excess heat load should be minimized for passage arrangement. In the present paper, a detailed scheme is presented in Section 2.2 based on the second method to implement the passage arrangement. The temperature crossover mentioned above is substantially induced by the heat load unbalance throughout the heat exchanger. For the scheme used in the present paper, when each passage is arranged, all possible arrangements are considered to find out the minimal cumulative heat load, of which the purpose is to minimize the heat load unbalance and reduce the temperature crossover throughout the heat exchangers.

2.2. Implementation of passage arrangement

In this section, the method for passage arrangements is presented and discussed in detail, including the pre-determination of the passage quantity for each stream, the modification of the passage quantity by verifying the pressure drop and the length deviation, and the detailed passage arrangement scheme.

2.2.1. Pre-determination of passage quantity

The total quantity of passages is given by

$$N_j = \frac{V_j \rho_j}{3600 g_j A_f} \tag{1}$$

where g_j is the mass flow rate of stream j in each passage (kg m^{-2} s^{-1}); V_j is the total volume flow rate of all passages for stream i in standard state (Nm^3 h^{-1}); ρ_j denotes the density of fluid i in standard state (kg m^{-3}); N_j denotes the total passage quantity for stream i; and A_f denotes the section area of each passage (m^2).

However, the determination method of variable g_j is not given in most of the previous research, and hence the number of passages is often determined by experience, or is given directly with a fixed number. In the heat exchangers of the ASU, there is a proper range for the mass flow rate of streams in each passage, which is generally about 6 kg m^{-2} s^{-1} to 12 kg m^{-2} s^{-1}. In the present paper, the mass flow rate is initially set as the maximum value 12 kg m^{-2} s^{-1}, and then the initial value of the passage quantity for each stream, the heat transfer coefficient, the heat exchanger length and the pressure losses can be figured out, which is discussed below.

The Renault number for each stream is given by