

TITLE:

Heat Exchanger Perforated Fins

BACKGROUND

[0001] Plate fin heat exchangers are generally used for exchanging heat between process streams for the purpose of heating, cooling, boiling, evaporating, or condensing the process streams. The process conditions in these heat exchangers may involve single phase or two phase flow and heat transfer. While some plate fin exchangers contain only two streams, others contain multiple streams in multiple sets of plate fin passages. Individual streams may be fed into and withdrawn from the heat exchanger using nozzles and headers. Each stream flows into specific plate-fin passages allocated within the bank of adjacent plate-fin passages. The individual plate-fin passages are contained between pairs of parting sheets, which are spaced apart by the fins and the plate-fin passages are enclosed on the outer periphery by sidebars and endbars so they can be isolated from each other and can contain the fluids of interest. When streams at different temperatures flow in the plate-fin passages that are adjacent to each other, they exchange heat through the parting sheets which are referred to as primary heat transfer surfaces as well as the fin legs that separate them, which are referred to as secondary heat transfer surfaces.

[0002] Plate fin exchangers may be formed by using many different types of fins such as plain, perforated, serrated and wavy. One embodiment of the current invention deals with perforated fins which have been employed in the industry, but in an inefficient manner. The plate fin heat exchangers having perforated fins, according to the present invention, have particular application in cryogenic processes such as air separation, although these plate fin heat exchangers may be used in other heat transfer processes.

[0003] When a stream or fluid enters a plate fin heat exchanger channel it exhibits high heat transfer coefficients due to the well-known entrance effect. Post entrance effect, the stream or fluid will soon reach a steady state condition with a much lower heat transfer coefficient. In particular when the flow is characterized as being in a turbulent state or in a transition state between laminar and turbulent states, laminar and viscous boundary layers are known to form adjacent to all the surfaces that the fluid flows along.

The overall effect is to lower the average heat transfer coefficients in such an exchanger. The lower heat transfer coefficient condition can be at least partially reversed by periodically disturbing this boundary layer through a variety of means such as, for example, introduction of perforations or serrations in the fins. Introduction of perforations or serrations in the fins will increase the heat transfer performance, however, such introduction will also increase pressure losses and, therefore, the geometry and arrangement of the perforations or serrations in the fins is critical for achieving improved performance. It is particularly important in the case of perforated fins because while they disturb the flow leading to an increase in the local heat transfer coefficient proximate to the perforations, introduction of perforations in the fins also results in a loss of surface area from the original material which would otherwise have been beneficial for the overall heat transfer from the heat exchanger. Also removal of metal, for example, in the form of perforations can greatly reduce the strength of the remaining material. Thus, the problem of improving the performance of plate fin heat exchangers by using perforated fins is complicated and it is particularly important to organize the geometry and arrangements of using such perforations to achieve improved performance.

[0004] Historically, publications concerning plate fin heat exchangers provided general descriptions of the overall geometry and the elementary methods for the manufacture of plate fin heat exchangers. While these publications discuss the many constituent parts of plate fin heat exchangers, their relationship to one another, and how they are assembled and brazed together, the publications are brief in their description of the perforated fins that may be utilized in such plate fin heat exchangers. Even in cases where some nominal details are disclosed, the publications simply fail to discuss any preferred geometry and patterns to use.

[0005] For example, in "Aluminum Brazed Plate Fin Heat Exchangers for Process Industries," a chapter of *Compact Heat Exchangers for the Process Industries*, edited by R.K. Shah, proceedings of the International Conference for the Process Industries, held at Cliff Lodge and Conference Center, Snowbird, Utah, June 22-27, 1997, by Shozo Hotta from Sumitomo Precision Products (SPP), a general description of plate fin heat exchangers by SPP, a major supplier of such heat exchangers, is disclosed. Specifically, Figure 4 on page 181 of such reference provides photographic evidence of the common fin types including perforated fins. As described and taught therein, the perforated fins are formed by folding a sheet with regularly perforated small round

apertures or perforations at some large angle relative to a major axis of perforations on the flat sheet. No further details, however, are presented.

5 **[0006]** This method of manufacture is very common in the industry to minimize the overall cost. A few standard perforated sheet materials may be used to produce a wide range of finished fins with varying dimensions. This type of method of manufacture of perforated fins, however, leads to an irregular arrangement of the perforations on the fins resulting in poor performance of the perforated fins.

10 **[0007]** U.S. Patent No. 6,834,515 B2, entitled "Plate Fin Exchangers with Textured Surfaces," to Sunder et al., also discloses various perforated fins. The Sunder patent teaches use of surface texture to enhance the performance of other perforated fins. Figure 2B of the Sunder patent illustrates exemplary fins with a row of perforations along the top and sides of the fins where the perforations are laterally aligned. Example 1 of the Sunder patent states that the perforated fins have an open area of about 10%. No other details, however, are provided regarding the perforations.

15 **[0008]** U.S. Patent No. 5,603,376, entitled "Heat Exchanger for Electronics Cabinet," to Hendrix, describes a heat exchanger for passive heat exchange between a weather-tight, sealed electronics cabinet, and the outside environment. Figure 2 of the Hendrix patent shows heat generation side fins 21 with perforations 25 contained therein. The Hendrix patent teaches that fins 21 are formed by pleating or folding perforated sheet material. The perforations are said to be perpendicular to the direction of the folds. Figure 2 of the Hendrix patent illustrates that the perforations are a single row of perforations along the sides of fins 21, however, no perforations are shown on the underside where the valleys or crests of the waves would form. Further, the Hendrix patent provides no teaching regarding the position of the perforations.

25 **[0009]** In "Three-dimensional numerical simulation on the laminar flow and heat transfer in four basic fins of plate-fin heat exchangers", by Y. Zhu and Y. Li, *Journal of Heat Transfer*, November 2008, vol. 130, 111801-1 to 8, a Computational Fluid Dynamics (CFD) based calculation is performed concerning the performance of four samples (plain, perforated, strip offset (which is another term for serrated) and wavy fins) is disclosed. The Zhu and Li paper lists many major publications on compact heat exchangers that have appeared since they were first introduced, and goes on to state that, "[t]o the best of the authors' knowledge, complete three-dimensional flow and heat transfer in the perforated fins have received scant attention in literature."

[0010] Such statement is significant and appears to support and lead to the conclusion of Applicants, namely that what is known in the art concerning perforated fins is sub-optimal.

[0011] As part of comparing the four types of fins, the authors of the Zhu and Li paper conducted CFD calculations on one specific exemplary perforated fin geometry. To keep the computation size and time reasonable, the authors only included a minimum repeating structure as illustrated in Figures 2a and 2b on page 2 of the paper. The cross section modeled for the perforated fin represents one half of a wavelength of a fin, which includes a half each of the top and bottom fin lengths and one full fin height. These in turn include a series of half perforations on the top and bottom and a series of full perforations on the fin height all along the flow length. The full structure, also as illustrated in Figure 1D, corresponds to exactly one row of perforations along the top, bottom, and side of each fin channel along the flow length, all of which are laterally aligned. The diameter of the perforations is 0.8 mm as illustrated in Table 1 and the spacing of the perforations along the fins appears to be approximately 1.4 mm from center to center as can be inferred from Figures 6C and 7C. This frequency of perforations represents approximately 16% open area on only the sides of the plate fin passages (*i.e.*, the Zhu and Li paper does not count or consider the perforations on the top or the bottom of the fins for determining open area because fins perforations on the top and bottom of the fins are covered by the parting sheets). This open area determination is illustrated in Table 1 under the column on specifications. Such a pattern would work out to approximately 20% open area on the flat perforated sheet prior to its being formed into fins. It appears that this geometry represents a typical case the authors chose to model with no indication or teaching as to what they might consider preferred in terms of perforation patterns and geometry.

[0012] Thus, the one specific exemplary perforated fin geometry described above is merely a representative perforated fin that the authors used to compare against the four types of fins (plain, perforated, strip offset and wavy types). The pattern and geometry the authors modeled are different from those taught under the current application.

[0013] In summary, prior descriptions concerning perforated fins were brief in the details concerning the geometry of the perforated fins used in plate fin exchangers. And even when aspects of the geometry such as open area were cited, there is no teaching on how to position the perforations or how to select the best geometry for the

perforations to obtain the best performance so that the overall capital and operating costs of the plate fin heat exchangers may be minimized.

[0014] It is desired to increase the efficiency and improve the performance of plate-fin heat exchangers.

- 5 **[0015]** It is further desired to improve the turbulence characteristics of a single phase stream within the plate-fin passages of a plate-fin exchanger in order to improve the heat transfer efficiency.

- 10 **[0016]** It is still further desired to have a plate-fin exchanger that exhibits high performance characteristics for cryogenic applications, such as those used in air separation, and for other heat transfer applications.

[0017] It is still further desired to have a more efficient air separation process utilizing a plate-fin exchanger which is more compact and/or more efficient than previously disclosed.

- 15 **[0018]** It is still further desired to have a plate-fin exchanger design which minimizes the size, weight, and/or cost of the heat exchangers, which would result in an air separation process more efficient and/or less expensive per unit quantity of product produced.

- 20 **[0019]** It also is further desired to have a method for assembling a plate-fin heat exchanger which uses fins with perforation patterns and geometry that affords better performance than the fins previously disclosed, and which overcomes the disadvantages of the fins previously disclosed to provide better and more advantageous results.

SUMMARY

- 25 **[0020]** The disclosed embodiments satisfy the need in the art by providing novel patterns and novel geometry of fin perforations for use in plate fin heat exchangers to maximize the overall heat transfer performance within the allowable pressure drop constraints. The benefits of such novel patterns and novel geometry of fin perforations over previously disclosed fin patterns and geometry include: (1) a significant reduction in the volume; (2) a significant increase in heat transfer efficiency; (3) a significant reduction in pressure drop losses; or (4) some judicious combination of factors (1) to (3)
- 30 such that the overall capital and operating cost of the heat exchanger system is reduced, thereby also reducing the capital and operating cost of the process that utilizes such a heat exchanger system.

[0021] While the disclosed embodiments contained herein are mainly aimed at easyway fins, wherein the flow is largely parallel to the fin flow channels, the teachings may also be applicable to distribution fins, which simultaneously perform some heat transfer function and wherein the flow is predominantly, but not exclusively, parallel to the fin flow channels. The embodiments disclosed herein are particularly suitable for applications in which the fluid streams experience heat transfer without any phase change over at least 80% of the flow length, more preferably over at least 90% of the flow length, and most preferably over 100% of the flow length within the plate-fin passages of the plate fin exchanger, for example, containing fin channels with the perforation patterns and geometry disclosed herein.

[0022] In a first embodiment a plate fin heat exchanger is disclosed comprising a folded fin sheet comprising fins having a height, a width, and a length, the folded fin sheet being positioned between a first parting sheet and a second parting sheet; and a first side bar and a second side bar, wherein the first side bar is positioned between the first parting sheet and the second parting sheet and adjacent to a first side of the folded fin sheet, and wherein the second side bar is positioned between the first parting sheet and the second parting and adjacent to a second side of the folded fin sheet thereby forming at least a part of a plate fin passage; wherein the fin sheet comprises a plurality of perforations, such plurality of perforations are positioned on the fin sheet in parallel rows when such fin sheet is in an unfolded state, such parallel rows of perforations on the fin sheet comprise a first spacing between the parallel rows of perforations (S1), a second spacing between sequential perforations within the parallel row of perforations (S2), a third spacing (or offset) between the perforations in adjacent parallel rows of perforations (S3), and a perforation diameter (D), wherein the ratio of the first spacing between the parallel rows of perforations to the perforation diameter (S1/D) is in the range of 0.75 to 2.0, and wherein the angle between the fins and the parallel rows of perforations is less than or equal to five degrees ($\leq 5^\circ$).

[0023] In a second embodiment a process for exchanging heat between at least two streams in a plate fin heat exchanger in accordance with the first embodiment is disclosed, wherein at least one stream undergoes heat transfer without phase change over at least 80% of the length of the plate-fin passages, and wherein the Reynolds Number of the at least one stream is in the range of 800 to 100,000 and more preferably in the range of 1,000 to 10,000.

[0024] In a third embodiment, a process for separating nitrogen, oxygen and/or argon from air by cryogenic distillation, which utilizes the plate fin heat exchanger in accordance with the first embodiment is disclosed, wherein at least one stream undergoes heat transfer without phase change over at least 80% of the length of the plate-fin passages, more preferably over at least 90% of the length of the plate-fin passages, and most preferably over 100% of the length of plate-fin passages.

[0025] In a fourth embodiment, a method for manufacturing a plate fin heat exchanger is disclosed, which comprises the steps of: providing at least one perforated sheet, the at least one perforated sheet comprising a plurality of perforations arranged in parallel rows, wherein such parallel rows of perforations on the perforated sheet comprise a first spacing between the parallel rows of perforations (S1), a second spacing between sequential perforations within the parallel row of perforations (S2), a third spacing (or offset) between the perforations in adjacent parallel rows of perforations (S3), and a perforation diameter (D), wherein the ratio of the first spacing between the parallel rows of perforations to the perforation diameter (S1/D) is in the range of 0.75 to 2.0; folding the at least one perforated sheet into fins to form a folded perforated sheet such that the angle between the fins and the parallel rows of perforations is less than or equal to five degrees ($\leq 5^\circ$); positioning a first side bar adjacent to a first side of the at least one folded perforated sheet, a second side bar adjacent to a second side of the at least one folded perforated sheet, a first distributor fin adjacent to a first end of the at least one folded perforated sheet, a second distributor fin adjacent to a second end of the at least one folded perforated sheet, a first endbar adjacent to the first distributor fin, and a second endbar adjacent to the second distributor fin to form a preliminary plate fin passage; placing the preliminary plate fin passage of step (c) between a first parting sheet and a second parting sheet thereby forming a plate fin passage therebetween; combining the plate fin passage of step (d) with other plate fin passages to form the plate fin heat exchanger; and brazing the plate fin heat exchanger.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[0026] The foregoing summary, as well as the following detailed description of exemplary embodiments, is better understood when read in conjunction with the appended drawings. For the purpose of illustrating embodiments, there is shown in the drawings exemplary constructions; however, the invention is not limited to the specific methods and instrumentalities disclosed. In the drawings:

[0027] Figure 1 is an exploded perspective view of a basic element or sub-assembly of a plate-fin heat exchanger with fins having a perforation pattern and geometry according to one embodiment of the present invention;

5 [0028] Figure 2 is a schematic diagram illustrating an embodiment of the perforation pattern on a flattened plate prior to their being formed into fins according to the present invention; and

[0029] Figure 3 is a graph illustrating the relative heat transfer and pressure loss performance of perforated fins as a function of S1/D with an indication of the preferred range.

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DETAILED DESCRIPTION

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[0030] One embodiment of the current invention relates to plate fin exchangers that comprise perforated fins in at least a portion of the plate-fin passages and to the methods for assembling such plate fin exchangers. The perforated fins are assembled using flat perforated sheets. The formed fins have a special relationship to the perforation pattern on the flat sheet. While some plate-fin passages have the aforesaid fins, other plate-fin passages may have different types of fins, including plain, perforated, strip offset and wavy types, for example. Plate-fin heat exchangers that comprise such perforated fins have particular application in cryogenic processes such as air separation, although they may also be used in other heat transfer processes.

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[0031] Referring to Figure 1, a plate-fin heat exchanger of the current invention comprises several plate fin passages, some of which are made by placing at least one fin sheet 10 in between parting sheets or plates 30,40 sidebars 50,60, distributing fins (not shown but generally known in the art) and endbars (not shown but generally known in the art). These plate-fin passages comprise special patterns of perforations 20 in at least some portion of such plate-fin passages.

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[0032] Prior to being formed into the fin sheet 10 as illustrated in Figure 1, the fin sheet 10 is a flattened sheet made of a metal such as aluminum, copper, another alloy, or any other heat conducting material known in the art for fabrication of fins. The flattened fin sheet 10, as illustrated in Figure 2, comprises the perforations 20. The flattened sheet has special perforation patterns comprising several parallel rows of perforations 100,200,300 with each parallel row 100,200,300 comprising perforations 1A,1B,1C; 2A,2B,2C; and 3A,3B,3C. In one embodiment, the rows of perforations 1A,1B,1C;

2A,2B,2C; and 3A,3B,3C will align in a direction that is parallel to the desired direction of the fins when the flattened sheet is folded to form the fin sheet 10 as depicted in the Figure 1. When the fins are employed as easyway fins, the nominal stream lines of the flow will be parallel to the direction of perforations as illustrated in Figure 2.

5 **[0033]** As illustrated in Figure 2, the perforations have a diameter (D). The spacing between parallel rows of perforations 100, 200, 300 is designated S1 while the spacing between sequential perforations (i.e., between perforation 2A and 2B) in the stream flow direction is designated as S2. The offset between perforations in adjacent parallel rows 100, 200, 300 (i.e. between 2A and 3A) is designated as S3.

10 **[0034]** In one embodiment, Applicants found with surprising result that when the following parameters are held within the following ranges: (1) perforation diameters D in the range of 1 mm to 4 mm; (2) open area in the range of 5% to 25%; (3) the ratio S3/S2 in the range of 0.25 – 0.75; (4) and the ratio S1/D in the range of 0.75 to 2.0 with a most preferred range of 0.75 to 1.0, the plate-fin heat exchangers exhibited higher efficiencies
15 and improved the performance compared with traditional heat exchangers not designed accordingly.

20 **[0035]** In the most preferred arrangement/embodiment, the fluid flow direction is parallel to the parallel rows of perforations 100,200,300, but in a preferred arrangement/embodiment the direction of fluid flow is within five degrees (5%) to the direction of the parallel rows of perforations 100,200,300. This means that as the fins are formed, the fin sheet 10 should be folded such that the angle between the fin folds and such parallel rows of perforations 100,200,300 is less than or equal to five degrees, while the most preferred arrangement is where such angle is zero degrees (0°).

25 **[0036]** The fin sheets 10 may comprise perforations 20 that are circular as illustrated in Figures 1 and 2, however, those skilled in the art will recognize that non-circular perforations may also be used including, but not limited to perforations in the shape of ellipses, rectangles, parallelograms, and other such shapes.

30 **[0037]** In yet another embodiment, the arrangement of the offset rows of perforations will repeat every two rows as illustrated in Figure 2 (i.e., Row 100 shall be offset similar to Row 300, 500 (not shown), 700 (not shown), etc.). Further, when the flat perforated sheets are folded into fins in a finning operation, the structure of perforations that result on the finished fin sheet 10 tend to have a complex relationship because of the mechanical details of how the material flows in the finning dies. In one embodiment, the

flattened sheet is folded such that the perforation patterns on the finished fin sheet 10 repeat at least once every ten (10) fin wavelengths and more preferably at least once every five (5) fin wavelengths, in at least fifty percent (50%) of the heat exchanger plate-fin passages containing such perforated fins, more preferably in at least eighty percent 5 (80%) of the plate-fin passages and most preferably in one-hundred percent (100%) of the plate-fin passages.

[0038] In a further embodiment, surface texture may be applied to the perforated sheets prior to the material being folded into fins as taught by U.S. Patent No. 6,834,515 B2, entitled "Plate Fin Exchangers with Textured Surfaces," to Sunder et al., that is 10 incorporated by reference in its entirety. Alternatively the surface texture may be created in the process of creating the fins from the flat perforated sheets.

[0039] The embodiments described herein are suitable for plate fin heat exchangers wherein at least a portion of the fins have a height in the range of 0.25 inches to 1 inch (.635 centimeters to 2.54 centimeters), more preferably in the range of 0.40 inches to 15 0.75 inches (1.016 centimeters to 1.905 centimeters) and most preferably in the range of 0.5 inches to 0.6 inches (1.27 centimeters to 1.524 centimeters). The embodiments are advantageously applied when the fluid flow conditions in such plate fin passages are in a transition state between laminar and turbulent states or in a turbulent state. This may be expressed as a Reynolds Number range of 800 to 100,000 and more preferably a range 20 of 1,000 to 10,000. The Reynolds Number is calculated as follows:

$$Re = \rho V D / \mu, \text{ where}$$

Where,

Re = Reynolds number;

ρ = fluid density;

25 V = fluid velocity;

μ = fluid viscosity;

$D = 4A/P$;

A = fluid flow cross sectional area; and

P = fluid flow perimeter

30 For plate-fin passages, it is common to calculate the hydraulic diameter D based on individual plate-fin passages and the current calculations are based on using the base

metal sheets without adjusting for the perforations for their contributions to the A (fluid flow cross sectional area) and P (fluid flow perimeter).

5 [0040] Embodiments of the present invention have significant value because plate fin heat exchangers may be made more compact relative to conventional plate-fin exchangers, thus, saving combined capital and operating costs of the plant, such as an air separation plant.

EXAMPLE 1

10 [0041] To better understand the influence of the perforations within the fin geometry, several sample problems were solved using Computational Fluid Dynamics (CFD). In using this technique, it is common to restrict the computation to some repeating structure in order to limit the computational size of the problem. But when one tries to quantify the effect of specific perforation patterns, the overall geometry of the heat exchanger is very complicated, even when one limits the problem to a single subchannel within plate-fin passages. For this reason a different type of approximation was used.

15 [0042] In most plate fin exchangers the secondary surface area tends to be the dominant fraction of the total area. As noted before, this is the area represented by the fin legs that span and separate the parting sheets or plates 30,40 that represent the primary surface area. To understand the effect of the positioning of the perforations, a representative periodic area of two infinite parallel plates was modeled to quantify the heat transfer and pressure losses that occur when air flows between them. The general scheme of the perforations on the flattened sheet is illustrated in Figure 2.

[0043] Example 1 concerns easyway fins that are used for heat transfer and/or distribution purposes, wherein, as previously stated, the direction of flow is generally parallel to the fin direction as indicated in Figure 2.

25 [0044] A number of exemplary cases were solved using CFD, wherein the various spacings (S1, S2, and S3) were varied while keeping the diameter (D) of the perforations and the overall open area constant. Specifically, spacings S1 and S2 were varied simultaneously, while the offset S3 was set equal to one-half of the spacing S2. In these exemplary cases, there was only one independent parameter and the results are listed in Table 1 and illustrated in Figure 3.

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Table 1

Parameter	S1/S2	S1/D	Relative heat transfer	Relative pressure loss
Case 1	0.037	0.5417	1.2626	1.2140
Case 2	0.071	0.7500	1.2469	1.1806
Case 3	0.127	1.0000	1.2465	1.1789
Case 4	0.224	1.3292	1.2162	1.1689
Case 5	0.348	1.6583	1.1951	1.1554
Case 6	0.500	1.9875	1.1881	1.1505
Case 7	0.679	2.3167	1.1347	1.1031
Case 8	0.886	2.6458	1.0632	1.0483
Case 9	1.120	2.9750	1.0000	1.0000

[0045] The exemplary calculations show the relative values of the pressure losses and heat transfer rates that are obtained merely by changing the pattern of perforations. The exemplary data was plotted after scaling relative to the values that occur when the ratio of spacing to the perforation dimension was approximately 3. As this ratio is lowered to approximately 2, significant improvement occurs in heat transfer. As noted in Table 1, the increase in heat transfer is higher than the increase in the corresponding pressure loss. Thus, a heat exchanger designed at a ratio of 2 may be shorter by a factor of about 1.2 compared to a heat exchanger designed at a ratio of 3, while the overall pressure loss will also be lower. This is a significant reduction in length and thereby the volume. If the ratio is reduced below 2, the improvement continues and particularly good values are obtained between the values of the ratio between 0.75 and 1. In this range of ratios there is an improvement in heat transfer by a factor of about 1.25. The length or volume required will be the reciprocal of this ratio namely 0.80 or eighty percent (80%). This represents a substantial size reduction by twenty percent (20%) while the pressure loss will also be reduced by the ratio of 1.18/1.25 which is equal to 0.94 or ninety-four percent (94%). Thus, there can be a twenty percent (20%) reduction in length or volume while there is also a six percent (6%) reduction in pressure loss.

[0046] These are significant improvements that can be obtained by arranging the perforation positions as disclosed herein which was not known or disclosed previously. In fact, either through express statements, implication, or illustrations, some previous disclosures taught away from such arrangements. As illustrated in Figure 3, the range of ratios from 0.75 to 2.0 is preferred wherein the range from 0.75 to 1.0 is particularly preferred.

EXAMPLE 2

[0047] Example 2 illustrates an exemplary improvement obtained using the teaching contained herein. As noted before, traditional teachings concerning perforated fins in plate fin heat exchangers did not discuss preferred geometry or perforation patterns as outlined herein. The CFD paper by Zhu et al., cited earlier, however, did study the effect of a specific perforated fin in comparison with other forms of fins such as plain, serrated and wavy fins. The current example has been generated by applying the perforation pattern used in the CFD paper by Zhu et al. in the same manner as described in Example 1.

[0048] The parameters of the perforation pattern on the flat sheets before being folded into fins are as follows: perforation diameter (D) = 0.8 mm; open area = 20%; S1 = 1.81 mm; S2 = 1.39 mm; and S3 = 0. The calculated relative performance of a heat exchanger that utilizes such prior art fins is shown in Table 2.

Table 2

Parameter	CFD Paper	Disclosed exemplary embodiment
Perforation diameter, mm	0.8	2.4
Open area, %	20	10
S1, mm	1.81	2.4
S2, mm	1.39	18.96
S3, mm	0.0	9.48
S1/D	2.26	1.0
S3/S2	0.0	0.5

Relative heat transfer coefficient	1.00	1.26
Relative pressure gradient	1.00	1.26
Relative length of exchanger	1.00	0.79
Relative volume of exchanger	1.00	0.79
Relative pressure loss in exchanger	1.00	1.00

[0049] As illustrated in Table 2, because the Relative heat transfer coefficient and Relative pressure gradient of the disclosed exemplary embodiment are 26% higher than the CFD paper heat exchanger, a heat exchanger constructed according to the teachings of the disclosed exemplary embodiment can have a lesser relative length (21% less) and a lesser relative volume (21% less) compared with a heat exchanger constructed based on the teachings of the CFD paper where both heat exchangers have equal or matching heat transfer duty and pressure drop. This is a substantial benefit for utilizing fins made in accordance with the teachings of the disclosed exemplary embodiment over the teachings of the CFD paper.

[0050] While aspects of the present invention has been described in connection with the preferred embodiments of the various figures, it is to be understood that other similar embodiments may be used or modifications and additions may be made to the described embodiment for performing the same function of the present invention without deviating therefrom. For example, the following aspects should also be understood to be a part of this disclosure:

[0051] Aspect 1. A plate fin heat exchanger, comprising:

a folded fin sheet comprising fins having a height, a width, and a length, the folded fin sheet being positioned between a first parting sheet and a second parting sheet; and

a first side bar and a second side bar, wherein the first side bar is positioned between the first parting sheet and the second parting sheet and adjacent to a first side of the folded fin sheet, and wherein the second side bar is positioned between the first parting sheet and the second parting and adjacent to a second side of the folded fin sheet thereby forming at least a part of a plate fin passage;

wherein the fin sheet comprises a plurality of perforations, such plurality of perforations are positioned on the fin sheet in parallel rows when such fin sheet is in an unfolded state, such parallel rows of perforations on the fin sheet comprise a first spacing between the parallel rows of perforations (S1), a second spacing between sequential perforations within the parallel row of perforations (S2), a third spacing (or offset) between the perforations in adjacent parallel rows of perforations (S3), and a perforation diameter (D), wherein the ratio of the first spacing between the parallel rows of perforations to the perforation diameter (S1/D) is in the range of 0.75 to 2.0, and wherein the angle between the fins and the parallel rows of perforations is less than or equal to five degrees ($\leq 5^\circ$).

[0052] Aspect 2. The plate fin heat exchanger of Aspect 1, wherein the angle between the fins and the parallel rows of perforations is zero degrees (0°).

[0053] Aspect 3. The plate fin heat exchanger of Aspect 1 or Aspect 2, wherein the ratio of the first spacing between the parallel rows of perforations to the perforation diameter (S1/D) is in the range of 0.75 to 1.0.

[0054] Aspect 4. The plate fin heat exchanger of any one of Aspects 1 to Aspect 3, wherein the ratio of the third spacing (or offset) between perforations in adjacent parallel rows of perforations (S3) and the second spacing between sequential perforations within the parallel row of perforations (S2) is in the range of 0.25 to 0.75.

[0055] Aspect 5. The plate fin heat exchanger of any one of Aspects 1 to Aspect 4, wherein 5% to 25% of the area of the folded fin sheet in the unfolded state is occupied by the perforations.

[0056] Aspect 6. The plate fin heat exchanger of any one of Aspects 1 to Aspect 5, wherein the perforation diameter (D) is in the range of 1 mm to 4 mm.

[0057] Aspect 7. The plate fin heat exchanger of any one of Aspects 1 to Aspect 6, wherein the perforations are circular.

[0058] Aspect 8. The plate fin heat exchanger of any one of Aspects 1 to Aspect 6, wherein the perforations are in the shape of ellipses, rectangles, or parallelograms.

[0059] Aspect 9. The plate fin heat exchanger of any one of Aspects 1 to Aspect 8, wherein the adjacent parallel rows of perforations are offset in alternating fashion such that the position of the parallel rows of perforations repeats every other row of perforations.

[0060] Aspect 10. The plate fin heat exchanger of any one of Aspects 1 to Aspect 8, wherein the adjacent parallel rows of perforations are offset such that the position of the parallel rows of perforations on the fins of the folded fin sheet repeat exactly at least once every 10 fin wavelengths and more preferably at least once every 5 fin wavelengths, in at least 50% of the heat exchanger plate fin passages containing such perforated fins, more preferably in at least 80% of the plate fin passages and most preferably in 100% of the plate fin passages.

[0061] Aspect 11. The plate fin heat exchanger of any one of Aspects 1 to Aspect 10, wherein the folded fin sheet comprises a surface texture.

[0062] Aspect 12. The plate fin heat exchanger of any one of Aspects 1 to Aspect 11, wherein the fin height is in the range of 0.25 inches to 1 inch, more preferably in the range of 0.4 inches to 0.75 inches, and most preferably in the range of 0.5 inches to 0.6 inches.

[0063] Aspect 13. The plate fin heat exchanger of any one of Aspects 1 to Aspect 12, wherein the folded fin sheet is an easyway heat transfer fin or distributor fin.

[0064] Aspect 14. The plate fin heat exchanger of any one of Aspects 1 to Aspect 13, wherein the plate-fin passages are adapted to accept a fluid stream, and wherein the fluid stream undergoes heat transfer without phase change over at least 80%, more preferably over at least 90%, and most preferably over 100% of the length of the plate-fin passages.

[0065] Aspect 15. A process for exchanging heat between at least two streams in a plate fin heat exchanger constructed in accordance with any one of Aspects 1 to Aspect 13, wherein at least one stream undergoes heat transfer without phase change over at least 80% of the length of the plate-fin passages, and wherein the Reynolds Number of the at least one stream is in the range of 800 to 100,000 and more preferably in the range of 1,000 to 10,000.

[0066] Aspect 16. A process for separating nitrogen, oxygen and/or argon from air by cryogenic distillation, which utilizes the plate fin heat exchanger of any one of Aspects 1 to Aspect 13, wherein at least one stream undergoes heat transfer without phase change over at least 80% of the length of the plate-fin passages, more preferably over at least 90% of the length of the plate-fin passages, and most preferably over 100% of the length of plate-fin passages.

[0067] Aspect 17. A method for manufacturing a plate fin heat exchanger which comprises the steps of:

- 5 (a) providing at least one perforated sheet, the at least one perforated sheet comprising a plurality of perforations arranged in parallel rows, wherein such parallel rows of perforations on the perforated sheet comprise a first spacing between the parallel rows of perforations (S1), a second spacing between sequential perforations within the parallel row of perforations (S2), a third spacing (or offset) between the perforations in adjacent parallel rows of perforations (S3), and a perforation diameter (D), wherein the ratio of the first spacing between the parallel rows of perforations to the perforation diameter (S1/D) is in the range of 0.75 to 2.0;
- 10 (b) folding the at least one perforated sheet into fins to form a folded perforated sheet such that the angle between the fins and the parallel rows of perforations is less than or equal to five degrees ($\leq 5^\circ$);
- 15 (c) positioning a first side bar adjacent to a first side of the at least one folded perforated sheet, a second side bar adjacent to a second side of the at least one folded perforated sheet, a first distributor fin adjacent to a first end of the at least one folded perforated sheet, a second distributor fin adjacent to a second end of the at least one folded perforated sheet, a first endbar adjacent to the first distributor fin, and a second endbar adjacent to the second distributor fin to form a preliminary plate fin passage;
- 20 (d) placing the preliminary plate fin passage of step (c) between a first parting sheet and a second parting sheet thereby forming a plate fin passage therebetween;
- 25 (e) combining the plate fin passage of step (d) with other plate fin passages to form the plate fin heat exchanger; and
- (f) brazing the plate fin heat exchanger.

[0068] Aspect 18. A method for manufacturing a plate fin heat exchanger according to Aspect 17, further comprising applying a surface texture to at least one perforated sheet prior to folding the at least one perforated sheet in step (b).

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[0069] The claimed invention, therefore, should not be limited to any single embodiment or aspect, but rather should be construed in breadth and scope in accordance with the appended claims.

CLAIMS

1. A plate fin heat exchanger, comprising:

a folded fin sheet comprising fins having a height, a width, and a length, the folded fin sheet being positioned between a first parting sheet and a second parting sheet; and

a first side bar and a second side bar, wherein the first side bar is positioned between the first parting sheet and the second parting sheet and adjacent to a first side of the folded fin sheet, and wherein the second side bar is positioned between the first parting sheet and the second parting and adjacent to a second side of the folded fin sheet thereby forming at least a part of a plate fin passage;

wherein the fin sheet comprises a plurality of perforations, such plurality of perforations are positioned on the fin sheet in parallel rows when such fin sheet is in an unfolded state, such parallel rows of perforations on the fin sheet comprise a first spacing between the parallel rows of perforations (S1), a second spacing between sequential perforations within the parallel row of perforations (S2), a third spacing (or offset) between the perforations in adjacent parallel rows of perforations (S3), and a perforation diameter (D), wherein the ratio of the first spacing between the parallel rows of perforations to the perforation diameter (S1/D) is in the range of 0.75 to 2.0, and wherein the angle between the fins and the parallel rows of perforations is less than or equal to five degrees ($\leq 5^\circ$).

2. The plate fin heat exchanger of claim 1, wherein the angle between the fins and the parallel rows of perforations is zero degrees (0°).

3. The plate fin heat exchanger of claim 1, wherein the ratio of the first spacing between the parallel rows of perforations to the perforation diameter (S1/D) is in the range of 0.75 to 1.0.

4. The plate fin heat exchanger of claim 1, wherein the ratio of the third spacing (or offset) between perforations in adjacent parallel rows of perforations (S3) and the second spacing between sequential perforations within the parallel row of perforations (S2) is in the range of 0.25 to 0.75.

5. The plate fin heat exchanger of claim 1, wherein 5% to 25% of the area of the folded fin sheet in the unfolded state is occupied by the perforations.

6. The plate fin heat exchanger of claim 1, wherein the perforation diameter (D) is in the range of 1 mm to 4 mm.
7. The plate fin heat exchanger of claim 1, wherein the perforations are circular.
8. The plate fin heat exchanger of claim 1, wherein the perforations are in the shape of
5 ellipses, rectangles, or parallelograms.
9. The plate fin heat exchanger of claim 1, wherein the adjacent parallel rows of perforations are offset in alternating fashion such that the position of the parallel rows of perforations repeats every other row of perforations.
10. The plate fin heat exchanger of claim 1, wherein the adjacent parallel rows of
10 perforations are offset such that the position of the parallel rows of perforations on the fins of the folded fin sheet repeat exactly at least once every 10 fin wavelengths and more preferably at least once every 5 fin wavelengths, in at least 50% of the heat exchanger plate fin passages containing such perforated fins, more preferably in at least 80% of the plate fin passages and most preferably in 100% of the plate fin
15 passages.
11. The plate fin heat exchanger of claim 1, wherein the folded fin sheet comprises a surface texture.
12. The plate fin heat exchanger of claim 1, wherein the fin height is in the range of 0.25 inches to 1 inch, more preferably in the range of 0.4 inches to 0.75 inches, and most
20 preferably in the range of 0.5 inches to 0.6 inches.
13. The plate fin heat exchanger of claim 1, wherein the folded fin sheet is an easyway heat transfer fin or distributor fin.
14. A process for exchanging heat between at least two streams in a plate fin heat
25 exchanger constructed in accordance with claim 1, wherein at least one stream undergoes heat transfer without phase change over at least 80% of the length of the plate-fin passages, and wherein the Reynolds Number of the at least one stream is in the range of 800 to 100,000 and more preferably in the range of 1,000 to 10,000.

15. A process for separating nitrogen, oxygen and/or argon from air by cryogenic distillation, which utilizes the plate fin heat exchanger of claim 1, wherein at least one stream undergoes heat transfer without phase change over at least 80% of the length of the plate-fin passages, more preferably over at least 90% of the length of the plate-fin passages, and most preferably over 100% of the length of plate-fin passages.
16. A method for manufacturing a plate fin heat exchanger which comprises the steps of:
- (a) providing at least one perforated sheet, the at least one perforated sheet comprising a plurality of perforations arranged in parallel rows, wherein such parallel rows of perforations on the perforated sheet comprise a first spacing between the parallel rows of perforations (S1), a second spacing between sequential perforations within the parallel row of perforations (S2), a third spacing (or offset) between the perforations in adjacent parallel rows of perforations (S3), and a perforation diameter (D), wherein the ratio of the first spacing between the parallel rows of perforations to the perforation diameter (S1/D) is in the range of 0.75 to 2.0;
 - (b) folding the at least one perforated sheet into fins to form a folded perforated sheet such that the angle between the fins and the parallel rows of perforations is less than or equal to five degrees ($\leq 5^\circ$);
 - (c) positioning a first side bar adjacent to a first side of the at least one folded perforated sheet, a second side bar adjacent to a second side of the at least one folded perforated sheet, a first distributor fin adjacent to a first end of the at least one folded perforated sheet, a second distributor fin adjacent to a second end of the at least one folded perforated sheet, a first endbar adjacent to the first distributor fin, and a second endbar adjacent to the second distributor fin to form a preliminary plate fin passage;
 - (d) placing the preliminary plate fin passage of step (c) between a first parting sheet and a second parting sheet thereby forming a plate fin passage therebetween;
 - (e) combining the plate fin passage of step (d) with other plate fin passages to form the plate fin heat exchanger; and

(f) brazing the plate fin heat exchanger.

17. A method for manufacturing a plate fin heat exchanger according to claim 16, further comprising applying a surface texture to at least one perforated sheet prior to folding the at least one perforated sheet in step (b).