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DES CHAMPS

(54) APPARATUS AND METHOD FOR EQUALIZING HOT FLUID EXIT PLANE PLATE TEMPERATURES IN HEAT EXCHANGERS

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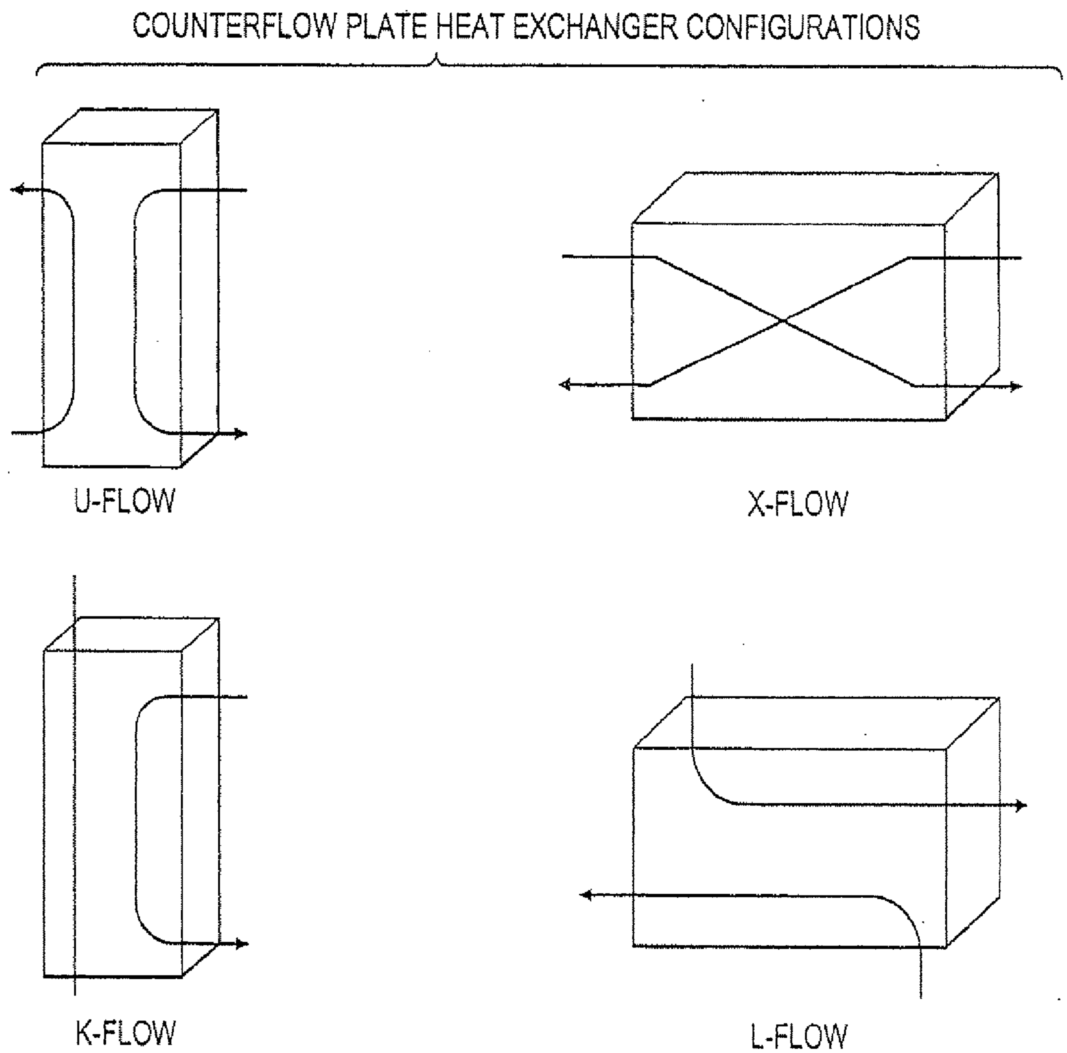
(57) **ABSTRACT**

An apparatus and method for minimizing cold spots on plates of a plate-type fluid-to-fluid heat exchanger averages the plate temperature at a hot-fluid exit plane of the heat exchanger. The heat exchanger matrix is constructed to internally vary the flow patterns of opposing hot and cold fluid streams so that the heat transfer coefficient values of one or both fluid streams, designated as h, are optimized so the hot fluid value is a greater value than that of a cold fluid value. Plate variable flow structures are arranged in a manner that allows higher velocity hot fluid flow and possible lower velocity cold fluid flow in areas where the plate temperatures are coolest and the opposite configuration where plate temperatures are hottest.



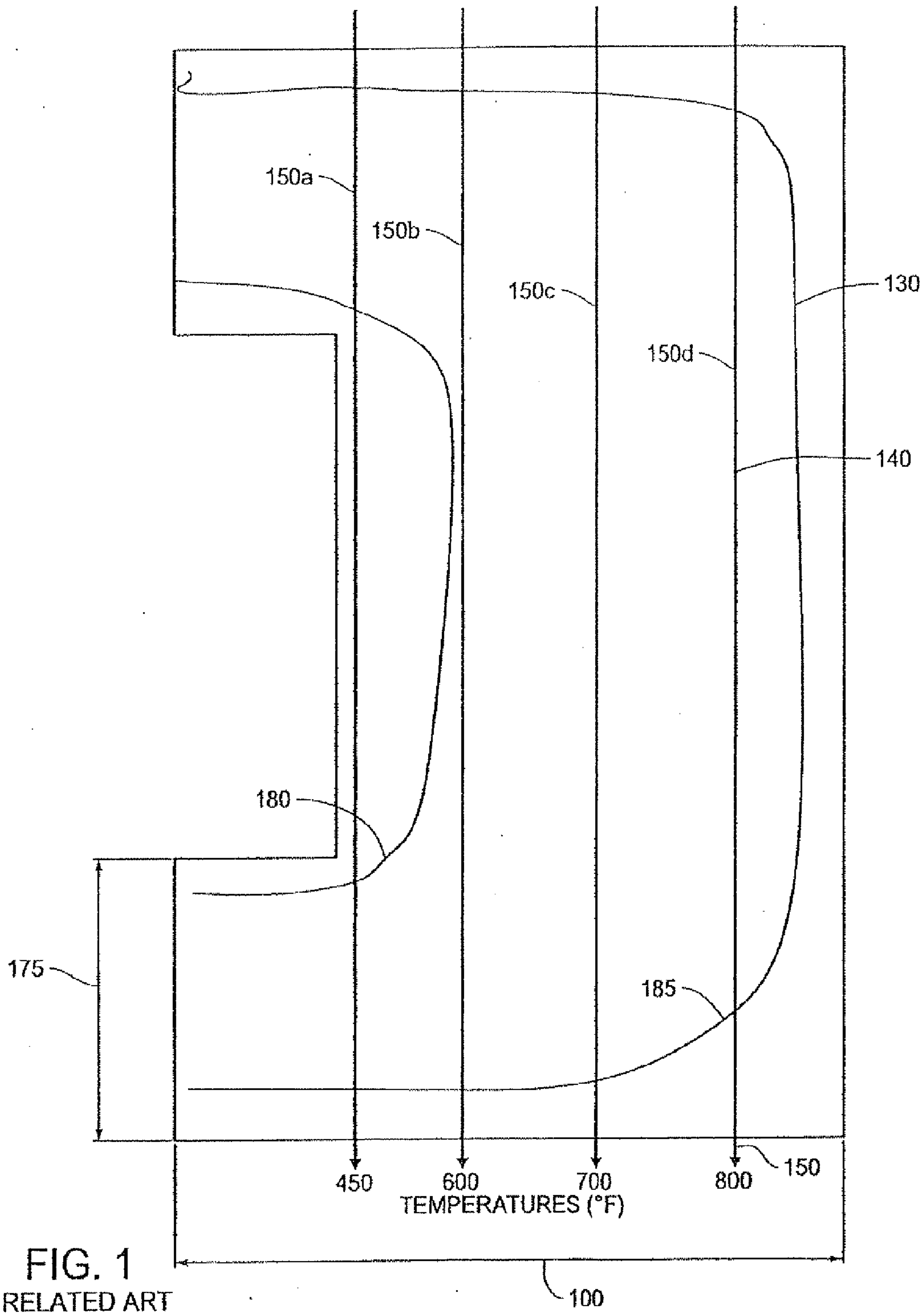


FIG. 1
RELATED ART

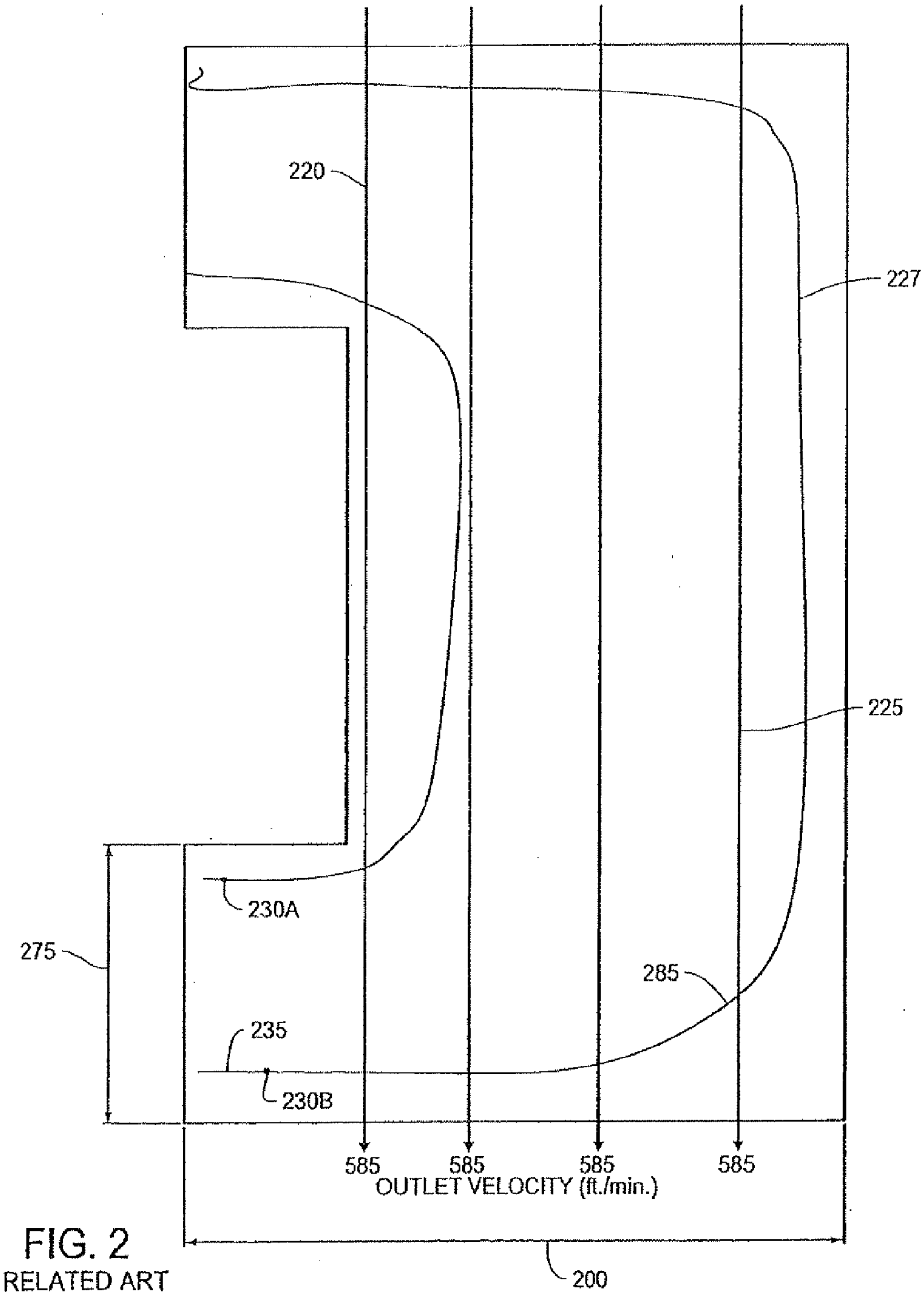


FIG. 2
RELATED ART

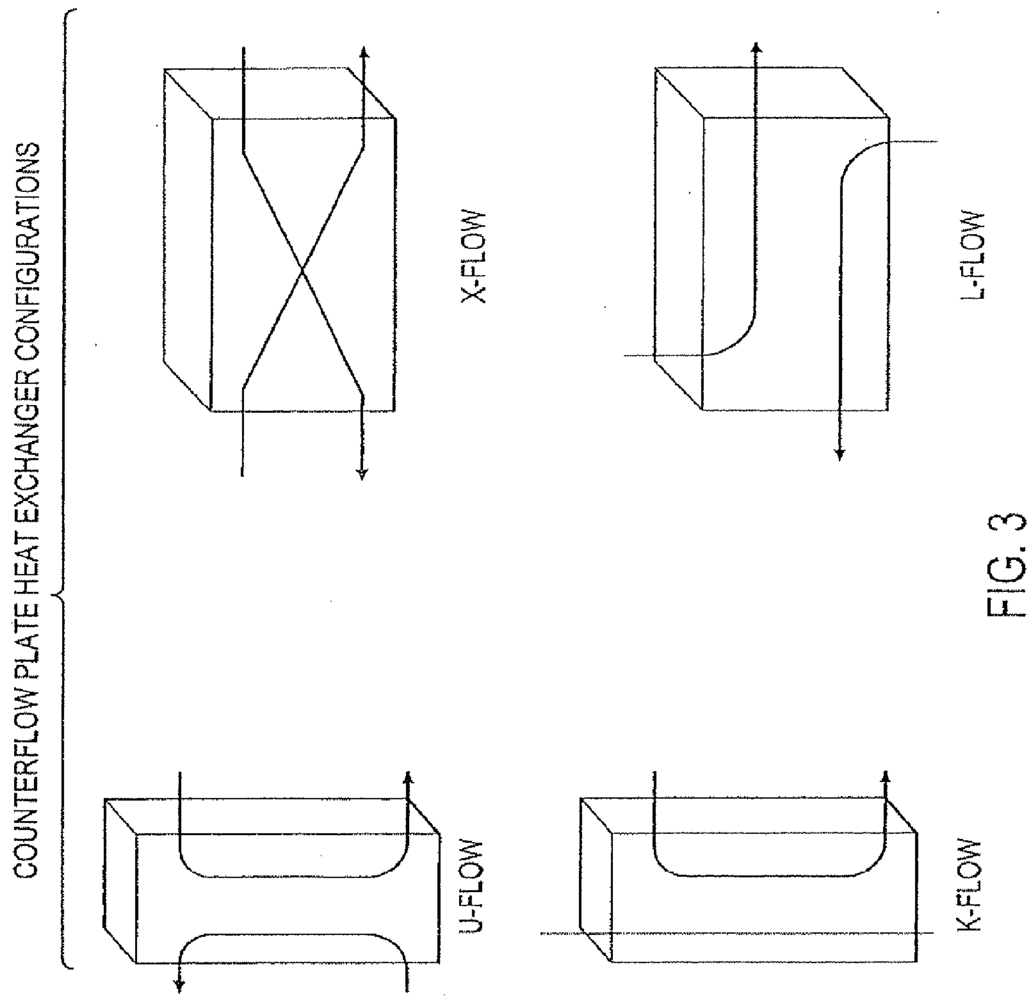

COUNTERFLOW PLATE HEAT EXCHANGER CONFIGURATIONS
X-FLOW
L-FLOW
U-FLOW
K-FLOW

FIG. 3

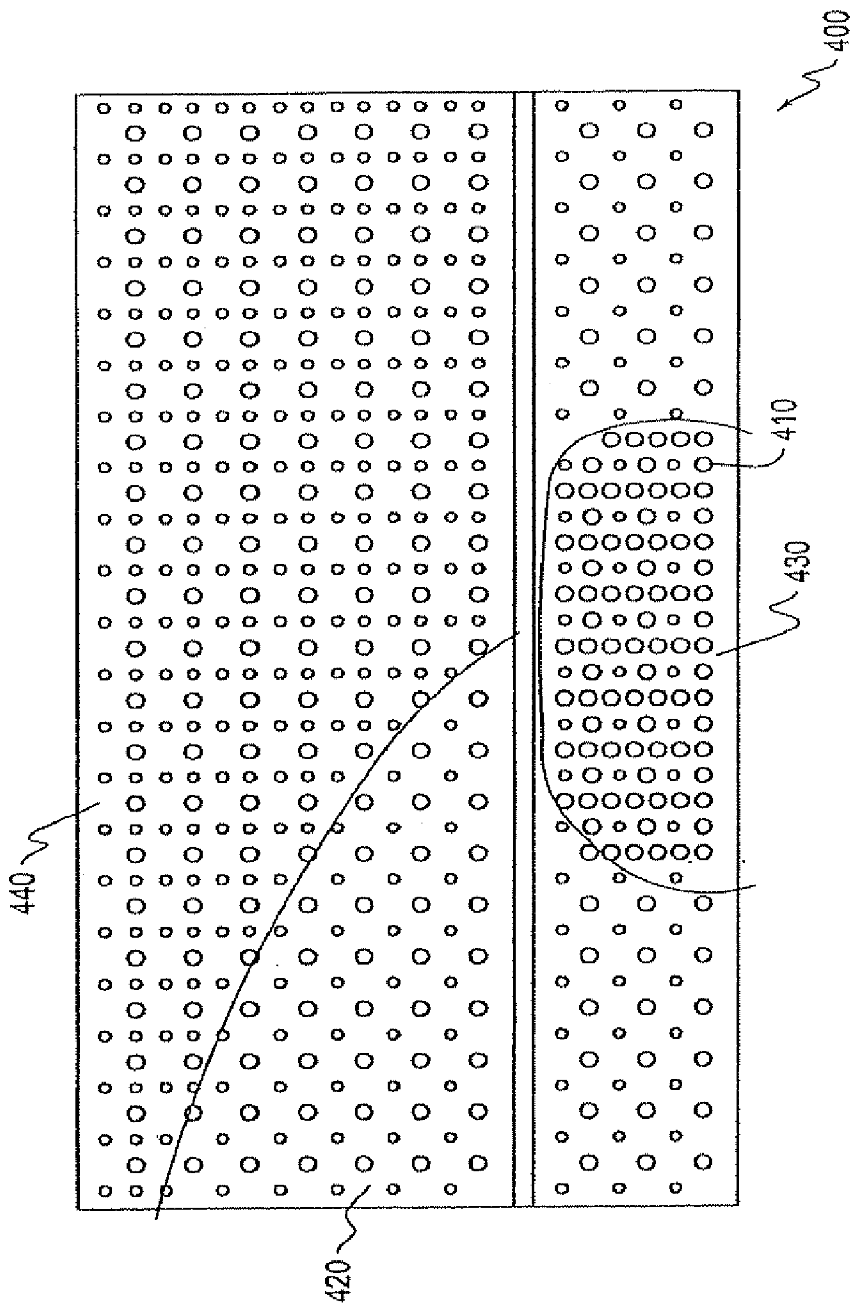


FIG. 4

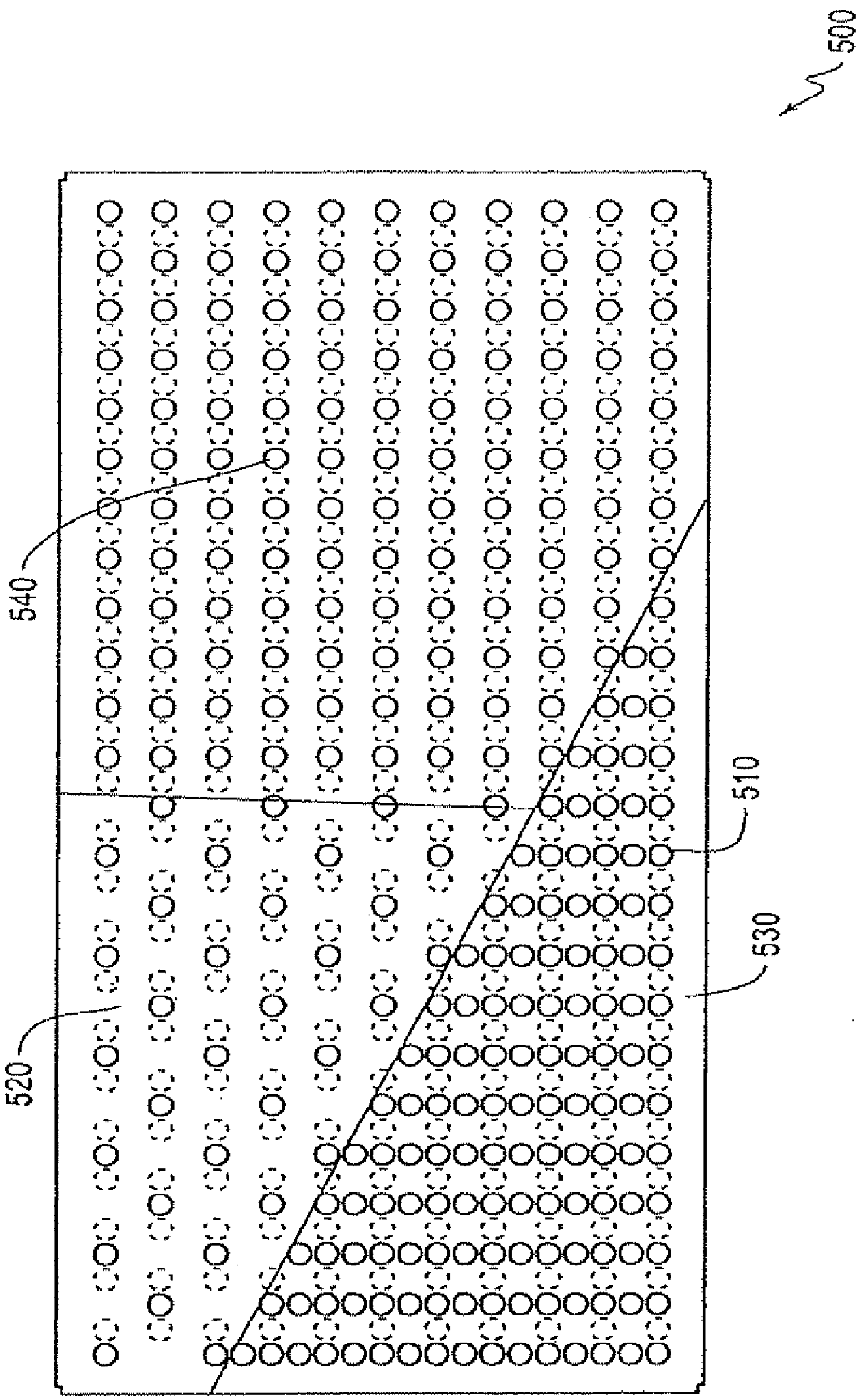


FIG. 5

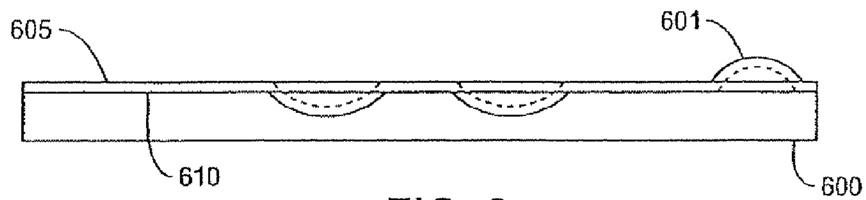


FIG. 6

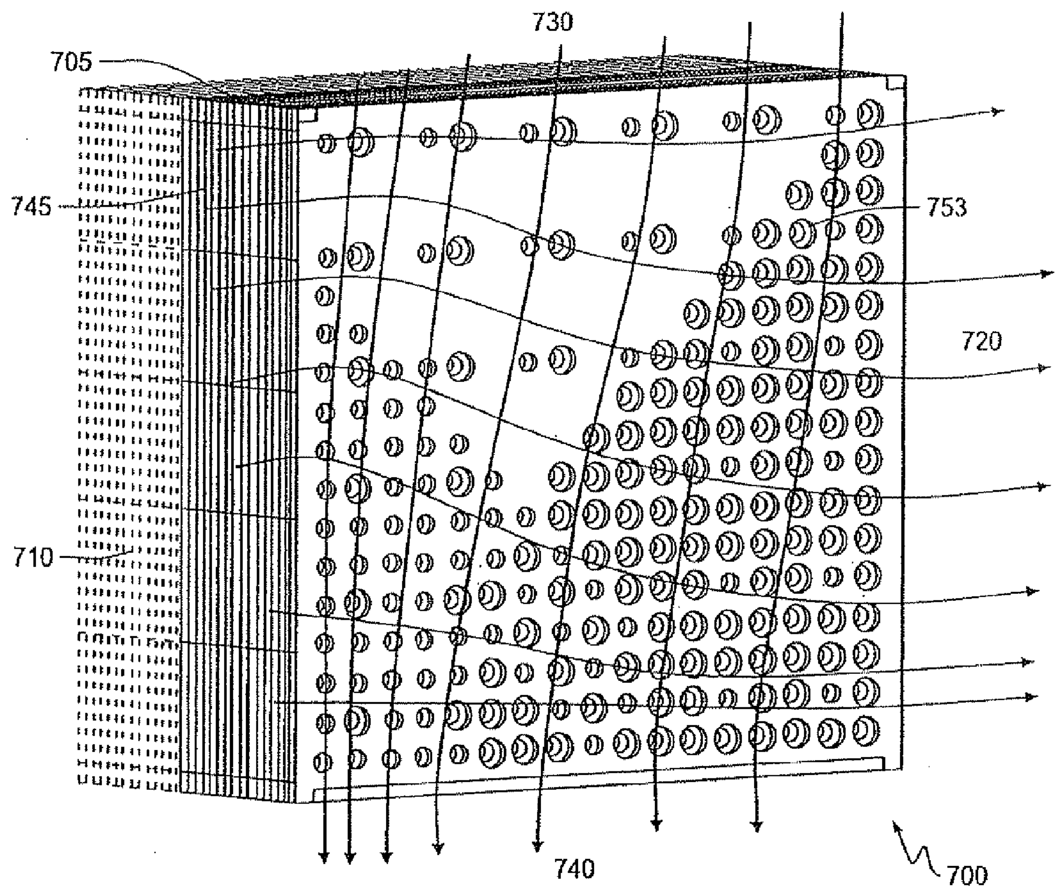
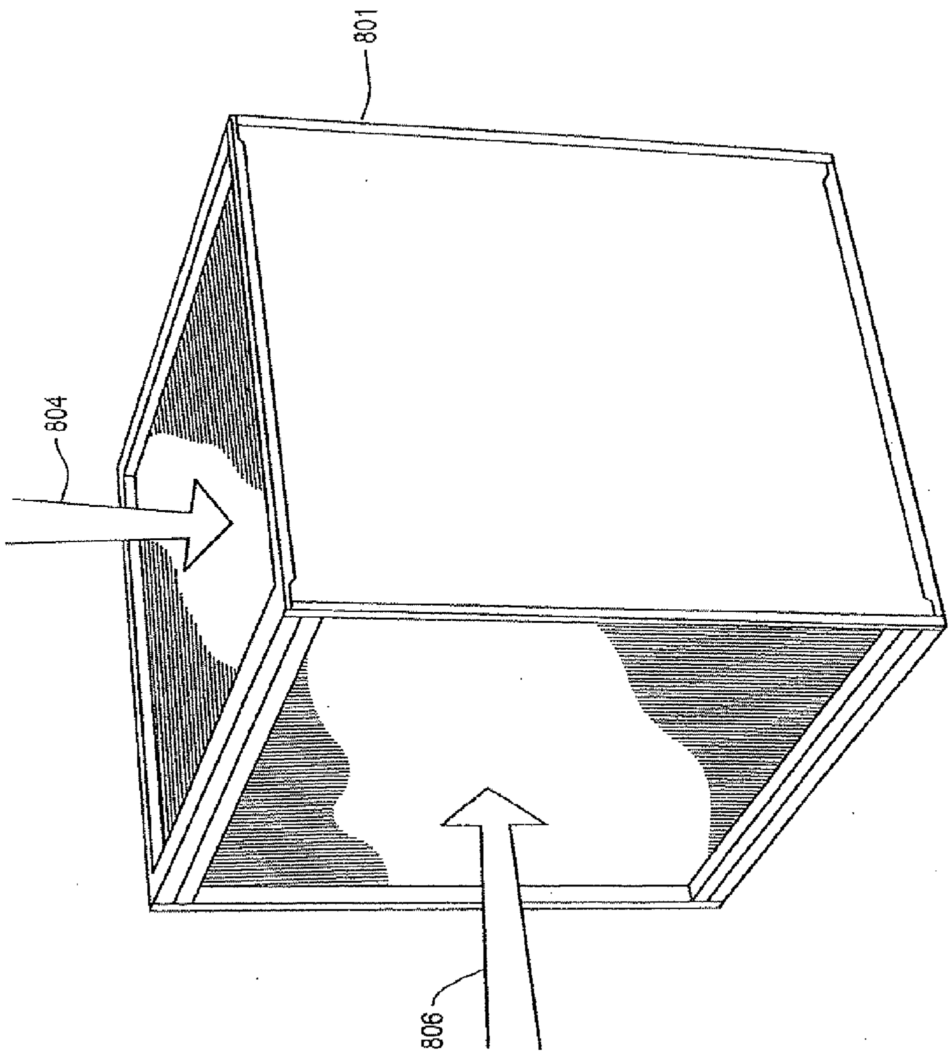


FIG. 7



CROSS-FLOW SENSIBLE PLATE HEAT EXCHANGER

FIG. 8

APPARATUS AND METHOD FOR EQUALIZING HOT FLUID EXIT PLANE PLATE TEMPERATURES IN HEAT EXCHANGERS

[0001] This is a Division of application Ser. No. 12/461,855 filed Aug. 26, 2009. The disclosure of the prior application is hereby incorporated by reference herein in its entirety.

BACKGROUND

[0002] Exemplary embodiments of an apparatus and method for equalizing hot fluid exit plane plate temperatures relate to plate-type fluid-to-fluid heat exchangers. More specifically, the embodiments relate to heat exchangers constructed to minimize deleterious effects attributable to cold spots on plates that form a heat exchanger matrix.

[0003] A fluid-to-fluid heat exchanger matrix is designed to extract energy from, for example, hot exhaust gas. As the hot gas stream proceeds through the matrix, a cooler opposing gas stream draws thermal energy from the hot gas stream across intervening plates and cools the hot gas stream. Accordingly, toward the end of the hot gas flow path, i.e. the hot gas exit plane, the temperature of the hot gas is low as it comes into contact with a metal surface of a plate that separates incoming cooler gas from the exiting cooled hot gas. At the hot gas exit plane, the plate temperature may be low due to close proximity to the cool gas entry plane. When the hot gas contacts cool or low temperature portions of the metal plate separating the two gas streams, a dew point temperature of hot gas constituents may be reached, and condensation may occur. Thus, when corrosive constituents are present in the gas streams, corrosive condensation or fouling due to particulate accumulation may cause premature failure of the heat exchanger matrix.

[0004] An ideal fluid-to-fluid heat exchanger (hereinafter a gas-to-gas heat exchanger by way of example only) should cool hot process gas to a temperature that merely approaches the dew point temperature of corrosive constituents so that the hot gas exits the heat exchanger matrix without first condensing the constituents on a cold spot near the hot gas exit plane, or any portion of a plate of the heat exchanger matrix. Heat exchangers generally do not accommodate true counterflow of hot and cool gas streams and therefore hot process gas, at a plane perpendicular to gas flow, does not cool evenly as it progresses through and exits the heat exchanger matrix. Thus, cold spots may form on plates of the heat exchanger matrix.

SUMMARY

[0005] There are known approaches for minimizing the potential for cold spots on heat exchanger plates. One approach is to use a parallel flow heat exchanger. This approach does not, however, optimize the amount of heat transferred for the surface area of the heat exchanger matrix. For example, for equal mass flow and equal heat capacity of two gas streams in a parallel flow heat exchanger, the maximum theoretical recovery efficiency is 50%.

[0006] Another approach is to design a "true" counterflow heat exchanger having a theoretical recovery efficiency of 100%. This is not practical, however, because the complexity and cost associated with a manifold construction that would allow two gas streams to enter and exit channels between plates in a counterflow manner is prohibitive.

[0007] Due to economics of manufacture, gas-to-gas heat exchangers used today are of a crossflow or quasi-counterflow design. Unless special design procedures are used, heat exchanger matrix plate temperatures near the hot gas exit plane (and cold gas exit plane) may exhibit temperatures lower than other points on the plates. In order to achieve optimal heat transfer and at the same time avoid condensation at a localized cold area near the hot fluid exit plane of a plate, yet another approach for reducing the influence of incoming cold gas on plate temperature is to thermally insulate part of the heat exchanger plates. Insulation technology may be used to increase the metal plate temperature in a cold corner of the plate at the hot gas exit plane, resulting in condensation-free operation. However, this technique may result in added costs and wasted heat exchanger surface area.

[0008] A typical plate-type gas-to-gas heat exchanger matrix is shown in FIG. **1**. Hot gas (represented by arrows **140**) enters at the top of the matrix at a temperature T**3** of, for example, 1000° F., and exits at the bottom of the matrix. Cooling gas enters the matrix at a cool gas entry plane **175** on a side of the matrix adjacent to its bottom (represented by arrow T**1**) and exits the matrix on a side of the matrix adjacent to its top (represented by arrow T**2**). At the hot gas exit plane **100**, a varying temperature distribution exists due to leaving hot gas **150** (cooled hot gas). At plate point **150***a*, the temperature of the leaving hot gas is lowest, 450° F. For the distance between each plate point **150***b*, **150***c* and **150***d*, the temperature of the leaving hot gas **150** increases by about 100° F., respectively. At plate point **100**, the temperature of the leaving hot gas **150** is 800° F. While the average temperature of leaving hot gas **150** is 650° F., the deviation among temperatures of leaving hot gas **150** at plate points **150***a*-**150***d* is significant. Plate point **150***a*, the point at which the temperature of the leaving hot gas **150** is lowest, is also near the cool gas entry plane **175** of the heat exchanger matrix. The applicant has discovered that it is desirable to have substantially equal metal plate temperatures at plate points **150***a*-**150***d*. This allows for maximum heat transfer without condensation on the plates, and concomitant corrosion and/or fouling due to particulate accumulation.

[0009] Plate temperature is affected by the temperature of the hot and cool gas streams adjacent to an intervening plate, and the heat transfer coefficients of each gas stream at the same x, y coordinates on opposing surfaces of the plate. This relationship is derived from the general equation for heat transfer:

$$U=1/(1/h_1+f_1+t/k+f_4+1/h_4)$$

$$h \cong Re^{0.8}=(\rho VD_h/\mu)^{0.8}$$

$$h=f[Re^{0.8}Pr^{0.3}]$$

$$Re=\rho VD_h/\mu$$

Q=heat transferred

A=area

ΔT=temperature difference between the hot gas and the cold gas at a point on the transfer plate

U=overall conductance

h_1=cold gas heat transfer coefficient, btu/(hr ft^2° F.)

f_1=cold gas fouling factor

t/k=metal thickness divided by the metal thermal conductivity

f_4=hot gas fouling factor

h_4=hot gas heat transfer coefficient, btu/(hr ft^2° F.)

Re=Reynolds Number

ρ=gas density, lb/ft^3

V=velocity of gas, ft/hr

D_h=hydraulic diameter of flow channel, ft

μ=viscosity of gas, btu/(hr ft ° F.)

Cp=specific heat of gas, btu/(lb ° F.)

k=thermal conductivity of gas, btu/(hr ft ° F.)

[0010] Thus, the velocity V is the only parameter that can be varied in any degree with given inlet flow conditions. In other words, in view of the foregoing, it may be stated that the heat transfer coefficient h varies with velocity, e.g., $h \sim V^{0.8}$. The temperature of a point on a plate in a heat exchanger matrix may be influenced by manipulating the velocity V of the process gasses at locations throughout the matrix. The heat exchanger embodiments described herein accomplish this by varying the spacing between protrusions, or variable flow structures, on plates within the matrix. Variable flow structures may be formed during the manufacturing process to maintain desired gas flow by way of spacing between heat transfer plates. The variable flow structures may be protrusions that are defined in the matrix design by a protrusion height and protrusion spacing, i.e., the distance between the protrusions when stamped on the metal plate.

[0011] An increase in hot gas velocity at a given plate point, all other parameters remaining constant, results in an increase in heat transfer coefficient h_4 of the hot gas and thus an increase in the plate temperature at that point. Therefore, the variable flow structures of a plate may be arranged or patterned to affect gas velocity at different plate points and thereby optimize the values of h_4 (and possibly h_1) and equalize to an extent the plate temperatures at points at or near the hot gas exit plane and elsewhere on plates of the matrix.

[0012] Specifically, variable flow structures may be arranged on plates within the matrix so as to increase a velocity of hot gas flow and possibly lower a velocity of a cold gas flow at plate points that are normally cooler. The opposite configuration may be used at plate points where the plate would normally be hotter. When hot gas flow velocity increases and thus the hot gas heat transfer coefficient increases, the metal plate temperature may be influenced more by the hot gas temperature than that of the opposing cold gas stream. Conversely, a decreased velocity cold gas flow may cause the metal plate temperature to be less influenced by the cold gas temperature. Therefore, at a lowest temperature point on the plate, it may be advantageous to increase the hot gas flow velocity to optimize h_4, and perhaps reduce the cold gas flow velocity to optimize h_1, to thereby cause the metal temperature to increase.

[0013] Variable flow structures on a surface of a plate facing a hot gas stream may also be arranged so that an artificial flow resistance forces hot gas to an area where the cold gas enters the heat exchanger. Conversely, variable flow structures on a surface of a plate facing a cold gas stream may be arranged so that an artificial flow resistance forces cold gas away from portions of a plate that exhibit cold spots.

[0014] Exemplary embodiments are described herein. However, it is envisioned that any heat exchanger arrangement that may incorporate the features of the method and apparatus for minimizing cold spots in the plates of a plate-type gas-to-gas heat exchanger described herein are encompassed by the scope and spirit of the exemplary embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. **1** shows a diagrammatical cross-sectional view of a heat exchanger matrix plate in accordance with the related art and hot gas exit plane gas temperatures;

[0016] FIG. **2** shows a diagrammatical cross-sectional view of the heat exchanger plate shown in FIG. **1** and gas velocities;

[0017] FIG. **3** shows counterflow heat exchanger configurations for use in an exemplary embodiment.

[0018] FIG. **4** shows a cold gas flow channel plate surface having a variable flow structure pattern in accordance with an exemplary embodiment;

[0019] FIG. **5** shows a hot gas flow channel plate face having a variable flow structure pattern in accordance with an exemplary embodiment;

[0020] FIG. **6** shows a side view of a plate having a variable flow structure pattern in accordance with an exemplary embodiment; and

[0021] FIG. **7** shows a cross-sectional perspective view of a portion of a heat exchanger matrix in accordance with an exemplary embodiment.

[0022] FIG. **8** shows a perspective view of a crossflow heat exchanger having a matrix in accordance with an exemplary embodiment.

EMBODIMENTS

[0023] The exemplary embodiments are intended to cover all alternatives, modifications and equivalents as may be included within the spirit and scope of the method and apparatus as defined herein.

[0024] For an understanding of an apparatus and method for equalizing hot gas exit plane plate temperatures to minimize cold spots on plates of gas-to-gas heat exchanger matrices, reference is made to the drawings. In the drawings, like referenced numerals have been used throughout to designate similar or identical elements. The drawings depict various embodiments and data related to embodiments of illustrative heat exchangers incorporating features of exemplary embodiments described herein.

[0025] FIG. **1** shows a related art plate-type heat exchanger wherein the h values of cold gas stream **130** and hot gas stream **140** are not optimized and thus the metal plate temperature is uneven at hot gas exit plane **100**. Specifically, the metal temperature at plate points **150*a*-150*d*** deviate from one another substantially.

[0026] Related art plates of the type shown in FIG. **1** typically have symmetrical variable flow structure arrangements. FIG. **2** shows a diagrammatical cross-sectional view of the heat exchanger plate shown in FIG. **1**. Instead of temperatures of leaving hot gas as shown in FIG. **1**, FIG. **2** shows velocities of hot gas (represented by arrows **225**) near or at hot gas exit plane **200**, and velocities of entering cool gas **235**, and specifically velocities of entering cool gas **235** at plate points **230*a*** and **230*b*** near or at the cool gas entry plane **275**.

[0027] At the cool gas entry plane **275**, cold gas stream **235** has a high velocity causing the plates to be coldest near cool gas entry plane **275** where a blast of cold air enters the heat exchanger. As shown in FIG. **2**, cool gas stream **235** has a velocity at plate point **230***a* of about 1000 ft/min, while the velocity of the cool gas stream **235** at plate point **230***b* is about 470 ft/min.

[0028] Contrarily, the velocity of the exiting hot gas stream **225** may be relatively even across the vicinity of the hot gas exit plane **200**, the velocity being about 585 ft/.in. If the cool gas stream **235** has a higher velocity at a plate point than does the hot gas stream **225**, then the plate temperature may be influenced more by the cool air stream **235** and its temperature. Thus, and as shown in FIG. **1**, the exiting hot gas **150** may have a temperature that varies from a low near the vicinity of the cool air entry plane to a high at a portion of the plate distal to the cool air entry plane **175**. Indeed, FIG. **1** shows declining exiting hot gas **150** temperatures from plate points **150***d* through **150***a* approaching the cool gas entry plane **175**, plate point **150***d* being distal to cool gas entry plane **175**.

[0029] Spacing between the plates of a heat exchanger matrix may be defined by dimples, or other variably shaped protrusions (collectively referred to herein as variable flow structures), formed on the plates with a height that is typically half of the spacing between the plates. The dimples on opposing plates contact one another to define the plate spacing and provide structural support. That is, for a half-inch plate spacing, the dimple height on each plate would be a quarter inch.

[0030] A variable flow structure pattern on a plate may be selected for the purpose of: (1) supporting the plates to withstand a pressure differential between the fluid streams to prevent the plates from collapsing onto one another as a result of high gas pressure; (2) increasing flow turbulence to enhance h; (3) decreasing turbulence to lower gas flow pressure drop; or (4) a combination of 1, 2 and 3 to control temperature and overall performance. While protrusions or dimples are discussed as exemplary variable flow structures, any structure that varies the velocity of an adjacent gas stream may constitute a variable flow structure in accordance with an exemplary embodiment.

[0031] A related art heat exchanger has plates with dimples or protrusions that may be equally spaced or symmetrical, and may exhibit velocities and plate temperatures as shown in FIGS. **1** and **2**. As discussed above, the hot gas temperature varies from a low at the cold gas entrance plane **175** to a high at the side opposite the inlet, e.g., plate point **150***d*. As shown in FIGS. **1** and **2**, the hot gas streams have substantially equal velocity through the entire length of the heat exchanger because the dimples on the hot side are evenly spaced and arranged symmetrically over the entire plate surface. The cold gas streams are typically in a "U-flow" pattern and have differing velocities, a highest velocity corresponding to the shortest flow length and a lowest velocity corresponding to the longest flow length. The velocity relationship between the flow streams when the dimples are evenly spaced as in the related art may be expressed as follows:

$$V12b=sqrt[(L12a/L12b)\times V12a].$$

[0032] FIG. **2** shows that the velocity of cool gas flow stream **180** of FIG. **1** (corresponding to flow stream **235** at plate point **230***a*) is more than two times the velocity of cool gas flow stream **185** of FIG. **1** (corresponding to flow stream **235** at plate point **230***b*). The cool gas has a greater influence on plate temperature along flow stream **180**'s path than along flow stream **185**, and thus a lower exiting hot gas temperature (e.g., 450° F. at plate point **150***a*) nearest the cool gas entry plane **175**, as shown in FIG. **1**. Cool gas flow stream **185** has the opposite effect. Because the velocity of flow stream **185** at a plate point is less than that of the hot gas on the opposite side of the plate at that point, the hot gas is cooled less than that of the hot gas flow stream **228** near the cold-air inlet and thus hot gas flow stream **227** leaves the heat exchanger at a higher temperature (e.g., 800° F. at plate point **150***d*) and affects the surrounding plate temperature accordingly.

[0033] Because the value of h of a gas stream near the surface of the plate that separates two gas streams has a direct influence on the temperature of the plate at a given location, the temperature of the plate can be controlled to a degree by designing the variable flow structure pattern to influence gas flow distribution, and thus velocity throughout the heat exchanger. As discussed above, the higher the velocity of a gas stream, the higher the value of coefficient h of the gas stream. If h_4 of the hot gas is greater than h_1 of the cold gas, then the plate is influenced more by the hot gas stream temperature. Thus, as the heat transfer coefficient is changed, an effect on plate temperature, Tp may be observed. The relationship may be expressed as follows:

$$h_1Tp-h_1Tc=h_4Th-h_4Tp$$

$$Tp(h_1+h_4)=h_1Tc+h_4Th$$

$$Tp=(h_1Tc+h_4Th)/(h_1+h_4).$$

[0034] It is possible to calculate a variable flow structure arrangement that may change the velocity distribution of one or both of the cold gas stream and the hot gas stream in a manner that may optimize their values of h to effect a metal temperature that evens out at the hot gas exit plane.

[0035] While a counterflow plate heat exchanger configuration wherein cold gas streams are typically in a "U-flow" pattern are discussed by way of example, it will be appreciated that the features and functions disclosed herein may be desirably combined into various heat exchanger configurations. For example, FIG. **3** shows counterflow plate heat exchanger configurations in accordance with exemplary embodiments. Variable flow structure arrangements may be applied in heat exchanger configurations other than "U-flow" such as "X-flow," "K-flow," and "L-flow." These configurations are mentioned by way of example. Likewise, it will be appreciated that species of both counterflow and crossflow configurations may be used.

[0036] FIG. **4** shows a plate surface facing a cold gas stream having a preferred arrangement of protrusions or dimples, i.e., variable flow structures **410**. A heat exchanger matrix in accordance with an exemplary embodiment may include a plate surface facing a cold gas stream having a variable flow structure arrangement that is symmetrical while a plate surface facing a hot gas stream has a variable flow structure arrangement arranged to optimize h_4 of the hot gas stream.

[0037] The preferred variable flow structure arrangement of a plate surface facing a cold gas stream shown in FIG. **4** may effect idealized plate temperature, and may cause the h values of the hot and cold fluid streams to approach each other in value at any given x, y plate coordinate, thus increasing the overall performance of the heat exchanger. In other words, overall conductance U, has a greater average value in matrices having plates with variable flow structures **410** arranged in accordance with an exemplary embodiment than matrices having plates with substantially symmetrical variable flow structure spacing. This results in less surface area being required in the heat exchanger to produce the same thermal performance, or conversely, for the same surface area the overall effectiveness of the heat exchanger matrix increases. The overall pressure drop, even with the increased performance, remains essentially unchanged. Although uneven variable flow structure **410** spacing may lead to greater turbulence and greater pressure drop, this may be offset by greater plate spacing (less plates) to achieve the same effectiveness.

[0038] The exemplary cold side plate surface **400** shown in FIG. **4** embodies a variable flow structure **410** pattern that is asymmetrical and achieves the advantages discussed immediately above. For example, portion **440** of plate **400** has variable flow structures **410** arranged with a spacing between the variable flow structures **410** that is substantially equal throughout portion **440**. However, the density of variable flow structures **410** differs between portions **420**, **430**, and **440**. For example, the spacing between variable flow structures **410** of portion **420** of plate **400** is much greater than the spacing between variable flow structures **410** of portion **430** of plate **400**.

[0039] Similarly, FIG. **5** shows a preferred pattern arrangement of variable flow structures **510** of a plate surface facing a hot gas stream. FIG. **5** shows that the variable flow structures **510** of plate **500** may have different spacing therebetween among different portions of plate **500**. For example, in an exemplary embodiment, spacing between variable flow structures **510** in portion **540** may be substantially equal throughout portion **540**. However, the density of variable flow structures **510** of portion **520** may be substantially less than that of the variable flow structures **510** of portion **540**, i.e., spacing between variable flow structures **510** of portion **520** may be greater than that of portion **540**. Similarly, the variable flow structure **510** density in portion **530** of plate **500** may be greater than that of portions **540** and **520**.

[0040] A heat exchanger having one or both of the variable pattern plate surfaces shown in FIGS. **4** and **5** may effect a change in velocity of hot and cold gases to optimize the values of h for either or both the hot and cold gases to result in a metal temperature that is substantially even across plate points at or near a hot gas exit plane.

[0041] FIG. **6** shows a side view of a plate having a variable flow structure pattern in accordance with an exemplary embodiment. From FIG. **6** it may be understood that variable flow structures **601** may be arranged on plate **600** such that variable flow structures **601** are arranged on a first surface **605** of plate **600** that may face a hot gas stream. Variable flow structures **601** may also be arranged on a second surface **610** of plate **600** that may face a cold gas stream. Thus, surfaces **605** and **610** may be formed on or defined by a single plate **600**. Moreover, variable flow structures **601** may be formed on both surfaces **605** and **610** of a single plate **600**. Thus, during manufacture, variable flow structures **601** may be formed from or on the same plate **600**.

[0042] FIG. **7** shows a cross-sectional perspective view of a crossflow heat exchanger in accordance with an exemplary embodiment. Crossflow heat exchanger **700** may include a heat exchanger matrix **705** in accordance with an exemplary embodiment, including plates having variable flow structure patterns as described above. Specifically, crossflow heat exchanger **700** may have a cold gas flow stream inlet **710** and a corresponding cold gas flow stream outlet **720** where cold gas may enter and exit the heat exchanger matrix. Crossflow heat exchanger **700** may include a hot gas flow stream inlet **730** and a corresponding hot gas flow stream outlet **740**. Plates **745** may be arranged to form a matrix **750**. At least one plate **745** may include variable flow structures **753** arranged in a pattern that affects the velocity of flow streams passing over plate **745**. For example, a varying density of variable flow structures **753** across plate **745** may affect the direction of and velocity of an adjacent gas flow stream and correspondingly affect the value of h for the flow stream. As the value of h is optimized by way of the variable structure **753** pattern arrangement, the occurrence of cold spots on plate **745** may be reduced as the temperature of plate **745** across, for example, hot gas flow stream outlet **740** is made substantially even.

[0043] FIG. **8** shows a perspective view of a crossflow heat exchanger **800**. Specifically, FIG. **8** shows a crossflow heat exchanger **800** that may include the matrix shown in FIG. **7** in accordance with an exemplary embodiment. Crossflow heat exchanger **800** may include a hot gas flow stream inlet **804** that may accommodate a hot gas flow in a first direction. Crossflow heat exchanger **800** may also include a cold gas flow stream inlet **806** that may accommodate cold gas flow in a second direction substantially perpendicular to the first direction of the hot gas air flow. An alternative embodiment may include a counterflow heat exchanger, as discussed above, without departing from the scope and spirit of the exemplary embodiments.

[0044] While minimization of cold spots on plates of a plate-type gas-to-gas heat exchanger by optimizing the heat transfer coefficients of process gas streams has been described in relation to specific embodiments, it is evident that many alternatives, modifications, and variations will be apparent to those skilled in the art. Accordingly, embodiments of the method and apparatus as set forth herein are intended to be illustrative, not limiting. There are changes that may be made without departing from the spirit and scope of the exemplary embodiments.

[0045] It will be appreciated that the above-disclosed and other features and functions, or alternatives thereof, may be desirably combined into many other different systems or applications. Also, various presently unforeseen or unanticipated alternatives, modifications, variations, or improvements therein may be subsequently made by those skilled in the art, and are also intended to be encompassed by the following claims.

What is claimed is:

1. A method of manufacturing a plate for a fluid-to-fluid heat exchanger matrix having minimal deviation in plate temperature at a hot fluid exit plane, the method comprising:

forming first variable flow structures on a first surface of a plate by stamping a second side of the plate such that the first variable flow structures are arranged to have at least two regions on the first surface, each region having different densities of variable flow structures.

2. The method of manufacturing the plate for a fluid-to-fluid heat exchanger matrix according to claim **1**, the method further comprising:

forming second variable flow structures on a second surface of the plate by stamping a first side of the plate such that the second variable flow structures are arranged to have at least two regions on the second surface, each region having different densities of variable flow structures.

* * * * *