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References cited:
EP-A2-1 715 278
DE-U1-836 063
DE-U1-202008 002 466
JP-A-2008 057 944
US-A-4 690 211

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FIELD OF THE INVENTION

[0001] The present invention relates to the field of heat exchangers.
[0002] Particularly, the present invention relates to the enhancement of heat transfer coefficient in heat exchangers.

DEFINITIONS OF TERMS USED IN THE SPECIFICATION

[0003] As used in the present specification, the following words and phrases are generally intended to have the meanings as set forth below, except to the extent that the context in which they are used indicates otherwise.
[0004] The term "ovular" used in the specification is to define a structure such as an oval, a tear-drop, egg-shaped, aerofoil-shaped, aerodynamic-shape, and the like.
[0005] The abbreviation "W1" used in the specification defines the width of the wide end of the ovular structure.
[0006] The abbreviation "W2" used in the specification defines the width of the narrow end of the ovular structure.
[0007] The term "Nusselt number (Nu)" used in the specification is the ratio of convective to conductive heat transfer across (normal to) the boundary.
[0008] The term "Reynolds number" used in the specification is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces. The term "frictional loss/factor (\( f \))" refers to the loss in flow momentum due to drag offered by the wall roughness while moving through a pipe, hose, or other limited space.
[0009] The term "Reynolds-Averaged Navier-Stokes equations" used in the specification are time (ensemble)-averaged equations of motion for fluid flow.
[0010] The term "dimples" used in the specification are projections or depressions on the surface of the tube.
[0011] Enhancement efficiency: It is defined as:

\[
\eta = \left( \frac{Nu}{Nu_0} \right) \left( \frac{f}{f_0} \right)^{1/3}
\]

where \( \eta \) is heat transfer enhancement efficiency and subscript "0" refers to the corresponding values for the smooth tube.

Other Correlations Used:

[0012] To get friction factor and Nusselt number for smooth tubes, correlations provided by B.S. Petukhov in "Heat transfer and friction in turbulent pipe flow with variable physical properties in Advances in Heat transfer" have been used:

Friction factor:

\[
f = (0.790 \ln Re - 1.64)^2
\]

for 3000 <= Re <= 5*10^6

Nusselt number:

\[
Nu = \left( \frac{f/8 \cdot (Re - 1000) \cdot Pr}{(1+12.7((f/8)^1/2) \cdot ((Pr^{2/3})-1))} \right)
\]

for 3000 <= Re <= 5*10^6

[0013] For other configurations, friction factor and Nusselt number are calculated using following relationship, respectively:

\[
f = 2 \Delta PD / LP U^2
\]
\[ \Delta u = hD/k \]

Where:

\[ \Delta P = \text{Pressure gradient per unit tube length (L) (in Pascal/m)} \]
\[ L = \text{Tube length used in CFD analysis (i.e. one pitch length for coil inserts and five pitch lengths for dimple tubes).} \]
\[ D = \text{Inside diameter of the tube} \]
\[ \rho = \text{Fluid density} \]
\[ U = \text{Mean velocity of the fluid} \]
\[ h = \text{Heat transfer coefficient} \]
\[ T_{\text{wall}} = \text{Wall temperature (area weighted average)} \]
\[ T_{\text{bulk}} = \text{Fluid temperature (mass weighted average)} \]
\[ q = \text{Wall heat flux (W/m}^2) \]
\[ k = \text{Thermal conductivity} \]

[0014] These definitions are additions to those expressed in the art.

BACKGROUND OF THE INVENTION & PRIOR ART

[0015] Heat exchanger is a device facilitating efficient heat transfer from one fluid to another; the heat exchanging fluids are generally separated by a solid wall to prevent their mixing, however in some cases can be kept in direct contact. Heat exchangers are widely used in industries, prime applications including thermal power plants, chemical processing units, refrigeration, air conditioning, and radiators in automobiles. Heat exchangers typically comprise a plurality of metal tubes generally arranged in a tightly packed serpentine pattern to form multiple passes. In the past, several attempts have been made to reduce the size and increase the efficiency of the heat exchangers; to provide compact, cost-effective, and efficient heat exchangers having an improved heat transfer coefficient.

[0016] It is known in the art that the heat transfer coefficient can be enhanced by increasing the heat transfer surface area and providing turbulence thereof. These objectives can be achieved by providing one or more baffles within the heat exchanger tubes for breaking the laminar flow of the heat exchange fluid and increasing the heat transfer area. Further, the heat exchanger tubes can be flattened at certain locations to cause turbulence; or projections and protrusions can be provided to increase the overall heat transfer efficiency. The convective heat transfer inside a heat exchanger tube suffers largely due to the presence of a laminar sub-layer adjacent to the heat exchanger wall. In the past, helical coil inserts and similar roughness elements have been used to enhance the heat transfer. Such alterations help in increasing the level of turbulence by breaking the laminar sub-layer. More recently, to achieve the highest possible thermal efficiency in heat exchangers, dimples are provided on the outer surface of the heat exchanger tubes, where the dimples form corresponding protrusions on the inner surface of the tube. The protrusions cause the flow of the fluid within the tubes to be turbulent which enhances the heat transfer. Also, the dimples increase the heat transfer surface area of the heat exchanger tube, thus, improving the thermal efficiency of the heat exchanger. However, these alterations result in varying cross-section area along the length of the heat exchanger tubes, typically causing an increase in the pressure drop of the fluid flowing through the tubes. This increase in the pressure drop adversely affects the thermal efficiency of the heat exchanger, thus, offsetting the improvement in thermal efficiency brought by the alterations.

[0017] Figure 1 to Figure 6 disclose patterns of tube inserts and roughness causing elements that have been used in the past in heat exchangers to increase turbulence within the heat exchanger tubes by breaking the laminar sub-layer. Figure 1 shows a helical tube insert having a circular cross-section and Figure 2 shows a helical tube insert having a square cross-section. The helical tube insert is typically a tube which is to be placed inside a heat exchanger tube to produce turbulence, wherein the helical tube insert has a helical pattern formed on the surface. The helical tube insert, referenced by numeral 100 in Figure 1, shows a helical pattern 102 having a circular cross-section of diameter 3 mm on the surface. The helical tube insert, referenced by numeral 200 in Figure 2, shows a helical pattern 202 having a square cross-section of side 3 mm on the surface. The helical tube inserts 100 and 200 provide a thick laminar sub-layer along the walls of the heat exchanger and further cause a high pressure drop in the fluid flowing through the heat exchanger tubes, which affect the overall efficiency of the heat exchanger and result in high operating costs for the heat
Figure 3, 4, 5 and 6 show a heat exchanger tube provided with dimples on the outer surface such that the dimples form corresponding protrusions on the inner surface of the heat exchanger tube. Figure 3 illustrates a heat exchanger tube, referred in Figure 3 by numeral 300, comprising hemispherical dimples 302 on the surface, wherein the hemispherical dimples 302 are arranged inline on the heat exchanger tube 300. Figure 4 illustrates a heat exchanger tube, referred in Figure 4 by numeral 400, comprising hemispherical dimples 402 on the surface, wherein the hemispherical dimples are oriented in a staggered pattern. Figure 5 illustrates a heat exchanger tube, referred in Figure 5 by numeral 500, comprising hemispherical dimples 502 on the surface, wherein the hemispherical dimples 502 are oriented at an angle of 10 degrees to the flow in a staggering pattern. Figure 6 illustrates a heat exchanger tube, referred in Figure 6 by numeral 600, comprising ovular dimples 602 on the surface, wherein the ovular dimples 602 are oriented in a helical pattern. Although, the dimpled tube configurations as illustrated in Figure 3, 4, 5 and 6 increase heat transfer efficiency of the heat exchanger by providing turbulence, at a high Reynolds number flow result in excessive pressure loss which substantially affects the efficiency of the heat exchanger; the experimental data showing the performance of a dimpled tube configuration with respect to Reynolds number is illustrated in Figure 15, where it is seen that with an increase in the Reynolds number the efficiency of the heat exchanger tube comprising a dimple configuration is decreased.

Therefore, there is a need to provide a heat exchanger tube with alterations which substantially enhance the overall thermal efficiency of the heat exchanger while providing a low pressure drop and reducing the size of the heat exchanger, thereby providing a cost-effective compact heat exchanger capable of handling relatively high performance applications. Several attempts have been made to provide heat exchangers with modified tubes that give the aforementioned benefits, some of the related patent documents are listed in the following section dealing with the prior art.

US 2009/0229801 discloses a tube configuration for a heat exchanger, typically a radiator, the tube configuration comprising a plurality of protuberances formed on the inner surface of the tube such that the cross-sectional hydraulic area along the length of the tube is kept constant. The tube as disclosed in US 2009/0229801 has a rectangular cross-section with circular, rectangular, oval, square, or oblong protuberances along the longitudinal axis. The tube configuration as disclosed in US 2009/0229801 is suitable only for radiators used in automobiles.

US 2005/0161209 discloses a tubular heat exchanger provided with at least one pair of dimples which are extruded into at least one tube of the heat exchanger by deforming the tube wall inwardly; the dimples of each pair being provided in a facing relationship but being offset from each other in a direction parallel to a longitudinal axis of the tube. The offset design allows each dimple to protrude beyond the centerline of the tube enhancing turbulence in the heat exchanger tube during operation. The tube as claimed in US 2005/0161209 is generally U-shaped where only one of the leg portions is dimpled with elliptical concave indentations. The above disclosed invention is only applicable for serpentine tube heat exchangers.

EP 1179719 discloses a method for making a heat exchanger tube comprising an elongated strip of aluminum based material with dimples formed in a row on the surface of the strip such that the dimples project from the other side of the strip, the strip is folded to obtain two rows of dimples one above the other and with their projections facing each other. A slit is placed between the apexes of the two rows of dimples to close the passage between dimples creating flow paths. The dimples are employed for inducing turbulence and/or providing pressure resistance within the interiors of the heat exchanger tube.

US 4043388 discloses a heat exchanger for transmitting thermal energy from one fluid to another fluid. The heat exchanger comprises a casing containing a folded sheet of heat conductive material, each folded section comprising a multiplicity of pairs of dimples formed therein, wherein each dimple pair including a raised dimple and an adjacent depressed dimple having height one-half the width of the fluid passage. The arrangement provides a low pressure drop for the fluid passing through the fluid passages. US 4043388 discloses a particular structure for a heat exchanger comprising a casing and folded sheets with pairs of dimples forming a flow path therethrough. US 3664928 discloses a heat transfer wall particularly for a distillation device having a plurality of dimples which protrude from the evaporating surface forming a tortuous flow path between the plurality of dimples. The dimpled heat transfer walls enhance the overall effective heat transfer surface of the walls; however, the dimpled heat transfer walls as disclosed in US 3664928 are particularly applicable only for distillation apparatus. Document US 4690211 discloses a heat exchanger tube comprising a tubular body having a circular cross section wherein a plurality of ovular indentations in a direction substantially parallel to the longitudinal tube axis is formed and wherein the indentations are oriented on the wall of said tubular body in a helical pattern. Therefore, there is a need for an improved heat exchanger tube configuration that overcomes the drawbacks listed in the prior art and which can be used effectively for enhancement of the heat transfer coefficient in the heat exchanger and make the heat exchanger more compact.

OBJECTS OF THE INVENTION

An object of the present invention is to provide a heat exchanger tube for enhancement of the heat transfer coefficient higher than that offered by conventional heat transfer enhancements in tubes.
Another object of the present invention is to provide a heat exchanger tube which can operate efficiently over a wide range of Reynolds number.

Still another object of the present invention is to provide a heat exchanger tube which would lead to a compact heat exchanger.

Yet another object of the present invention is to provide a heat exchanger tube which is adapted to meet both the criteria of a low pressure drop and a low boundary layer thickness.

One more object of the present invention is to provide a heat exchanger tube which will lead to less frictional losses.

Still one more object of the present invention is to provide a heat exchanger tube which is suitable for various applications such as water, smoke, fire tube boilers or heat exchangers.

Yet one more object of the present invention is to provide a heat exchanger which is less in cost and economical to operate.

In accordance with the present invention is provided a heat exchanger tube, said heat exchanger tube comprising:

- a tubular body defined by a wall having an exterior surface, an interior surface, and a conduit through said tubular body defining a longitudinal axis; and
- a plurality of ovular indentations directionally substantially parallel to said axis formed in said wall extending from said exterior surface and protruding through said interior surface of said wall, said plurality of ovular indentations defined by a relatively wide end and a relatively narrow end, said wide end being arranged in the upstream direction of the flow relative to said narrow end.

Typically, in accordance with the present invention, said plurality of ovular indentations form humped protrusions on said interior surface of said tubular body. In accordance with the present invention, the ratio of the width of said wide end (W1) to the width of said narrow end (W2) is between 1.25 to 3.75.

Additionally, in accordance with the present invention, the cumulative volume of said plurality of ovular indentations is between 1.5% to 3.5% of the volume of said conduit. In accordance with the present invention, said plurality of ovular indentations are oriented at an inclination. In accordance with the present invention, said plurality of ovular indentations are oriented in a helical pattern.

The invention will now be described with reference to the accompanying drawings, in which;

Figure 1 illustrates a helical tube insert having a circular cross-section;

Figure 2 illustrates a helical tube insert having a square cross-section;

Figure 3 illustrates a heat exchanger tube having hemispherical dimples arranged inline on the tube surface;

Figure 4 illustrates a heat exchanger tube having hemispherical dimples oriented in a staggered pattern on the tube surface;

Figure 5 illustrates a heat exchanger tube having hemispherical dimples oriented in a staggering pattern at an angle of 10 degrees to the flow;

Figure 6 illustrates a heat exchanger tube having ovular dimples oriented in a helical pattern on the tube surface;

Figure 7 illustrates a heat exchanger tube having a plurality of ovular indentations in a direction substantially parallel to the longitudinal tube axis;

Figure 8 illustrates a heat exchanger tube having a plurality of ovular indentations arranged in a staggered pattern along the tube surface;

Figure 9 illustrates a heat exchanger tube having a plurality of ovular indentations oriented in a staggering pattern.
at an angle of 10 degrees to the flow;

**Figure 10** illustrates a heat exchanger tube having a plurality of ovular indentations arranged helically on the tube surface;

**Figure 11** illustrates a graph plotted with friction factor on y-axis and Reynolds number on x-axis for a helical tube insert having a circular cross-section with 3 mm dia. and 15mm pitch;

**Figure 12** illustrates a graph plotted with Nusselt number on y-axis and Reynolds number on x-axis for a helical tube insert having a circular cross-section with 3 mm dia. and 15mm pitch;

**Figure 13** illustrates a graph plotted with friction factor on y-axis and Reynolds number on x-axis for a helical tube insert having a square cross-section with 3 mm side and 15mm pitch;

**Figure 14** illustrates a graph plotted with Nusselt number on y-axis and Reynolds number on x-axis for a helical tube insert having a square cross-section with 3 mm side and 15mm pitch; and

**Figure 15** illustrates a graph plotted with heat transfer enhancement efficiency on y-axis and Reynolds number on x-axis for hemispherical dimple tube configuration and the ovular indentation heat exchanger tube configuration of the present invention (by using experimental data and computational fluid dynamics (CFD) simulation); and

**Figure 16** illustrates a graph plotted with possible area reduction of heat exchanger on y-axis and Reynolds number on x-axis for hemispherical dimple tube configuration and the ovular indentation heat exchanger tube configuration of the present invention (by using experimental data and computational fluid dynamics (CFD) simulation).

**DETAILED DESCRIPTION OF THE ACCOMPANYING DRAWINGS**

[0035] The invention will now be described with reference to the accompanying drawings which do not limit the scope of the invention. The description provided is purely by way of example and illustration.

[0036] The present invention envisages a heat exchanger tube for enhancing the heat transfer efficiency of a heat exchanger. The heat exchanger tube of the present invention comprises a plurality of ovular indentations formed directionally substantially parallel on the surface of the heat exchanger tube and streamlined to the fluid flow; such as to increase turbulence, reduce the boundary layer thickness, and minimize pressure drop in the fluid flowing through the heat exchanger tube. The heat exchanger tube of the present invention can be used over a wide range of Reynolds number flow for a variety of boilers/heat exchangers including water, smoke, and fire tube boilers/heat exchangers. The heat exchanger tube of the present invention comprises a tubular body which is defined by a wall having an exterior surface, an interior surface, and a conduit through the tubular body which defines longitudinal axis. A plurality of ovular indentations are provided directionally substantially parallel to the longitudinal axis in the wall, wherein the plurality of ovular indentations extend from the exterior surface and protrude through the interior surface of the wall such as to form humped protrusions on the interior surface of the tubular body. The plurality of ovular indentations of the heat exchanger tube of the present invention are further characterized by a relatively wide end and a relatively narrow end, wherein the wide end is arranged in the upstream direction of the flow relative to the narrow end.

[0037] Referring to Figures 7, 8, 9 and 10, therein are disclosed several heat exchanger tubes having separate features of the present invention. The heat exchanger tube of the present invention comprises a tubular body which is defined by a wall having an exterior surface, an interior surface, and a conduit through the tubular body which defines longitudinal axis. A plurality of ovular indentations are provided directionally substantially parallel to the longitudinal axis in the wall, wherein the plurality of ovular indentations extend from the exterior surface and protrude through the interior surface of the wall such as to form humped protrusions on the interior surface of the tubular body. The plurality of ovular indentations of the heat exchanger tube of the present invention are further characterized by a relatively wide end and a relatively narrow end, wherein the wide end is arranged in the upstream direction of the flow relative to the narrow end.

[0038] The ratio of W1 (width of the wide end of the ovular indentation) to W2 (width of the narrow end of the ovular indentation) is between 1.25 and 3.75. Further, the cumulative volume of the plurality of ovular indentations is between 1.5 and 3.5 % of the volume of the conduit through the tubular body. The plurality of ovular indentations of the present invention is oriented at an inclination in a helical pattern and can be distributed continuously or discontinuously along the length of the wall of the tubular body. Further, the plurality of ovular indentations can be symmetrical or asymmetrical to each other with respect to the dimensions such as height, volume, surface area, depth etc. The heat exchanger tube of the present invention is made by rolling, pressing, attaching, brazing, welding, etc., wherein the plurality of ovular indentations and the tubular body can be made from the same or different material.

[0039] Referring to Figure 7 therein is disclosed a heat exchanger tube, wherein the plurality of ovular indentations 710 are arranged inline along the wall of the tubular body 702. The heat exchanger tube, referenced in Figure 7 by numeral 700, illustrates the tubular body 702 showing the exterior surface 704 and the interior surface 706. The conduit through the tubular body 702 defines the longitudinal axis which is referenced by numeral 708. The plurality of ovular indentations 710 showing the wide end 716 and the narrow end 718, wherein W1 is referenced by 712 and W2 is referenced by numeral 714. Figure 8 discloses a heat exchanger tube, referenced by numeral 800, wherein the plurality
of ovular indentations 804 are arranged in a staggering pattern along the wall of the tubular body 802. In the ovular indentation 804, the W1 is referenced by numeral 808 and W2 is referenced by 806. Figure 9 discloses a heat exchanger tube, referenced by numeral 900, wherein the plurality of ovular indentations 908 are oriented in a staggering pattern at an angle of 10 degrees to the fluid flow, along the wall of the tubular body 902 showing the exterior surface 904 and the interior surface 906. The ovular indentations 908 illustrating the wide end 910 and the narrow end 912 with the W1 and W2 being illustrated by numerals 916 and 914, respectively. Figure 10 illustrates a heat exchanger tube, referenced by numeral 1000, wherein the plurality of ovular indentations 1020 are oriented helically along the walls of the tubular body 1010. The wide end and the narrow end of the ovular indentations 1020 is represented by numerals 1040 and 1030 respectively.

[0040] The performance of the heat exchanger tubes with the ovular indentations (as shown in Figures 7, 8, 9 &10), disclosed in the present invention, is sensitive to the fluid flow direction, therefore, the indentations are provided directionally substantially parallel to the longitudinal axis with the wide end being upstream to the direction of flow relative to the narrow end. The upstream and down stream profiles of the plurality of ovular indentations is so chosen, that flow separation is minimized. Further, the ovular indentations are filleted to avoid stress concentration. As the flow encounters the ovular indentations, an adverse pressure gradient zone is formed around them, which thereby decreases the thickness of the boundary layer and enhances the level of turbulence near the wall. This combined effect of reduced pressure drop and increased turbulence level helps in increasing the convective heat transfer inside the heat exchanger tube.

[0041] The present invention further aims at developing a heat exchanger tube in accordance with the present invention using the computational fluid dynamics (CFD) simulation. The method of performing the CFD simulation and validation criteria for heat exchanger tubes with the plurality of ovular indentations is explained herein. To achieve this, first a parametric solid modeling was done for the helical tube inserts having circular and square cross sections (Figure 1 and Figure 2) and for the dimpled tube configurations (Figure 3 to Figure 6). Subsequently, a computational fluid dynamics (CFD) based approach was used to predict the heat transfer characteristics for a given heat exchanger tube and the results were validated using experimental data available in the literature. The data used for validation was chosen in such a way that it represented the typical baseline case for the tube inserts and the dimpled tube configurations (hemispherical and ovular). Furthermore, an ovular dimpled tube configuration was conceptualized to still enhance the heat transfer efficiency. This configuration was also studied and validated using the CFD approach for its improved performance.

[0042] The parametric modeling was done for the following configurations:

- Helical tube inserts of circular cross-section of 3mm diameter, and square cross-section of 3mm side, as shown in Figures 1 & 2.
- Hemispherical and ovular dimpled tube configurations, wherein the dimpled tubes can be oriented to the fluid flow direction at an angle, as shown in Figures 3, 4, 5, & 6.
- Heat exchanger tubes with plurality of ovular indentations which can be streamlined to the fluid flow, as shown in Figures 7, 8, 9, & 10.
- The critical parameters of the dimples/indentations considered during modeling were: W1 and W2, the ratio of W1 to W2, the height/distance between the wide end and the narrow end of the ovular indentations, the profile of the ovular section can be straight or curved to avoid excessive drag, the fillet radius with respect to the tube surface, the ends can be hemispherical or ovular to avoid excessive drag, the relative angle of the dimple/indentation with respect to the flow direction.
- All the dimples/indentations are arranged in-line, helically or staggered, with a suitable relative spacing longitudinally as well as azimuthally, as shown in Figures 3, 4, 5, 6, 7, 8, 9 & 10.

[0043] Validation of CFD simulation approach is done with the experimental data available for:

- Helical tube inserts of:
  - Circular cross-section of 3mm diameter, and
  - Square cross-section of 3mm side.
- Helical hemispherical dimpled tube configuration
The following parameters were considered while creating the solid model for the dimpled tubes:

W1 and W2 of the dimple/ovular indentation, pitch in circumferential and longitudinal directions, angle of the major axis or the minor axis of the dimple/ovular indentation with the flow direction, tube inside diameter (ID) and tube outside diameter (OD), tube length and fillet radius. Besides these parameters, the volume of the dimples/ovular indentations was kept the same for purpose of comparison.

Computational domain and boundary conditions:

A uniform heat flux of 100W/m² was applied on the wall. For all the cases, tube wall thickness was taken as 1.5mm and constant shell conduction condition was applied. Translational-periodic boundary condition was used to simulate fully developed flow regimes and the mass flow rate was varied to match the Reynolds number.

CFD Modeling:

In order to use CFD for predicting the performance of the heat exchanger tube of the present invention, first the approach was validated using experimental data from the literature for helical tube inserts. Fully developed flow simulated for two different configurations with five different Reynolds numbers for each case was used for comparison. The turbulent flow was modeled using Reynolds-averaged Navier-Stokes (RANS) approach with appropriate near wall modeling to capture the laminar sub-layer within the turbulent boundary layer. The validation was extended further using experimental data of hemispherical dimpled tube configuration. For each Reynolds number case, computational grid was refined in such a way that final results reported are independent of overall grid size and near wall resolution. Tests were performed on helical tube inserts having a circular and square cross-section and the analysis was extended for the different tube configurations. The analysis is reported in Figures 11, 12, 13 and 14.

TEST RESULTS:

Figure 11 illustrates a graph plotted with friction factor on y-axis and Reynolds number on x-axis for the helical tube insert (as shown in Figure 1) having a circular cross-section with 3 mm dia. and 15mm pitch, the graph is generally indicated by reference numeral 1100; and Figure 12 illustrates a graph plotted with Nusselt number on y-axis and Reynolds number on x-axis for a helical tube insert (Figure 1) having a circular cross-section with 3 mm dia. and 15mm pitch, the graph is generally indicated by reference numeral 1200. Experimental data for helical tube insert (Figure 1) having a circular cross-section is provided in "Thermal performance in circular tube fitted with coiled square wires," of Energy conversion and management by Pongjet Promvonge. Results obtained from both experimental data and CFD simulation are plotted in 1100 and 1200, and it is clearly seen that the data plotted using the CFD simulation matches with the experimental data and follows an identical path. Therefore, it can be assumed that the data obtained from the CFD simulation represents the real-time experimental data within the specified experimental uncertainty and can be used as actual.

Figure 13 illustrates a graph plotted with friction factor on y-axis and Reynolds number on x-axis for a helical tube insert having a square cross-section with 3 mm side and 15mm pitch, the graph is generally indicated by reference numeral 1300; Figure 14 illustrates a graph plotted with Nusselt number on y-axis and Reynolds number on x-axis for a helical tube insert having a square cross-section with 3 mm side and 15mm pitch, the graph is generally indicated by reference numeral 1400. Experimental data for a helical tube insert having a square cross-section is also provided in "Thermal performance in circular tube fitted with coiled square wires," of Energy conversion and management by Pongjet Promvonge. Results obtained from the experimental data and CFD simulation are plotted in 1300 and 1400, and again it is evident that data plotted using the CFD simulation matches with the experimental data and follows an identical path. Therefore, it can be assumed that the data obtained through the CFD simulation represents the real-time experimental data within the specified experimental uncertainty and can be used as actual.

Figure 15 illustrates a graph plotted with heat transfer enhancement efficiency on y-axis and Reynolds number on x-axis for hemispherical dimple tube configuration and the ovular indentation heat exchanger tube of the present invention (by using experimental data and computational fluid dynamics (CFD) simulation), the graph is indicated by reference numeral 1500. Experimental data for the hemispherical dimple tube configuration is provided in "Heat Transfer and pressure drop for low Reynolds turbulent flow in helically dimpled tubes," International Journal of Heat and Mass Transfer by P.G. Vicente et al. In Figure 15, the hemispherical dimpled tube (experimental data and CFD simulation) is represented by numbers 1 & 2 respectively; and the ovular indentation tube (experimental data of the present invention and CFD simulation) is represented by numbers 4 & 3 respectively. It is observed in Figure 15 that the heat transfer enhancement efficiency of the ovular indentation tube of the present invention is higher than that of the hemispherical dimpled tube.
Figure 16 illustrates a graph plotted with possible area reduction of heat exchanger on y-axis and Reynolds number on x-axis for hemispherical dimple tube configuration and the ovular indentation heat exchanger tube configuration of the present invention (by using experimental data and computational fluid dynamics (CFD) simulation), the graph is indicated by reference numeral 1600. Experimental data for the hemispherical dimple tube configuration is provided in "Heat Transfer and pressure drop for low Reynolds turbulent flow in helically dimpled tubes," International Journal of Heat and Mass Transfer by P.G. Vicente et al. In Figure 16, the hemispherical dimpled tube (experimental data and CFD simulation) is represented by numbers 1 & 2 respectively; and the ovular indentation tube (experimental data of the present invention and CFD simulation) is represented by numbers 4 & 3 respectively. It is observed in Figure 16 that the total area of heat exchanger using the ovular indentation tube of the present invention is substantially less than the total area of heat exchanger using the hemispherical dimpled tube.

A heat exchanger tube for enhancement of heat transfer efficiency, in accordance with the present invention has several technical advantages including but not limited to the realization of:

• a heat exchanger tube for enhancement of heat transfer coefficient;
• a heat exchanger tube which can operate efficiently over a wide range of Reynolds number;
• a heat exchanger tube which would lead to a compact heat exchanger;
• a heat exchanger tube which is adapted to meet both the criteria of low pressure drop and low boundary layer thickness;
• a heat exchanger tube which will lead to less frictional losses;
• a heat exchanger tube which is suitable for various applications such as water, smoke, fire tube boilers or heat exchangers; and
• a heat exchanger which is less in cost and economical to operate.

The numerical values mentioned for the various physical parameters, dimensions or quantities are only approximations and it is envisaged that the values higher/lower than the numerical values assigned to the parameters, dimensions or quantities fall within the scope of the invention, unless there is a statement in the specification specific to the contrary.

Claims

1. A heat exchanger tube comprising:

   a tubular body (702, 802, 902, 1010) having a circular cross section defined by a wall having an exterior surface (704, 904), an interior surface (706, 906), and a conduit (708) through said tubular body (702, 802, 902, 1010) defining a longitudinal axis and a direction of a flow of a fluid inside the tubular body (702, 802, 902, 1010), wherein a plurality of ovular indentations (710, 804, 908, 1020) in a direction substantially parallel to said axis is formed in said wall extending from said exterior surface (704, 904), which protrude through said interior surface (706, 906) of said wall and are oriented on the wall of said tubular body in a helical pattern, each of said plurality of ovular indentations (710, 804, 908, 1020) in a direction substantially parallel to said axis is formed in said wall extending from said exterior surface (704, 904), which protrude through said interior surface (706, 906) of said wall and are oriented on the wall of said tubular body in a helical pattern, each of said plurality of ovular indentations (710, 804, 908, 1020) being defined by a relatively wide end (716, 910, 1040) and a relatively narrow end (718, 912, 1030), wherein the ratio of the width of said wide end (W1) to the width of said narrow end (W2) is between 1.25 and 3.75, wherein said narrow end is filleted, said wide end (716, 910, 1040) being arranged in the upstream direction of the flow relative to said narrow end (718, 912, 1030), characterized in that said plurality of ovular indentations are oriented at an inclination from side wide end to said narrow end to have said wide end (W1) arranged in the upstream direction of the flow relative to said narrow end (W2), and the cumulative volume of said plurality of ovular indentations is between 1.5 and 3.5% of the volume of said conduit.

2. The heat exchanger tube as claimed in claim 1, wherein said plurality of ovular indentations (710, 804, 908, 1020) form humped protrusions on said interior surface (706, 906) of said tubular body (702, 802, 902, 1010).

Patentansprüche

1. Wärmetauscherrohr, Folgendes umfassend:

   Ein Rohrkörper (702, 802, 902, 1010) mit einem kreisförmigen Querschnitt, der durch eine Wand mit einer Außenfläche (704, 904), eine Innenfläche (706, 906) und einen Kanal (708) durch den Rohrkörper (702, 802,
1. Un tube pour échangeur de chaleur comprenant :

un corps tubulaire (702, 802, 902, 1010) dont la section transversale circulaire est définie par une paroi dotée d’une face externe (704, 904), d’une face interne (706, 906) et d’un conduit (708) traversant le corps tubulaire en question (702, 802, 902, 1010), définissant un axe longitudinal et le sens d’écoulement d’un fluide à l’intérieur du corps tubulaire (702, 802, 902, 1010) ;

où

plusieurs indentations ovales (710, 804, 908, 1020), dont la direction est sensiblement parallèle à celle de l’axe, sont façonnées dans la paroi susmentionnée s’étendant depuis la face externe (704, 904) pour faire saillie sur la face interne (706, 906) de la paroi, et sont orientées sur la paroi du corps tubulaire selon un modèle hélicoïdal. Chacune de ces indentations ovales (710, 804, 908, 1020) est définie par une extrémité relativement large (716, 910, 1040) et une extrémité relativement étroite (718, 912, 1030), où le rapport de largeur entre l’extrémité large (W1) et l’extrémité étroite (W2) est compris entre 1,25 et 3,75. L’extrémité étroite est arrondie, tandis que l’extrémité large (716, 910, 1040) se trouve en amont du sens d’écoulement par rapport à l’extrémité étroite (718, 912, 1030), caractérisé en ce que

lesdites différentes indentations ovales sont inclinées depuis l’extrémité latérale large vers l’extrémité étroite de façon à ce que l’extrémité large (W1) se trouve en amont du sens d’écoulement par rapport à l’extrémité étroite (W2) et que le volume cumulé des différentes indentations ovales soit compris entre 1,5 % et 3,5 % du volume du tube en question ;

2. Le tube pour échangeur de chaleur de la Demande 1, où les différentes indentations ovales (710, 804, 908, 1020) forment des saillies arrondies sur la face interne (706, 906) du corps tubulaire (702, 802, 902, 1010).
Friction factor vs Reynolds number

FIGURE 11
FIGURE 12
FIGURE 14
FIGURE 15
REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 20090229801 A [0020]
- US 20050161209 A [0021]
- EP 1179719 A [0022]
- US 404388 A [0023]
- US 3664928 A [0023]
- US 4690211 A [0023]

Non-patent literature cited in the description