

## Description

This invention is concerned with new shell and tube apparatus for heat transfer and with a new process for heat transfer, as employed in such apparatus.

It is a constant endeavour in the field of heat transfer to improve the efficiency of heat transfer processes in order to improve the efficiency and also if possible lower the cost of the apparatus employing the improved process. To this end a number of prior proposals have been made among which are:

a) reducing the thickness of the boundary-layers of the fluid flowing in a passage by the promotion of turbulence in the fluid flow, for example by roughening the flow passage walls and/or the provision of turbulence promoters in the passage (see GB 1172247, US 1862219).

b) the induction of boundary-layer separation from the heat transfer surfaces by use of curved or wavy heat transfer surfaces (see e.g. "Heat Transfer Handbook" by A.P.V. Company Inc. of Tonawanda, New York, and W. M. Kays and A. L. London "Compact Heat Exchangers" 2nd edition, p. 216—217, McGraw Hill Series in Mechanical Engineering, New York, 1964), and

c) the interruption of the heat transfer surfaces, as with the so-called "split-fin" apparatus (see US 2360123, and p. 212 of "Compact Heat Exchanges").

A frequent serious problem with such proposals is that, although the promotion of turbulence of the interruption of the heat transfer surfaces in laminar flow do increase the heat transfer per unit area, they also cause a disproportionate increase in the pumping power per unit area required to maintain the fluid flow at the required rate, because of the increased turbulence and inefficient laminar flow diffusion mixing, and a consequent considerable increase in manufacturing cost, with the result that in commercial practice therefore the undesirable results prevent the adoption of such proposals in many cases unless there is an overriding need, for example, for compactness in size.

EP—A—42613 describes a new process and apparatus for heat transfer by which the heat transfer can be increased without a corresponding disproportionate increase in pumping power, and with avoidance of turbulence in the presence of laminar wake-interference flow.

More specifically, EP—A—42613 discloses shell and tube heat exchange apparatus for heat exchange between two fluids comprising:

a shell having an inner wall, an inlet to the interior thereof and an outlet therefrom for the passage of a respective fluid through the shell space in the shell interior;

at least one tube mounted within the shell having an inner and an outer surface and having an inlet to the interior thereof and an outlet therefrom for the passage through the tube interior of a respective fluid, each tube wall constituting a heat exchange wall between the

two fluids in the shell interior and the tube interior;

fluid flow within the tube interior taking the form of a non-turbulent boundary layer immediately adjacent to the tube inner surface, and a core-layer interfacing with the boundary-layer;

a tube-side fluid flow interrupter structure within each tube comprising a plurality of longitudinally extending rows of spheroidal members contacting the inner wall of the passage, the structure interrupting non-turbulently the full development of at least the boundary-layer at the tube inner surface at a plurality of spaced interruption spots, whereby parts of the interrupted boundary-layer will separate non-turbulently from the tube inner surface between the interruption spots and mix with the core layer to effect heat transfer between the tube inner surface, its respective boundary-layer and the core-layer; and

the space between the longitudinally extending rows being filled with a space-filling material to prevent useless flow of fluid in the part of the tube interior remote from the tube inner surface.

An object of the present invention is to provide an improvement on such apparatus, permitting easier manufacture, assembly and disassembly.

According to the present invention, in a shell and tube heat exchanger as just described, the spheroidal members (28) and the space-filling material (58) constitute a unitary body, the spheroidal members protruding from the body engaging the inner wall of the tube (20).

Preferably fluid flow within the shell space also takes the form of a non-turbulent boundary layer immediately adjacent to the tube outer surface, and a core-layer interfacing with the boundary-layer, and there is a shell-side fluid flow interrupter structure within the shell space comprising a plurality of spheroidal members surrounding and contacting the tube outer wall, the structure interrupting non-turbulently the full development of at least the boundary-layer at the tube outer surface at a plurality of spaced interruption spots, whereby parts of the interrupted boundary-layer will separate non-turbulently from the tube outer surface between the interruption spots and mix with the core layer to effect heat transfer between the tube outer surface, its respective boundary-layer, and the core-layer; and the space between the shell-side interrupter structure spherical members and the shell inner wall is filled with a space-filling material to prevent useless flow of fluid in a part of the shell interior space remote from the tube outer surface.

The invention will now be further described, by way of example, with reference to the accompanying diagrammatic drawings wherein:

Figure 1 is a section showing the fluid flow obtained inside a heat transfer apparatus;

Figure 2 is a transverse cross-section on the line 2—2 of Figure through a single tube-in-shell heat exchanger of the prior art;

Figure 3 is a longitudinal cross-section on the line 3—3 of Figure 2;

Figure 4 is a perspective view of a unitary form of interrupter structure according to the invention for use in the interior of a heat exchanger tube.

It is known to those skilled in the art that fluid flowing within a passage has boundary-layers 30 immediately adjacent the passage surfaces 20, which act to insulate the wall surfaces from the main body of the fluid flowing in a core layer 32 between the interfacing with the boundary layers 30, and which therefore reduce the heat transfer between the surfaces 20 and the core layer 32. It is also known that an unobstructed boundary layer increases progressively in thickness in the direction of fluid flow, which will increase its insulating effect.

As disclosed in EP—A—42613 the boundary layers 30 are interrupted in a "spot-wise" manner at spaced spots 34 by means of fluid flow interrupter spheres 28 interposed between the heat transfer surfaces, while maintaining a non-turbulent fluid flow in the core 32. Not only are the heat transfer surfaces 20 not roughened, etc., but on the contrary they are made as smooth as is economically possible, to the extent that in many embodiments the surfaces 20 will be polished to the desired degree of smoothness. The disruption of the boundary layers 30 at the multitude of spaced spots 34 ensures that they stay thin, while the manner of their disruption ensures that turbulence is avoided that would cause unduly high friction drag. The polishing of all surfaces including those of the spheres also assists in the desired minimizing of the friction drag.

Thus, the ratio of convective heat transfer to friction power per unit heat transfer surface area is improved by providing specially shaped interrupting and mixing structures of low friction drag immediately adjacent a smooth heat transfer surface using hydraulic radii that guarantee total laminar flow. The mixing structures contain cellular voids, which are connected with one another. In each of which the fluid rotates spiral-like as a single laminar eddy. These eddies are very efficient means of mixing laminar streams, and preferably are obtained by coinciding a wake eddy downstream of an interruption point with an advance eddy upstream of a subsequent interruption point so as to produce wake-interference flow, which provides the highest efficiency. The boundary layers 30 on the curved surfaces of the mixing structures are fairly thick, whereas the boundary layers of the heat transfer surfaces, situated opposite the mixing-structure surfaces, remain very thin on average because they are reduced regularly and spotwise at the large number of contact points between the surface of the mixing structure and the heat transfer surface, and are in addition exposed to the highest local velocities which occur predominantly very close to the flat heat transfer surface. This allows rapid heat flow through the heat transfer surface.

It is also believed that efficiency is improved because the velocity gradients adjacent to the heat transfer surfaces are much larger than over the curved surfaces of the interrupting mixing

structure. These velocity gradients are, moreover, maintained largely at the heat transfer surfaces by virtue of the regularly spaced flow interruptions occurring at the large number of contact points between the mixing structure and the heat transfer surface. These interruptions also cause the flow to swirl at high velocity toward the heat transfer surface. Since it is well known from numerous experiments and theoretical analysis (see. e.g. pp 422—423. Principles of Heat Transfer, 3rd edition by F. Kreith, Publishers Harper and Row. New York, 1976) that temperature gradients are proportional to velocity gradients, the interrupting mixing structure which produces repeated steep velocity gradients similar to so-called "entrance effects", also promotes increased heat transfer while the flow remains laminar.

The general direction of flow of the fluid is indicated by arrows 31 and the flow interrupter structure causes the production of laminar flow eddies 38 of shape and rotational frequency that depend upon the geometry of the structure. Wake-eddies will be produced around the spots of interruption downstream of the flow, while advance eddies will be produced upstream of the flow. If the spacing of the interruption spots 34 is made such that the advance- and wake-eddies of immediately successive spots coincide, then wake-interference flow is obtained whereby, in the absence of turbulent friction-drag, very efficient non-turbulent mixing is obtained between the interrupted boundary-layers 30 and the adjacent core layer 32. A turbulent flow, which is to be avoided, may be distinguished from an eddy in that the former is irregular and there is no observable pattern as with an eddy. Eddies and swirls therefore do not constitute turbulence. Again a laminar eddy or vortex is confined by solid boundaries or by laminar fluid flows, while a turbulent eddy or vortex will be surrounded by other eddies and vortices which interact with the turbulent eddy or vortex. The conditions for maintenance of laminar flow with a particular structure can be observed for example by providing suitable windows in an experimental structure and adding visible fluids to the fluid flow if required.

It is not necessary for the interposed structure to touch the passage walls as long as it is sufficiently close thereto to provide the necessary extent of interruption to the boundary layers. Thus, in the illustrated embodiment the portion of each spherical surface around the actual point of contact and submerged in the boundary layer will also be effective in this interrupting function. The interrupter structure may therefore be suspended within the enclosure and not actually touch the walls, or touch the walls at fewer points than there are interruption points.

The profile of the interrupter structure elements of the structure of Figure 1 taken in the direction of flow of the fluid in the passage, is of course a circle. Other profiles can be used and should be such as to present a smoothly contoured surface to the fluid flow, so as to reduce friction losses to

a minimum and also to ensure the maintenance of laminar flow, for example an ellipsoidal profile shows an egg-shaped profile and a drop-shaped profile; in the latter two profiles the face of largest radius faces upstream.

Special situations arise for example when the fluid is very viscous, such as a viscous oil that is to be heated. When the fluid is of high viscosity the spacing apart of the parallel walls 20 of the passage can be increased considerably without the establishment of turbulent flow, but such a fluid is usually of low thermal conductivity and a thermal boundary layer will be established immediately adjacent to the heat transfer surface that is much thinner than the respective boundary layer. The interposed structure must be arranged to interrupt this thinner thermal boundary-layer irrespective of the thickness of the boundary layer. The principal factor in the determination of the thickness of the thermal boundary layer is the Prandtl number, which is high and the thermal conductivity is low.

One of the principal parameters to be considered in determining whether a particular fluid flow will be laminar and non-turbulent is the Reynolds number which is obtained by the relation:

$$R = \frac{\text{Fluid Mass Velocity} \times \text{Passage Equivalent Diameter}}{\text{Fluid Viscosity}}$$

Fluid Viscosity

Classically it was believed that with a Reynolds number less than about 4,000 the flow must be laminar, while if it was greater than about 6,000 it would become turbulent. It is not possible in the apparatus of the invention to determine the fluid velocities in the interrupter structure but only the overall velocity and the only proof that the flow will be laminar is to plot the so-called J-factor curve which will show an abrupt change in slope at the onset of turbulence. The existence of a J-factor curve of constant slope is therefore proof that laminar flow is occurring and this can occur with Reynolds numbers as high as 15,000.

The invention herein is applicable to heat exchangers of the shell and tube type. Figures 2 and 3 show a single tube-in-shell exchanger as disclosed in EP-A-42613 in which one fluid path with inlet and outlet 14 and is respectively is formed by the annular space between an outer shell 54 and an inner circular cross-section tube 22, while the other fluid path with inlet 48 and outlet 50 is of course formed by the tube 22. The annular shell space is of radial dimension just sufficient to receive flow-interrupting spheres 28 and the spaces between the spheres and the inner wall of the outer shell are completely filled with a suitable cementitious material 56 to prevent fluid flow therethrough that would be wasted. The interrupter system employed within the tube 22 comprises rows of smaller spheres that used to provide the necessary flow capacity with a sufficiently large number of interrupting points 34 both

along the length of the tube and also around its circumference. As with the shell-side interrupter system the useless space between the rows if filled with a cementitious or other suitable material 58, such as concrete or ceramic cement.

In accordance with the invention, as illustrated by the perspective view of Figure 3, the separate spheres 28 and cement 58 in which they are embedded can constitute a unitary structure formed for example by casting, so that the spheroidal members 28 protruding from the central matrix will engage the inner tube wall. Such a unitary structure can be more easily manufactured and more easily assembled into and disassembled from the apparatus. It will be noted that successive spheroidal members along the length of the structure are displaced offset circumferentially, giving the same effect as if the rows of spheroidal members had been disposed helically, with a large number of flow interruption points adjacent the tube surface 20 and enhanced reduction of the flow cross-sectional area. Similarly, the cylinder of spheroidal members and the space-filling material 56 that are disposed against the shell inner wall can constitute a cylindrical unitary structure that is slid into position and removed as a unit.

The invention is applicable to a multiple tube in shell heat exchanger in which a plurality of parallel tubes 22 are disposed within a single outer shell 54. The outer spheres 28 may be arranged in rows, circles or helices thereof with some of the spheres contacting two adjacent tubes, so that it disrupts the boundary layers of both tubes.

## Claims

1. Shell and tube heat exchange apparatus for heat exchange between two fluids comprising:  
an outer shell (54) having an inner wall, an inlet (14) to the interior thereof and an outlet (16) therefrom for the passage of the first fluid through the shell space in the shell interior;

at least one tube (22) mounted within the outer shell (54) having an inner and an outer surface and having an inlet (48) to the interior thereof and an outlet (50) therefrom for the passage through the tube interior of the second fluid, each tube wall constituting a heat exchange wall between the two fluids in the shell interior and the tube interior;

fluid flow within the tube interior taking the form of a non-turbulent boundary layer (30) immediately adjacent to the tube inner surface, and a core-layer (32) interfacing with the boundary-layer;

a tube-side-fluid flow interrupter structure within each tube comprising a plurality of longitudinally extending rows of spheroidal members (28) contacting the inner wall of the passage, the structure interrupting non-turbulently the full development of at least the boundary-layer at the tube inner surface at a plurality of spaced interruption spots, whereby parts of the

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fluid flow within the tube interior taking the form of a non-turbulent boundary layer (30) immediately adjacent to the tube inner surface, and a core-layer (32) interfacing with the boundary-layer;

a tube-side-fluid flow interrupter structure within each tube comprising a plurality of longitudinally extending rows of spheroidal members (28) contacting the inner wall of the passage, the structure interrupting non-turbulently the full development of at least the boundary-layer at the tube inner surface at a plurality of spaced interruption spots, whereby parts of the



interrupted boundary-layer will separate non-turbulently from the tube inner surface between the interruption spots and mix with the core layer to effect heat transfer between the tube inner surface, its respective boundary-layer and the core-layer; and

the space between the longitudinally extending rows being filled with a space-filling material to prevent useless flow of fluid in the part of the tube interior remote from the tube inner surface,

characterised in that the spheroidal members (28) and the space-filling material (58) constitute a unitary body, the spheroidal members protruding from the body engaging the inner wall of the tube (22).

2. Shell and tube heat exchange apparatus as claimed in claim 1 in which the first fluid flow within the shell space takes the form of a non-turbulent boundary layer immediately adjacent to the tube outer surface, and a core-layer interfacing with the boundary-layer; and including

a shell-side fluid flow interrupter structure within the shell space comprising a plurality of spheroidal members (28) surrounding and contacting the tube outer wall, the structure interrupting non-turbulently the full development of at least the boundary-layer at the tube outer surface at a plurality of spaced interruption spots, whereby parts of the interrupted boundary-layer will separate non-turbulently from the tube outer surface between the interruption spots and mix with the core layer to effect heat transfer between the tube outer surface, its respective boundary-layer, and the core-layer;

the space between the shell-side interrupter structure spherical members and the shell inner wall being filled with a space-filling material (56) to prevent useless flow of a fluid in a part of the shell interior space remote from the tube outer surface.

3. Shell and tube heat exchange apparatus as claimed in claim 2, and comprising a plurality of tubes mounted within the shell interior parallel to one another, wherein some of the spheres of the shell-side interrupting structure contact the outer surface of more than one tube.

4. Shell and tube heat exchange apparatus as claimed in claim 1, 2 or 3 wherein the spacing of immediately successive spaced interruption spots in the direction of flow is such that wake-interference flow is established between the said successive spots.

5. Shell, and tube heat exchange apparatus as claimed in any preceding claim, wherein the spheroidal elements are disposed in a helical configuration.

#### Patentansprüche

1. Wärmeaustauschvorrichtung zum Austauschen von Wärme zwischen zwei Fluiden,

bei der ein äußeres Gehäuse (54) eine Innenwand, einen Einlaß (14) ins Innere davon und einen Auslaß (16) daraus zum Durchtritt des ersten Fluidums durch den Gehäuse-Innenraum aufweist,

bei der in dem äußeren Gehäuse (54) mindestens ein Rohr (22) angeordnet ist, das eine Innenfläche und eine Außenfläche sowie einen Einlaß (48) zum Inneren und einen Auslaß (50) zum Durchtritt von Fluidum durch das Rohrrinnere aufweist und bei dem jede Rohrwand eine Wärmeaustauschwand zwischen den zwei Fluiden im Gehäuseinneren und im Rohrrinneren darstellt,

wobei der Fluidum-Strom im Rohrrinneren die Form einer nicht-turbulenten Grenzschicht (30) unmittelbar an der Rohr-Innenfläche und einer an die Grenzschicht angrenzenden Kernschicht (32) einnimmt,

bei der ein in jedem Rohr vorgesehenes rohrseitiges Strömungsunterbrecher-Gebilde eine Vielzahl von langgestreckten Reihen von kugeligen Gliedern (28), welche die innere Wand des Durchtrittes berühren, aufweist und in nicht-turbulenter Weise die volle Entwicklung wenigstens der Grenzschicht an der Innenfläche des Rohres an einer Vielzahl von Abstand voneinander aufweisenden Unterbrechungsstelle unterbricht, wobei Teile der unterbrochenen Grenzschicht sich zwischen den Unterbrechungsstellen auf nicht-turbulente Weise von der Rohr-Innenfläche trennen und sich mit der Kernschicht mischen, um eine Wärmeübertragung zwischen der Rohr-Innenfläche, der entsprechenden Grenzschicht und der Kernschicht zu bewirken, und bei der der Raum zwischen den langgestreckten Reihen mit einem raumfüllenden Material gefüllt ist, um in dem von der Rohr-Innenfläche ferngelegenen Teil des Rohrrinneren nutzlosen Fluidumfluß zu verhindern,

dadurch gekennzeichnet, daß die kugeligen Glieder (28) und das raumfüllende Material (58) einen einheitlichen Körper bilden, wobei die kugeligen Glieder von dem Körper unter Berührung der inneren Wand des Rohres (22) vorragen.

2. Wärmeaustauschvorrichtung nach Anspruch 1, wobei der erste Fluidum-Strom in dem Gehäuse-Raum die Form einer nicht-turbulenten Grenzschicht unmittelbar an der Rohr-Außenfläche und einer an die Grenzschicht angrenzenden Kernschicht einnimmt, dadurch gekennzeichnet, daß ein gehäusesseitiges Strömungsunterbrecher-Gebilde in dem Gehäuse-Raum eine Vielzahl von kugeligen Gliedern (28) aufweist, welche die äußere Rohrwand umgeben und berühren, und in nicht-turbulenter Weise die volle Entwicklung wenigstens der Grenzschicht an der Außenfläche des Rohres an einer Vielzahl von Abstand voneinander aufweisenden Unterbrechungsstellen unterbricht, wobei Teile der unterbrochenen Grenzschicht sich zwischen den Unterbrechungsstellen auf nicht-turbulente Weise von der Rohraußenfläche trennen und sich mit der Kernschicht mischen, um eine Wärmeübertragung zwischen der Rohr-Außenfläche, der entsprechenden Grenzschicht und der Kernschicht zu bewirken,

und daß der Raum zwischen den kugeligen Gliedern des gehäusesseitigen Strömungsunterbrecher-Gebildes und der Rohr-Trennwand mit einem raumfüllenden Material (56) gefüllt ist, um in einem von der Rohr-Außenfläche ferngelegenen Teil des Rohrrinnenraumes nutzlosen Fluidum-



fluß zu verhindern.

3. Wärmeaustauscher nach Anspruch 2, dadurch gekennzeichnet, daß im Inneren des Gehäuses eine Vielzahl von zueinander parallelen Rohren angeordnet ist und einige der Kugeln des gehäuseseitigen Unterbrecher-Gebildes die Außenfläche von mehr als einem Rohr berühren.

4. Wärmeaustauschvorrichtung nach Anspruch 1, 2 oder 3, dadurch gekennzeichnet, daß der Abstand von einander unmittelbar folgenden Unterbrechungsstellen in Strömungsrichtung derart ist, daß eine Sog-Interferenz-Strömung zwischen den einander folgenden Unterbrechungsstellen gebildet ist.

5. Wärmeaustauscher nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß die kugeligen Glieder in Form einer Wendel angeordnet sind.

#### Revendications

1. Appareil tubulaire échangeur de chaleur pour l'échange thermique entre deux fluides, comprenant: une enveloppe extérieure (54) qui présente une paroi interne, un orifice d'entrée (14) vers son intérieur et un orifice de sortie (16) à partir de celui-ci pour le passage du premier fluide à travers le volume de l'enveloppe dans l'intérieur de l'enveloppe; au moins un tube (22) monté dans l'enveloppe extérieure (54), présentant une surface interne et une surface externe et comportant un orifice d'entrée (48) vers son intérieur et un orifice de sortie (50) à partir de celui-ci pour le passage du second fluide à travers l'intérieur du tube, chaque paroi de tube constituant une surface d'échange thermique entre les deux fluides dans l'intérieur de l'enveloppe et l'intérieur du tube; l'écoulement de fluide dans l'intérieur du tube prenant la forme d'une couche limite non turbulente (30) à proximité immédiate de la surface interne du tube et d'une couche de coeur (32) en interface avec la couche limite; une structure interruptrice de l'écoulement du fluide du côté tube, à l'intérieur de chaque tube, comprenant plusieurs rangées dirigées longitudinalement d'éléments sphéroïdaux (28) en contact avec la paroi interne du passage, cette structure interrompant de façon non turbulente le développement complet de la couche limite au moins sur la surface interne du tube, au niveau d'une multiplicité de points d'interruption espacés, de telle manière que des parties de la couche limite interrompue se séparent de façon non turbulente de la surface interne du tube entre les points d'interruption et se mêlent à la couche de coeur pour que se produise un transfert de chaleur entre la surface interne du tube, sa couche limite respective et la couche de coeur; et le volume

entre les rangées dirigées longitudinalement étant rempli d'une matière de remplissage pour empêcher l'écoulement infructueux de fluide dans la partie de l'intérieur du tube à distance de la surface interne du tube, caractérisé en ce que les éléments sphéroïdaux (28) et la matière de remplissage (58) forment un corps unitaire, les éléments sphéroïdaux (28) qui font saillie sur le corps étant en contact avec la paroi interne du tube (22).

2. Appareil tubulaire échangeur de chaleur selon la revendication 1, dans lequel l'écoulement du premier fluide à l'intérieur du volume de l'enveloppe prend la forme d'une couche limite non turbulente à proximité immédiate de la surface externe du tube et d'une couche de coeur en interface avec la couche limite, et comprenant une structure interruptrice de l'écoulement du fluide du côté enveloppe, dans le volume intérieur de l'enveloppe, comprenant une multiplicité d'éléments sphéroïdaux (28) qui entourent la paroi extérieure du tube et sont en contact avec elle, cette structure interrompant de façon non turbulente le développement complet de la couche limite au moins sur la surface externe du tube, au niveau d'une multiplicité de points d'interruption espacés, de telle manière que des parties de la couche limite interrompue se séparent de façon non turbulente de la surface externe du tube entre les points d'interruption et se mêlent à la couche de coeur pour que se produise un transfert de chaleur entre la surface externe du tube, sa couche limite respective et la couche de coeur; et l'espace entre les éléments sphériques de la structure interruptrice du côté enveloppe et la paroi interne de l'enveloppe étant rempli d'une matière de remplissage (56) pour empêcher l'écoulement infructueux de fluide dans une partie du volume intérieur de l'enveloppe à distance de la surface externe du tube.

3. Appareil tubulaire échangeur de chaleur selon la revendication 2, et comprenant plusieurs tubes montés à l'intérieur de l'enveloppe parallèlement les uns aux autres, appareil dans lequel certaines des sphères de la structure interruptrice du côté enveloppe sont en contact avec la surface externe de plus d'un tube.

4. Appareil tubulaire échangeur de chaleur selon l'une quelconque des revendications 1 à 3, dans lequel l'écartement de points d'interruption espacés immédiatement successifs dans la direction de l'écoulement est tel qu'un écoulement de perturbation par traînée s'établisse entre lesdits points successifs.

5. Appareil tubulaire échangeur de chaleur selon l'une quelconque des revendications précédentes, dans lequel les éléments sphéroïdaux sont disposés en hélice.

