[0017] In another embodiment, the present invention is directed to a method for producing a helical flow path in a fluid flowing along a principal direction. The method comprises the step of providing a structure having a surface with a plurality of substantially linear grooves or protrusions oriented at an angle relative to the principal direction. The grooves or protrusions are formed to be parallel to and periodically spaced from each other. The method further comprises the step of causing the fluid to flow along the surface. The fluid flowing adjacent the surface has a Reynolds number that is less than about 100.

[0018] Other advantages, novel features, and objects of the invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings, which are schematic and which are not intended to be drawn to scale. In the figures, each identical, or substantially similar component that is illustrated in various figures is represented by a single numeral or notation. For purposes of clarity, not every component is labeled in every figure, nor is every component of each embodiment of the invention shown where illustration is not necessary to allow those of ordinary skill in the art to understand the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] **FIG. 1** is a schematic diagram of one embodiment of the present invention illustrating a system with channels defined in a substrate;

[0020] **FIG. 2***a* is a schematic diagram showing a perspective view of one embodiment of the mixing apparatus with a fluid flowing therethrough;

[0021] **FIG. 2***b* is an elevational view of the embodiment of **FIG. 2***a* illustrating the grooves defined on a channel wall thereon;

[0022] **FIG. 3** is a schematic diagram of one embodiment of the invention showing a channel having various configurations of grooves;

[0023] **FIG. 4***a* is a schematic diagram of one embodiment of the invention showing a top elevational view of a mixing apparatus having grooves;

[0024] **FIG. 4***b* is a diagram of the apparatus of **FIG. 4***a* along b-b schematically showing the transverse or helical flow component of a flowing fluid;

[0025] **FIG. 4***c* is a copy of a micrograph showing the transverse or helical flow component created within a fluid flowing in a mixing apparatus having grooves according to one embodiment of the present invention;

[0026] **FIG. 5** is a schematic diagram of one embodiment of the present invention illustrating a mixing apparatus having chevron-shaped grooves defined on a wall therein;

[0027] **FIGS. 6***a*-**6***f* are copies of micrographs illustrating the cross-section of the mixing apparatus of **FIG. 5** having two fluids flowing therethrough at different points along the length of the mixing apparatus;

[0028] **FIG. 7** is a graph showing how the number of cycles affects the standard deviation of intensity, as a measure of mixing progress;

[0029] **FIG. 8** is schematic diagram showing the dispersion of a plug of miscible solution along the principal direction of flow without (top) and with (bottom) continuous mixing according to one embodiment of the present invention; and

[0030] **FIG. 9***a*-b are copies of micrographs showing the difference between axial dispersion without (**FIG. 9***a*) and with (**FIG. 9***b*) mixing according to one embodiment of the present invention.

DETAILED DESCRIPTION

[0031] The present invention is directed to mixing apparatus and methods used to effect mixing between one or more fluid streams. The mixing apparatus generally functions by creating a transverse flow component in the fluid flowing within a channel without the use of moving mixing elements. The transverse or helical flow component of the flowing fluid can be created by the shape of the channel walls. For example, the transverse component can be created by grooves defined on the channel wall. The present invention can be used in systems where diffusion primarily controls fluid mixing. The term "transverse" is meant to describe a crosswise direction or at angle relative to a direction of a channel and the term "helical" is meant to describe a continuous plane curve that is extended in one direction and periodic in the other two. The term "principal direction" is meant as the direction of flow along a flow structure through which the bulk or the majority of the fluid can flow. For example, in a channel, the principal direction typically along the length of the channel, in contrast to across the width of the channel. Thus, the term "transverse flow component" is meant to describe a flow component that is oriented at an angle relative to a particular direction, preferably, relative to the principal direction. Notably, the present invention can be particularly useful when used in connection with microfluidic systems.

[0032] Patterned topography on surfaces according to the present invention can be used to generate chaotic flows in contexts other than pressure driven flows in microchannels. For example, chevron-shaped structures on the walls of round pipes and capillaries can provide efficient mixing. Thus, in one embodiment, fluid unit operation dependent on heat or mass transfer, such as a heat exchanger, may have turbulent flow in the bulk flowing fluid but may incorporate grooves, in a variety of geometries, on baffle plates to reduce or at least partially eliminate boundary limiting conditions that typically affect the overall transfer coefficient. That is, chaotic flows will also exist in the laminar shear flow in the boundary layer of an extended flow over a surface that presents the staggered herringbone features. This stirring of the boundary layer will enhance the rates of diffusion limited reactions at surfaces (e.g. electrode reactions) and heat transfer from solids into bulk flows. In another embodiment, electroosmotic flows in capillaries that contain the staggered herringbone features can be chaotic and promote stream mixing.

[0033] **FIG. 1** illustrates a microfluidic system **10** according to one embodiment of the present invention. System **10** includes a substrate **12** with a surface **14** having formed or defined therein a structure **16** that can be a part of a network or array (not shown) of similar and interconnected structures and features. Structure **16** includes a channel **18** formed on