METHODS OF MAKING DEVICES BY STACKING SHEETS AND PROCESSES OF CONDUCTING UNIT OPERATIONS USING SUCH DEVICES

FIELD OF THE INVENTION

[0001] The present invention relates to methods of making devices by stacking sheets. The invention also relates to methods of conducting unit operations on fluids in such devices.

[0002] Introduction

[0003] The following introduction section is intended to provide a clearer understanding of the invention, it includes descriptions of both inventive and prior technology.

[0004] Microchannel devices made from shims can be designed and fabricated using multiple shim styles. In a first style, the full flow channel is cut directly out of a thin metal shim. The thickness of the metal serves as the microchannel dimension (typically less than 2 mm). Adjacent to the channel formed via the cut out is a wall shim. The wall shim creates a fin that separates parallel channels of the same fluid. The channels are connected through the use of holes that are aligned in every shim. The connected passageway serves as the header for the group of parallel channels or a footer to collect the fluid after it has passed through the channels. A unit operation such as heat exchange, reaction, or separation, is achieved by creating another set of parallel channels underneath the first set of parallel channels. Channel orientation is denoted as top-bottom.

[0005] A device **10** laminated in this manner is illustrated in **FIG. 1***a*. Shims **12**, **14**, **16**, and **18** are stacked together wherein each shim is parallel to shim **12**. These shims are repeated as required to create the desired number of channels. The shims can be bonded together by a process such as diffusion bonding, reactive metal bonding, or laser welding. Typically, a shim will contain apertures **20** that open into channels **22**, **24**. A catalyst could be loaded into reaction chamber **15**. During operation of the laminated device, fluid flow (as indicated by arrows **30**, **32**, **34**) is substantially perpendicular to sheet thickness (substantially parallel to sheet width). Although flow through aperture **20** is substantially parallel to sheet thickness, overall flow is perpendicular to sheet thickness. Aperture **20** serves as a header or footer to connect flow channels rather than performing a unit operation within this flow path. Typically, channels **22**, **24** provide heat exchange. This design provides good supported areas for bonding and strength. In this design channels may be rectangular, trapezoidal, wavy, but not circular. The smallest dimension of the microfeatures are typically controlled by the thickness of the sheet.

[0006] An alternate design orientation is shown in **FIG. 1***b*. Through cuts are made in shims to create flow channels. A shim is placed adjacent to the flow channel to create a wall that separates two distinct flow streams. The second flow path is created by a third shim adjacent to the wall shim. The wall shim between the two fluid streams is the plane through which heat transfers for a unit operation, such as heat exchange or reaction. The third shim also contains a through cut to create a flow path. The headers and footers are made by through holes in each shim that open up to the respective flow paths of the two fluids. In this style, parallelepiped or other flat-walled channels can be economically constructed. Examples of flat-walled channels made with this style are shown in U.S. Pat. Nos. 6,129,973 and 6,192,596. Channel orientation is denoted as interleaved.

[0007] Alternatively, a device could be constructed as shown in **FIG. 2**. In this figure, the slices can be viewed as being stacked from bottom to top in the orientation of slice **51**. Advantages of this construction include: that microfeatures can be controlled by shim thickness; thick shim plates **52** can be used to resist pressure; a catalyst chamber **54** can be sized to match the area of heat exchanger channels; and catalyst chamber layers can be interleaved with heat exchange layers. Channels can be economically constructed from shims with rectangular apertures. In addition, wavy or other shaped channels could be formed on slice **51**.

[0008] Another design, sometimes referred to as a "clam shell" design (not shown), uses sheets having partially etched channels. If the partially etched channels are in the form of semi-circles, two corresponding sheets can be bonded to form tubular channels. The compact reactors pictured in WO 01/10773 A1 could be formed from a clam-shell design.

[0009] An advantageous alternative design is illustrated in **FIG. 3**. In this construction, a device **70** is made by stacking shims oriented in the direction of shim **72**, and bonding together. This design, in which, in the completed device, flow is substantially parallel to sheet thickness (substantially orthogonal to sheet width) and is referred to as an "ortho" design. Apertures **74** create a reaction chamber, while apertures **76** and **78** create heat exchange channels. A major advantage of the ortho design is that it allows the economical creation of shims with a myriad of aperture designs that could be made, for example, by stamping identical patterns in multiple sheets. Examples of designs made practical by the ortho design are shown in FIGS. **4**-**5**.

[0010] Hybrid shim styles can be created by combining these styles. One example is the semi-ortho style; sections of the shim are created with ortho features where the flow is substantially parallel to sheet thickness and sections of the shim are also created with alternate features where the flow travels substantially perpendicular to the sheet thickness. An example of this shim design style is shown in **FIG. 4***g*. The left-most features depict an interleaved heat exchanger, whereby one stream (fluid C) is heated (recuperative heat) with its own exhaust, then flows through a second unit operation such as a reactor. In the reactor section, the flow makes a U-bend to flow back into the recuperative heat exchanger, thus preheating the inlet reactant stream. A second fluid (fluid D) flows through the holes that are continuously aligned through each shim and created in the ortho style. Fluid D may be a heat exchange fluid providing heat to an endothermic reaction or to remove heat from an exothermic reaction.

[0011] The four shims shown in **FIG. 4***g* are stacked upon each other in addition to other similar shims as required to create the required number of channels to achieve the desired device capacity. A higher capacity for a unit operation requires numbering-up or adding more channels.

SUMMARY OF THE INVENTION

[0012] In a first aspect, the invention provides a process of making a device for conducting unit operations on a fluid