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SUMMARY OF THE INVENTION

[0024] In the present invention, surface features in microchannels can be used to enhance unit operations as the Reynolds number is increased. In the invention, the surface features can be advantageously employed at Re of 100 or more, in some embodiments Re is 200 or more, 1000 or more, and in some embodiments Re is in the range of 300 to 2200. Further, the use of surface features offers additional surprising enhancement in the turbulent regime as well.

[0025] An important element in many aspects of the present invention is the interaction of fluid molecules with an "active surface." A surface is considered active if either mass or heat is exchanged at the surface. The surface is inclusive of the floor and sides of the grooves as well as the ridges between features. A "ridge" is a wall or the surface that connects at least two open surface features and is open to the main flow channel. As the number of interactions of the fluid with the active surface is increased, the performance of the unit operation is further enhanced. For the case of a chemical reactor, a heterogeneous catalyst may be disposed within the surface features as well as on the tops or ridges or flat regions of the microchannel and optionally along all surfaces or selected surfaces. Rather than diffusion as the sole driving force for movement of the reacting species to the active wall, advection or flow convection becomes a dominant driving force for quickly moving reactants to the catalytic wall and removing products from the wall to the bulk flow stream. As an example, if diffusion alone is the dominant driving force for moving flow from the bulk to the active catalyst wall, a characteristic time may be on the order of a few to tens of milliseconds for gaseous chemical reactors that operate with an overall contact time of a few to tens of milliseconds. For a stream of methane and air in a 1 mm channel at 850 C and 1.0 bar the diffusivity is about $2.2 \text{ cm}^2/\text{sec}$ and the diffusion distance from the center of the channel gap (assuming that catalyst is disposed in active surface features on both sides of the microchannel gap) is about 0.5 mm. The resulting characteristic time for diffusion is on the order of 1 millisecond.

[0026] A characteristic average velocity in the main channel is 100 m/s for a high velocity and high laminar Reynolds number example (Re on the order of 700 for a dilute methane stream in air at 850 C and 1 atm). At this velocity for a purely laminar stream, the centerline velocity is 1.5 times the average, for a total of 150 m/s. In a 10 cm length channel, the molecules flowing along the centerline of the channel gap would spend on average roughly 0.7 ms in the channel. Thus diffusion alone would likely be insufficient for those reacting molecules to hit the active catalyst wall. Even if the velocity in the main channel were ten times lower, at an average velocity of 10 m/s for a Reynolds number less

than 100, the residence time of the centerline molecules (meaning molecules near the center of the channel gap) would raise to 7 milliseconds. In essence, by diffusion alone there would be on average of less than ten collisions of the centerline reacting molecules with the active catalyst wall.

[0027] Contrast this performance for the case of the active surface features where the push and pull forces fluid and reactants into the surface features. Model results have shown that the flow velocity in the x and y directions (where z is along the flow length, and x and y are in the lateral (side to side) and transverse (top to bottom) flow directions, respectively) does not exceed the average flow velocity in the z direction for a corresponding flat channel, but is on the order of 1%, or 5%, 100%, 20% or greater of the average flow velocity in the length direction. Correspondingly, for this example, an average velocity in the y direction (top to bottom of the microchannel or between the active surface feature walls assuming that active walls are disposed on both surfaces) is at least 1 m/s. At this velocity, the characteristic time for advection of the reacting molecules to the active surface feature walls is less than 0.5 milliseconds—or less than half the time required by diffusion. As the velocity in the y-direction increases further, the characteristic time for advection reduces correspondingly.

[0028] This time difference alone between convection and diffusion tells part of the advantage, but not the entire advantage. An additional advantage of the active surface features is a reduction in mass dispersion that makes the number of contacts of molecules from the bulk flow in the main gap with the active surface feature wall much higher. Further, once the molecules have entered the active surface feature groove, they are out of the main flow path and not subject to the same flow advection that moves the molecules away or down stream from the active surface feature grooves. By this manner, the classical Taylor-Aris dispersion is reduced by allowing molecules to spend more time in the active surface feature to promote the desired unit operation.

[0029] The disposition of a catalyst in a prior art surface feature would create only modest enhancement because the objective of the previous devices was to allow the molecules to mix in the bulk flow channel but not actively collide or interact with the active surface feature walls. For the present invention, it is desirable to have at least 1, or 2 or 3 or more collisions of the centerline molecules with the active surface feature walls for good performance. Further, it is advantageous to have at least 30% of all mass entering at least one channel that comprises at least one surface feature section to enter at least one surface feature at least once in a surface feature section. A "surface feature section" is defined as a continuous series of closely spaced surface features in a wall along the flow length of a microchannel. In methods of the