# SURFACE FEATURES IN MICROPROCESS TECHNOLOGY

## RELATED APPLICATIONS

This application is a continuation-in-part of U.S. patent application Ser. No. 11/089,440 filed 23 Mar. 2005. Also, in accordance with 35 U.S.C. sect. 119(e), this application claims priority to U.S. Provisional Applications Nos. 60/697,900 filed 8 Jul. 2005, 60/727,126 filed 13 Oct. 2005 and 60/731,596 filed 27 Oct. 2005.

## FIELD OF THE INVENTION

This invention relates to microchannel apparatus that includes microchannels with interior surface features for modifying flow; processes utilizing this microchannel architecture, and methods of making apparatus having these features.

## INTRODUCTION

In recent years there has been tremendous academic and commercial interest in microchannel devices. This interest has arisen due to the advantages from microtechnology including reduced size, increased productivity, the ability to size systems of any desired capacity (i.e., "number-up" channels), increased heat transfer, and increased mass transfer. A review of some of the work involving microreactors (a subset of microchannel apparatus) has been provided by Gavrilidis et al., "Technology And Applications Of Microengineered Reactors," Trans. IChemE, Vol. 80, Part A, pp. 3-30 (January 2002).

Surface features have been used for mixing within microchannels. The prior art employs surface features in microfluidic applications to enhance mixing of two fluid streams at very low Reynolds numbers. Typical values of Reynolds numbers are less than 100, and more often on the order of 0.1 to 10. A good mixer is defined by a small variation in mass composition in the cross sectional area exiting the micromixer. Further, the prior art suggests that the use of surface features is particularly useful at low Reynolds numbers, but the mixing efficiency decreases as the Reynolds numbers increases beyond 10 or 100.

The prior art micromixers that are based on the use of a grooved or recessed angled wall or walls was first discussed by Svasek in 1996, where a series of angled grooves (one constant angle diagonal groove per feature) were placed in one wall for mixing an iodine blue starch solution with a photographic fixer solution. Enhanced mixing was described as compared to a flat channel, where the objective was to mix by folding the flow in the main channel such that the diffusion distance of the two liquids in the main flow channel is reduced and diffusion can complete the final mixing. The groove depth to channel gap ratio is 0.25.

The use of grooved surfaces again appeared in December 2001 on the web by Johnson, Ross and Locascio who described the use of four diagonal grooves (one constant diagonal groove per feature) to enhance mixing in the main channel of a micromixer. The authors describe improved mixing at lower flowrates or lower Reynolds numbers for all cases evaluated. They also describe the addition of varying angles on diagonal grooves after a section of 4 repeated like grooves. While the performance was improved, mixing performance decreased as the Reynolds number increased. The well or groove depth to channel gap ratio was 2.74.



In January 2002, Strook et al describe in Science the use of two groove channel micromixers, one with a constant oblique angle groove and a second pattern referred to as a staggered herringbone mixer (SHM), where the angled features were changed after six features in series. The focus of this work was to improve mixing of two liquids across the microchannel for low Reynolds numbers streams (less than 100). The authors describe that the mixing length increases linearly with the log of the Peclet number. The Peclet number is defined by the velocity times the channel gap divided by the diffusivity. At higher velocities, the required mixing length increase, showing disadvantaged mixing. The groove depth to channel gap ratio was a maximum of 0.6 for the SHM.

Also in 2002, Strook et al describe in Analytical Chemistry a series of like oblique angles with constant angle for mixing a fluid mixture with a Reynolds number of, where The groove depth to channel gap ratio was a maximum of 1.175. The authors describe the helicity of the flow which reflects the pitch of the rotating flow stream. The authors state that the staggered herringbone mixer will speed up mixing in microfluid devices by creating Lagrangian chaos at low Reynolds numbers.

Johnson and Locascio in June 2002 describe a micromixer with four slanted grooves in series to enhance mixing in the bulk flow channel. The authors state that the transport of the liquid increased across the channel as the well or groove depth increased up to 50 microns, with no increase beyond this depth. Larger depths were stated as a dead zone area where flow or molecules could be trapped rather than mixed. The Reynolds number was less than 1. The authors also state that the axial dispersion of the channels with wells or grooves was higher than the axial dispersion for the flat or well-less walls. The groove depth to channel gap ranged from 0.32 to 2.74. Beyond a ratio of 1.6 the authors note no additional improvement. In all cases, the figures show little access of the mixing fluid against the inner wall of the groove.

Strook and Whitesides discuss, in Accounts of Chemical Research, in 2003 the use of the staggered herringbone mixer to stretch and fold the flow in the main channel by changing the orientation of the grooves at regular intervals or cycles. A groove depth to channel gap ratio of 0.44 was used for Reynolds numbers less than 1. The authors state that the mixing length is proportional to the log of the flow velocity because the staggered herringbone mixers (SHM) promote chaotic advection in the main flow channel. In unmixed channels, the mixing length is proportional to the flow velocity. The authors also state that the SHM reduces dispersion for Poiseuille flow in microchannels.

In 2003, Aubin et al describe in Chemical Engineering Technology that the diagonal mixer creates very little convective mixing because a strong helical flow is created around the edge of the channel but does not incorporate the center flow of the channel. The SHM by contrast creates very good in-channel mixing. The groove depth to channel gap ratio was less than 0.6 in this study. The Reynolds number was 2. The authors state that the lowest levels of fluid deformation (indicative of fluid stretching or movement) are found in the channel grooves but that this may not be a good metric for quantifying mixing performance.

Wang et al published in July 2003 in J. Micromech. Microeng a numerical investigation of microchannels with patterned grooves. The groove depth to channel gap ratio varied from 0.1 to 0.86. A Reynolds number range from 0.25 to 5 was used. The pattern consisted of a series of like oblique angled grooves, each with a constant angle. The authors state the groove aspect ratio as the most important variable for mixing, where the 0.86 was better than the 0.1. The flow patterns appear to be a single vortex in the main channel.