A VERTICAL LAMINATING MICROMIXER (VLM)
Won Seok Yang\textsuperscript{1}, Jun-Oh Ryu\textsuperscript{2} and Dong Sung Kim\textsuperscript{1}
\textsuperscript{1}Chung-Ang University, SOUTH KOREA and \textsuperscript{2}Allmedicus Co. Ltd, SOUTH KOREA

ABSTRACT
In this paper, a novel chaotic micromixer, named Vertical Laminating Micromixer (VLM), has been designed, fabricated and fully characterized numerically and experimentally. In the VLM, vertical lamination was achieved by means of locally increased aspect ratio at the recombination region made by periodic arrangement of the same mixing unit in two layers.

KEYWORDS: Design equation, Lamination, Micromixer, Splitting and recombination

INTRODUCTION
Mixing plays an important role in \textmu{TAS} \cite{1-3}. Lamination of the fluid flow could remarkably enhance the mixing efficiency by increasing interfacial area exponentially \cite{1-2}. In these mixers \cite{1-2}, a separation wall inside a microchannel was required to get the ideal lamination. However, it generally requires complicated fabrication processes and furthermore, hardly achievable to realize the mass production using polymer via, such as injection molding. In \cite{3}, the relatively good mixing was obtained without the wall by successive arrangement of F-shape mixing units, but the effective lamination could not be achieved due to one-directional recombination.

DESIGN AND THEORY
Figure 1 (a) shows a schematic diagram of the VLM proposed in this study. The periodic arrangement of the same mixing units in two layers induces continuous vertical lamination of the fluid flow. The flow is split into three directions (one for main and two for side channels) and they are joined vertically again at the recombination region indicated in Figure 1. The vertical lamination was almost perfectly achieved via two-directional recombination and locally increased aspect ratio. Therefore, it may result in the $2^N$ exponential growth of the interfacial area after passing $N$-mixing units as depicted in Figure 1(b).

Figure 1. (a) Schematic of vertical lamination micromixer (VLM) proposed in this study and (b) the conceptual cross-sectional mixing behaviors of the ideal laminating at each unit of which the indicated positions correspond to cross-sections in (a).
To obtain the same flow rate from a main channel and two side channels at the recombination region, a design equation was newly derived based on the fundamental fluid mechanics, thereby enabling us to determine the width of the main channel and two side channels as below:

$$W_{\text{side channel}} F_{\text{p, side channel}} = \frac{1}{2} \frac{L_{\text{side channel}}}{L_{\text{main channel}}} W_{\text{main channel}} F_{\text{p, main channel}}$$  \hspace{1cm} (1)

where, $F_p$ is a shape factor to consider the aspect ratio of a rectangular microchannel [4] defined as below:

$$F_p = 1 - \frac{192H}{\pi^2 W} \sum_{p=1,3,5,\cdots} \frac{1}{p^2} \tanh \frac{p\pi W}{2H}.$$  \hspace{1cm} (2)

**NUMERICAL ANALYSIS AND EXPERIMENTAL**

The CFD mixing simulations were conducted to confirm the chaotic mixing mechanism occurred in so designed VLM. Figure 2 shows numerical result of the VLM at the Reynolds number ($Re$) of 0.64 (the flow rate of 9.6 $\mu$l min$^{-1}$). The numerical result shows the almost perfect vertical lamination could be obtained by means of the VLM. The VLM and a vertical straight microchannel, as a reference for mixing experiment, were fabricated by SU-8 photolithography and PDMS replica molding. Mixing performance of the VLM was experimentally characterized in terms of an average mixing color intensity of phenolphthalein. Only the interface between two streams turns red, thereby enabling us to measure the mixing performance.

![Figure 2. Numerical mixing simulation result of the VLM at $Re \approx 0.64$.](image)

**RESULTS AND DISCUSSION**

Figure 3 shows mixing experimental results of the VLM and a vertical straight microchannel, as a reference, at $Re$ of 0.66.

![Figure 3. Mixing experimental result of the VLM and a vertical straight microchannel at the flow rate of 10 $\mu$l min$^{-1}$ ($Re \approx 0.66$).](image)
To quantify the mixing efficiency, we have measured the intensity of the red color at every pixel along the downstream. Plotted in Figure 4 is the change of normalized average intensity indicated in Figure 3, which clearly shows the high-level of mixing performance of the VLM.

![Figure 4](image-url)

*Figure 4. Normalized average intensity change of red color along the downchannel direction of the VLM and the vertical straight microchannel. symbols: experimental data, and curves: optimal fitting with $I = 1 - \exp(-z/\lambda)$. The optimal fitting parameter, (denoting the characteristic required mixing length) of the VLM and the straight channel are 2.22 and 8.28 mm, respectively.*

**CONCLUSIONS**

In this study, we have newly developed a chaotic micromixer, Vertical Laminating Micromixer (VLM) in which successive vertical lamination is achieved by periodic arrangement of the same mixing units in two layers. From both numerical and experimental mixing results, it was found that the VLM shows the high-level of mixing performance over the wide range of $Re$.

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**REFERENCES**


