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Particle Image Velocimetry Evaluation of a Novel Oscillatory-Flow Flexible Chamber Mixer

This paper describes a novel oscillatory-flow mixer consisting of a pair of flexible chambers connected by a perforated plate, or septum. During operation, the septum undergoes reciprocating motion such that the two chambers are alternately compressed and expanded. During compression, fluid is forced from one chamber to the other through the septum holes, creating an array of jets that drive the mixing process. Flow characterization within the mixer was conducted using particle image velocimetry. Tests were performed for Reynolds numbers ranging from 4 to 23,000, which encompass the creeping, laminar, and turbulent flow regimes. Results include mean and rms velocity maps, shear rate maps, vertical velocity profiles, and flow development data. The results suggest that the mixer is capable of gentle, continuous stirring (important for biological applications), as well as vigorous agitation. Finally, a comparison between this mixer and other existing mixing technologies is presented. [DOI: 10.1115/1.2409347]

Keywords: flexible-chamber mixer, oscillatory flow, perforated plate, PIV, particle image velocimetry, shear rate, jet, reciprocating

Introduction

The flexible chamber mixer (FCM) presented in this paper consists of two flexible chambers connected by a perforated septum plate. An artistic rendering of the setup (including a cutaway view) is shown in Fig. 1, and a full schematic is shown in Fig. 2. The mixing chambers used for the current experiments are made of simple plastic sheeting formed into cylinders. To induce mixing, the septum is oscillated vertically, alternately compressing one chamber and forcing the fluid into the second expanding chamber. Due to the septum motion, fluid issues in the form of jets from holes in the septum plate, driving the mixing process. A computer-controlled stepper motor supplies motive power, allowing for precise control over a wide range of septum oscillation configurations (combinations of multiple stroke lengths and frequencies within a single overall cycle), and septum speeds (3–300 mm/s). Additional details about the apparatus are provided in the procedure section.

Three key features of the mixer being studied here lend themselves to a wide variety of industrial, pharmaceutical, and biological applications. First, the mixer is designed so that all parts that contact the working fluid can be made disposable. The disposability feature eliminates the need for expensive cleaning processes required in current mixer designs, making the FCM ideal for applications involving biologically hazardous or toxic fluids, and applications requiring highly sterile conditions. The second advantage of the FCM design is the distribution of fluid jets throughout the entire mixing volume, as compared to an impeller mixer in which the high velocity/high shear region is limited to the immediate vicinity of the impeller. By controlling septum speed and perforation parameters, one can obtain very low shear rates while still thoroughly mixing the fluid. Alternatively, high shear can also be obtained by altering the aforementioned parameters. For example, extended-duration mixing at low shear rates is important in

mixing applications involving live cells, whereas high shear rates are required for homogenization. Finally, mixer scaleup is possible by simply enlarging the diameter of the septum and mixing chambers, and/or by stacking multiple septa and mixing chambers in a vertical chain.

A broad base of knowledge already exists for many mixer configurations, including impeller driven mixers, oscillatory flow baffled column mixers, and reciprocating plate mixers. Because our research focuses entirely on oscillatory mixers, we will restrict our attention to previous work relating to oscillatory flow mixers with some brief comparisons to the other mixer classes.

An oscillatory flow baffled column reactor consists of a long cylindrical tube with multiple orifice plates. Fluid is placed in the tube, and an oscillatory flow profile is imparted to the fluid. Previous research in this area includes measurement of strain rate via particle image velocimetry (PIV) [1], study of heat/mass transfer in an oscillatory flow baffled column [2,3], and general flow and mixing characterization [4,5]. Dickens et al. [5] also studied optimal baffle placement, which is relevant to FCM scaleup using multiple septa. Previously studied reciprocating plate mixers (which are similar to the FCM presented here) consist of a rigid cylinder and a plate that is oscillated inside of the outer cylinder, driving the mixing process. Several different designs have been studied, including both nonperforated and perforated plates [6,7] and plates with “flapping blades” [8,9]. The aforementioned work included studies of flow profiles [6], heat transfer characteristics [7], mass transfer from soluble solid objects [8], mixing time [9], and mixer power consumption [10].

The major difference in the current research resides in the flexible nature of our mixing chambers in contrast with the rigid mixers studied previously. Thus, the FCM represents a new class of mixer and results provided in this paper are therefore new and interesting. We have applied a number of techniques to qualitatively and quantitatively measure the mixing performance of the FCM, such as laser induced fluorescence and PIV. However, we restrict ourselves to PIV results in this paper.

Primary goals of this research include analysis of flow fields, shear rates, and turbulence for Reynolds number values ranging

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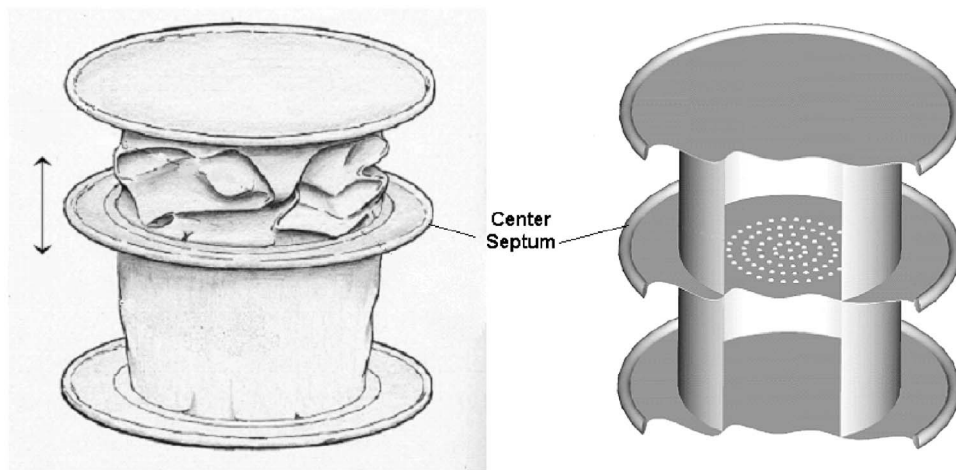


Fig. 1 Artistic rendering of mixer assembly

from 4 to 23,000, which encompass flow regimes ranging from creeping flow to turbulence. Study of a large Re range also allows analysis of mixing scenarios from gentle stirring to vigorous mixing and homogenization. Of additional interest is the potential impact of flexible chamber walls on mixing performance. Although the mixer is capable of complex oscillation configurations wherein multiple intermediate septum travel profiles can be incorporated within each overall repeating cycle, we will restrict ourselves in this study to the simplest case wherein the septum undergoes basic reciprocating motion at a prescribed frequency and stroke length. We used the same stroke length for all our experiments and varied the frequency (i.e., septum speed) to explore different flow regimes. Our data will help to evaluate the mixing effectiveness of the current design, suggest modifications for improved performance, and customize mixer parameters for different industrial applications.

Relevant Flow Parameters

As presented in the literature, such as Komoda et al. [6], Reynolds number is the key variable affecting flow characteristics. Komoda et al. [6] studied an oscillatory mixer with a solid disk, and proposed the following regimes: $Re < 20$, laminar creeping flow; $20 < Re < 200$, formation of ring vortices behind the disk; and $Re > 200$, turbulent flow. Idelchik [11] proposed three distinct Re ranges for pressure drop for flow across a perforated plate:

$Re < 10$, $10 < Re < 30$, and $30 < Re < 10^4$. These three ranges may be broadly classified as creeping flow, laminar flow, and turbulent flow, respectively.

In our case, the primary quantities of interest are the diameter of the septum (and the chambers as well) D_S , the working chamber length L_C , the stroke length L_S (we set $L_S \approx L_C$ in our experiments), the diameter of individual septum holes D_H , and their number N , which together determine the fractional area of the septum which is open A_O . All of these quantities were fixed for the experiments reported here. The septum speed V_{SL} was varied to create different flow regimes. The septum speed and septum-hole geometry determined the nominal fluid velocity through the septum hole (as seen by the septum) $V_{F-NOM/S}$. Using these variables, and the fluid kinematic viscosity ν , we define our Reynolds number as

$$Re = \frac{V_{F-NOM/S} D_H}{\nu} \quad (1)$$

Jets issuing from the septum holes drive the mixing process and are therefore the most important flow feature of the FCM. Accordingly, we have used the jet orifice diameter (D_H) to define our Reynolds number. Similarly, Komoda et al. [6] used the orifice hydraulic diameter in their Reynolds number definition. To fully understand Eq. (1), a definition for $V_{F-NOM/S}$ is also required; mass

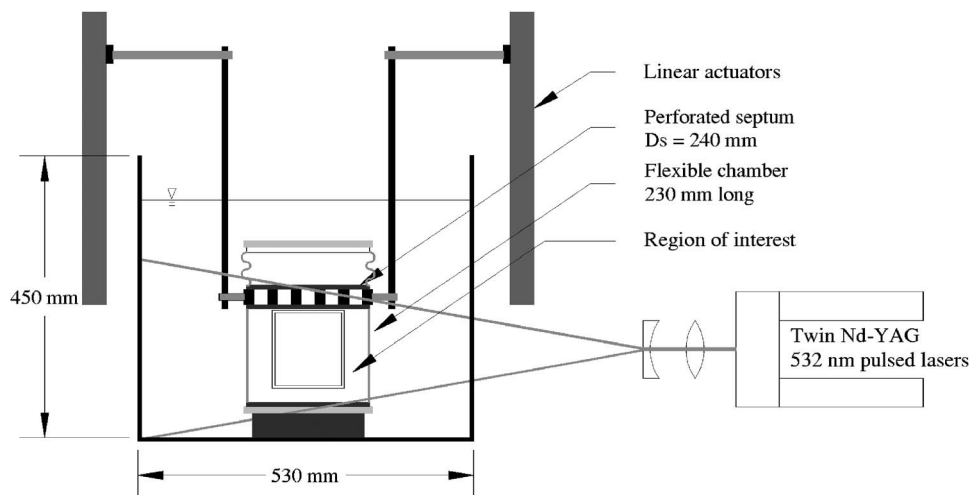


Fig. 2 Schematic of mixing apparatus

conservation gives $V_{F-NOM/S} = V_{S/L} / A_O$. From a stationary observer's viewpoint, the nominal through-hole velocity magnitude would then be $(V_{F-NOM/S} - V_{S/L})$. Note here that the subscripts $_{/S}$ and $_{/L}$ refer to the septum (moving) frame of reference, and the laboratory (stationary) frame of reference, respectively.

Next, the actual (as opposed to nominal) through-hole average velocity as seen by a stationary observer can be modeled as:

$$V_{F-AVG/L} = K V_{S/L} \left(\frac{1}{A_O} - 1 \right) \quad (2)$$

This expression differs from that for the nominal velocity by the introduction of the constant K , which accounts for deviations from the nominal velocity value caused by chamber folding characteristics; for example, when the chamber compresses, the chamber material sometimes will fold in a manner such that the outermost ring of holes is partially shaded. Consequently, the flow through the inner holes will speed up resulting in K values in excess of unity.

Finally, in the current design, the septum plate has a thickness of 76.2 mm, therefore, the flow through the hole may in fact develop to some extent depending on the Re under consideration. Such a thick septum was required to overcome visual obstruction caused by thick bag mounting rings, thus allowing clear optical access to both upper and lower septum edges. For small Re , the flow will emerge from the septum hole with a parabolic profile, for which $V_{F-MAX/S} = 2V_{F-AVG/S}$. For large Re , the emerging flow should resemble a plug flow (due to reduced flow development), and $V_{F-MAX/S} \approx V_{F-AVG/S}$. To account for flow development, the following equations for $V_{F-MAX/S}$ and $V_{F-MAX/L}$ are proposed

$$V_{F-MAX/S} = C V_{F-AVG/S} \quad (3a)$$

$$V_{F-MAX/L} = C V_{F-AVG/L} + (C - 1) V_{S/L} \quad (3b)$$

C is a measure of boundary layer development within the septum hole for a given flow profile. Fully developed laminar flow gives $C=2$, and fully developed turbulent flow gives $C \approx 1.23$ (for $Re = 10^4$) [12]. To determine C experimentally, $V_{F-AVG/L}$ was computed by numerically integrating the vertical through-hole velocity through the central hole. Putting Eq. (2) and (3b) together, we arrive at the following relationship between $V_{F-MAX/L}$ and $V_{S/L}$

$$V_{F-MAX/L} = V_{S/L} \left[CK \left(\frac{1}{A_O} - 1 \right) + (C - 1) \right] \quad (4)$$

A second key nondimensional parameter presented in the oscillatory-flow mixer literature [1] is the Strouhal number. Defining the Strouhal number as $St = \omega D_H / V_{F-AVG/S}$ [12], where ω is the oscillation frequency, it is straightforward to show that $St \sim D_H A_O / L_S$. Because this quantity does not vary in our experiments, the only parameter of interest hereafter will be the Reynolds number.

Another length scale witnessed in our work was jet penetration length. Jet penetration can be thought of simply as the jet length (as evidenced by the column of moving fluid) issuing from the septum hole. Using a simplified model, we can easily relate the nominal length of jet penetration (L_{JP}) to the septum speed $V_{S/L}$, fractional septum open area A_O , and septum travel time t

$$L_{JP} = V_{S/L} \left(\frac{1}{A_O} - 1 \right) t \quad (5)$$

Note that $V_{S/L}$ remains essentially constant throughout the stroke. But the stroke length L_S is given by $V_{S/L} t$, which gives

$$L_{JP} = L_S \left(\frac{1}{A_O} - 1 \right) \quad (6)$$

In our case, $A_O = 0.46$, so L_{JP} is roughly equal to stroke length, which was 195 mm. For smaller A_O , it is possible that $L_{JP} > L_S$ which simply means that the jet will travel through the chamber and eventually impact the lower boundary. If one accounts for the

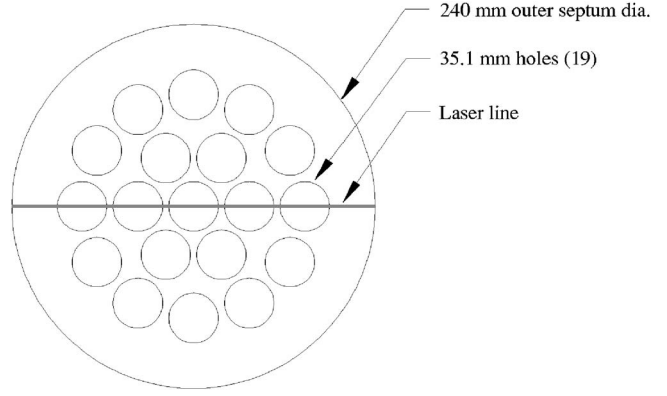


Fig. 3 Schematic of septum plate

slowing of the jet fluid as it travels away from the septum hole, and the effect of $K \neq 1$, Eqs. (5) and (6) would become approximations.

Additional nondimensional parameters used in our data analysis include the nondimensional velocity ratio V^* , shear rate ε^* , and nondimensional length parameters r^* and z^* (radial and vertical locations). All nondimensional velocity values are measured with respect to the lab frame L

$$V^* = \frac{V_{F/L}}{V_{S/L} \left(\frac{1}{A_O} - 1 \right)}, \quad \varepsilon^* = \frac{\varepsilon}{\varepsilon_{MAX-LAM}}, \quad \varepsilon_{MAX-LAM} = \frac{8 V_{F-NOM/S}}{D_H}$$

$$r^* = \frac{r}{D_S}, \quad z^* = \frac{z}{D_S}, \quad L_{JP}^* = \frac{L_{JP}}{D_S}, \quad L_{EP}^* = \frac{L_{EP}}{D_S}$$

The fluid in the FCM experiences the highest shear rate as it transits the septum hole. A convenient shear rate scale is the maximum value attained for fully developed laminar flow through the septum hole denoted by $\varepsilon_{MAX-LAM}$. Accordingly, we nondimensionalize shear rate with $\varepsilon_{MAX-LAM}$. Also, by referring back to Eq. (2), it is seen that $V_{F-AVG/L} = K$.

Experimental Setup

All experiments were conducted using a prototype mixer design based on the FlexMixer, now marketed by ILC Dover LP and Wave Biotech LLC. An artistic rendering of the mixer is shown in Fig. 1 and a full schematic in Fig. 2. Twin 230-mm-long transparent bags (ILC No. BPC 16) along with a rigid septum were used. The bags were made out of highly flexible (but inelastic) transparent polyethylene, and were approximately 0.2 mm thick. Each cylindrical bag was constructed with a slight conical shape (with the largest diameter facing the septum) to allow more efficient bag folding during operation. The bag diameter at the septum end was approximately 240 mm, and the smaller diameter was 230 mm. Each bag was sealed to rigid fixed end plates and the oscillating septum using oversized hose clamps and O-rings. Ports were installed in each end chamber to allow for filling and draining of the mixer. Significant care was taken to minimize the presence of air bubbles inside of the mixer. The septum (see Fig. 3) consisted of a 76.2-mm-thick plastic plate with 19 holes of diameter 35.1 mm arrayed in a pattern shown in Fig. 3, with a resulting open area of 46%. As stated earlier, the unusually large septum thickness was dictated by the need for direct visual access to the upper and lower edges of the septum. In a field version of the mixer, septum thickness would range from a few millimeters to 10–20 mm. Effective stroke length was limited to about 195 mm due to safety requirements and the bag mounting system. During a typical stroke, the septum would approach within approximately 15 mm of the top and bottom end plates.

Table 1 Summary data for all trials (boldface numbers refer to cases plotted in Figs. 4–6)

Experimental variables			Results							
$V_{S/L}$ (mm/s)	$V_{F-NOM/L}$ (mm/s)	Re	V_{F-MAX}^*	V_{F-AVG}^* K	C	L_{JP}^*	ε_{MAX} (1/s)	ε_{MAX}^*	L_{EP}^*	V_{RMS-FF}^*
Low Re high viscosity runs (viscosity ≈ 50 cP)										
2.9	3.44	4	1.7	0.9	1.5	0.4	0.7	0.5	0.1	0.1
6.1	7.17	9	2.0	1.0	1.6	0.4	1.5	0.5	0.1	0.1
10	11.7	15	2.3	1.1	1.6	0.4	2.7	0.5	0.1	0.1
50	58.7	76	2.7	1.3	1.7	0.6	15	0.6	0.5	0.1
300	352	460	1.9	1.3	1.3	0.6	111	0.7	0.5	0.3
High Re low viscosity runs (viscosity = 1 cP)										
50	58.7	3800	1.8	1.5	1.2	0.6	23	0.9	0.3	0.3
150	176	11,400	1.8	1.4	1.2	0.6	59	0.8	0.2	0.3
300	352	23,000	1.7	1.3	1.2	0.6	105	0.7	0.3	0.4

Motive power for the apparatus was supplied by a pair of linear actuators and a computer-controlled stepper motor. A constant velocity profile was used, with acceleration/deceleration (also constant) being limited to the first and last 20 mm of septum travel. Thus, the septum traveled at a constant velocity during most of the 195 mm stroke length. Dwell time at the end of each stroke was on the order of 0.1 s, and was due to the computer control system. The control system allowed the user to program drive speed, acceleration profiles, and stroke length.

Experiments were conducted with water, and in some cases an aqueous solution of sodium carboxymethylcellulose (NaCMC) was used to increase fluid viscosity to approximately 50 cP. Using a lookup table and an electronic balance accurate to 0.1 g, an appropriate amount of CMC was added to achieve the desired viscosity. Although aqueous NaCMC solutions can display shear-thinning behavior, the dilute concentrations used here ensured that shear-thinning effects were minimal. Various Reynolds number regimes were considered, ranging from $4 < \text{Re} < 23,000$. Table 1 lists the Reynolds numbers tested.

To improve viewing conditions, the entire bag assembly was fully submerged in a large square glass tank with a side dimension of 530 mm and a height of 450 mm. The tank was filled with water to a height sufficient to fully submerge both chambers. Additionally, a slight overpressure (about 150 mm of water) was applied to the mixing chamber to minimize optical distortions caused by folds in the bags. Perfect refractive index matching between the working fluid and the plastic chamber material was not essential as the chamber walls were thin (0.2 mm). It was, however, important that the fluid inside the mixing chamber have the same refractive index as the fluid in the outer square tank. Note that the addition of NaCMC to the water did not noticeably change the refractive index of the mixer fluid. The use of a square tank (allowing orthogonal viewing through a flat surface) eliminated the otherwise severe optical distortion that the camera would see through the curved bag surface.

Measurement Techniques

The PIV technique was used for data collection and analysis in this paper. As is shown in Fig. 2, all PIV measurements were taken in a region of interest (ROI) centered on the central septum hole, and extending downward to the bottom of the lower (expanded) chamber. Two specific ROIs were chosen: one spanning the central three septum holes and the second spanning the entire septum diameter. The smaller ROI (about 140 mm wide by 160 mm tall) was chosen to allow higher resolution data acquisition, especially important when determining strain rate values, while the larger ROI (about 250 mm wide by 150 mm tall) was used to investigate general circulation patterns. The ROI was illuminated with a pair of 532 nm Nd-YAG pulsed lasers (Con-

tinuum Surelite II) running at 10 Hz with a 6 ns pulse width. Output power was approximately 120 mJ/pulse. The laser sheet illuminated the mixer through the side, as shown in Fig. 2. The horizontal line in Fig. 3 represents the laser sheet. The presence of a drain port blocked some of the laser sheet from reaching the lowest part of the mixing chamber. (This region is blanked out in grey in the plots.) A LaVision Imager Intense (1376 $\times$ 1040 pixels) was used to acquire image pairs for PIV measurements. Camera magnification was varied using a Sigma 28–100 mm Aspherical Hyperzoom Macro lens. Additional cropping was performed during data analysis to remove extraneous effects due to the septum, bottom plate, and bag edges. Note that in the subsequent plots, only every other vector in the vertical direction is plotted to improve readability.

Camera triggering was accomplished with a LaVision PTU synchronization board, LaVision DaVis software, and a custom-designed optical triggering setup. Images were recorded upon triggering of an optical sensor during upstroke just before the septum reached top dead center (see below). Shot-to-shot septum jitter was limited to between 1 and 4 mm. Between 30 and 75 image pairs were recorded for time averaging of the velocity fields. For the lowest five Re tests, the septum was located approximately 165 mm from the bottom plate when the image was recorded. For the highest three Re values, the septum was located approximately 145 mm from the bottom plate. To ensure statistical independence of the data, only one image pair was recorded per stroke. Time separation between each image in a pair was optimized to maximize in-plane displacement (reducing random error) while limiting out-of-plane displacement (reducing the number of bad vectors). Time separation values ranged from 1 ms for the highest Re case to 0.1 s for the lowest Re. Cross correlation was used to complete the analysis, with a grid size of 32×32 pixels, and an overlap of 50%.

Fluorescent particles (20–40 μm) were used as tracers for PIV measurements. A long-wave filter was used to block scattered laser light, while allowing fluorescence to pass through to the camera. Use of this filter improved overall signal quality and protected the camera sensor from stray laser reflections from the apparatus.

Mean and rms velocity, and strain rate were computed in the usual manner. Nondimensional rms velocity in the far field (V_{RMS-FF}^*) was computed by averaging the rms velocity in a rectangular region near the lower left corner of the velocity fields. The lower right corner could not be considered in this calculation due to shading of the laser sheet. Strain and jet penetration depth (L_{EP} and L_{JP}) were determined by noting the distance at which the fluid shear rate or velocity dropped to less than $0.5\varepsilon_{MAX}^*$ or $0.5V_{F-MAX}^*$. Penetration depths were measured using data obtained from the jet issuing from the central hole.

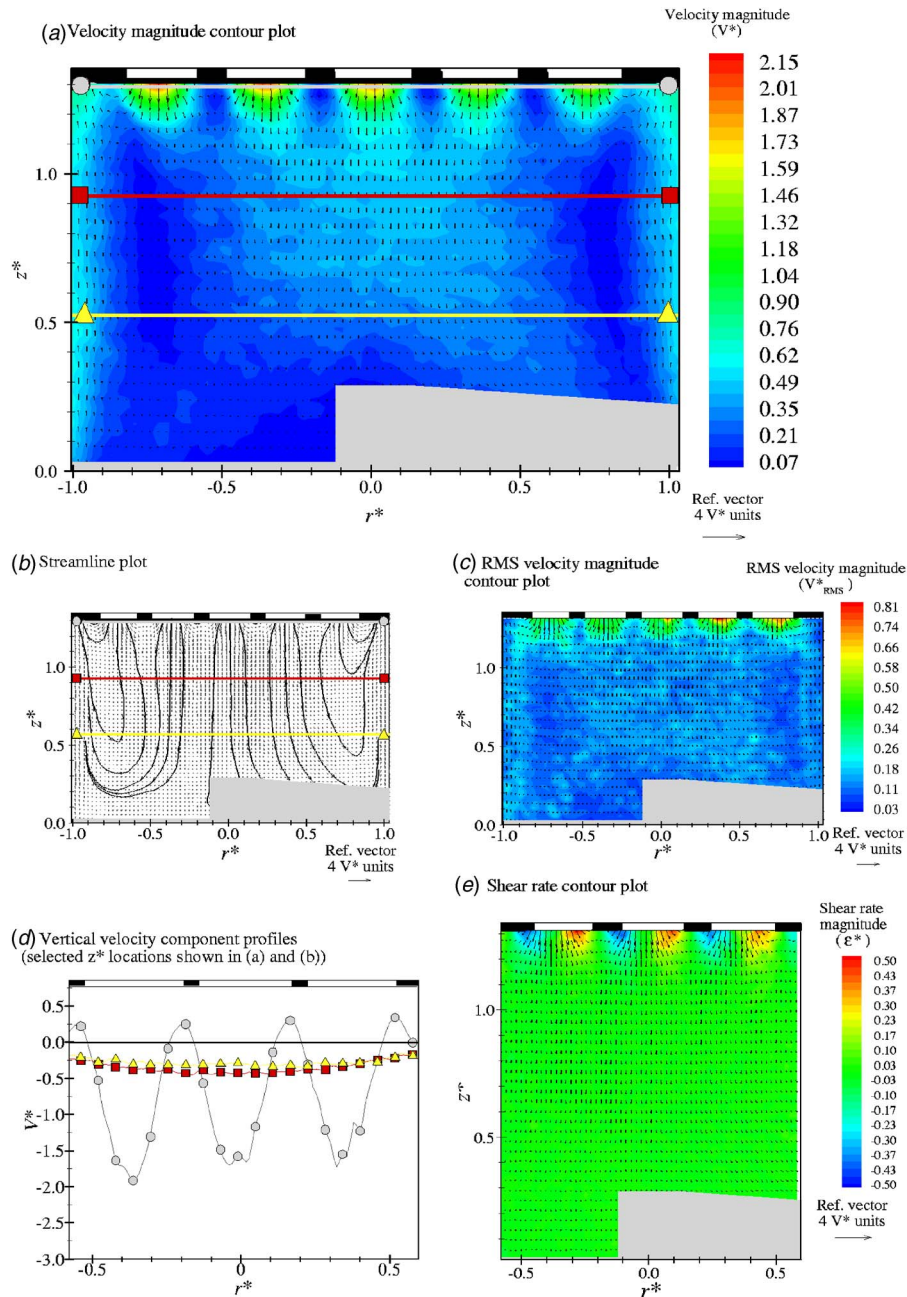


Fig. 4 Velocity magnitude, streamlines, rms velocity, vertical velocity profiles, and shear rate for $Re=4$

Experimental Uncertainty

Experimental uncertainty in the velocity measurements is primarily due to uncertainty in determining the location of the correlation peak to subpixel accuracy during PIV interrogation; the typically quoted value for this error is 0.1 pixel [13]. Typical peak pixel displacements at the jet centerline ranged from 4 to 8 pixels, resulting in a 1–3% velocity error at the centerline of each jet. To convert the data from pixel displacements to actual velocity values, a scale factor was used. The scale factor was accurate to within 2–3%. Table 1 contains summary data from all runs, and is accurate to about 10% of the stated value.

Additional sources of error include the aforementioned septum jitter, and the ability to line up the laser sheet with the center of

each hole. These uncertainties would contribute small errors in jet width and velocity values. It is not expected that these uncertainties will significantly impact our findings.

Results and Discussion

Table 1 presents summary data for all Re values tested (bold-face numbers represent the three cases that are plotted here). These three cases correspond to $Re=4$, 76, and 23,000. The lower two Re cases (Figs. 4 and 5) were conducted using aqueous NaCMC solutions as the working fluid, with an approximate viscosity of 50 cP. The high Re case presented in Fig. 6 was conducted using plain water. Five types of data are presented in each figure: (a) velocity fields; (b) streamline plots; (c) rms velocity

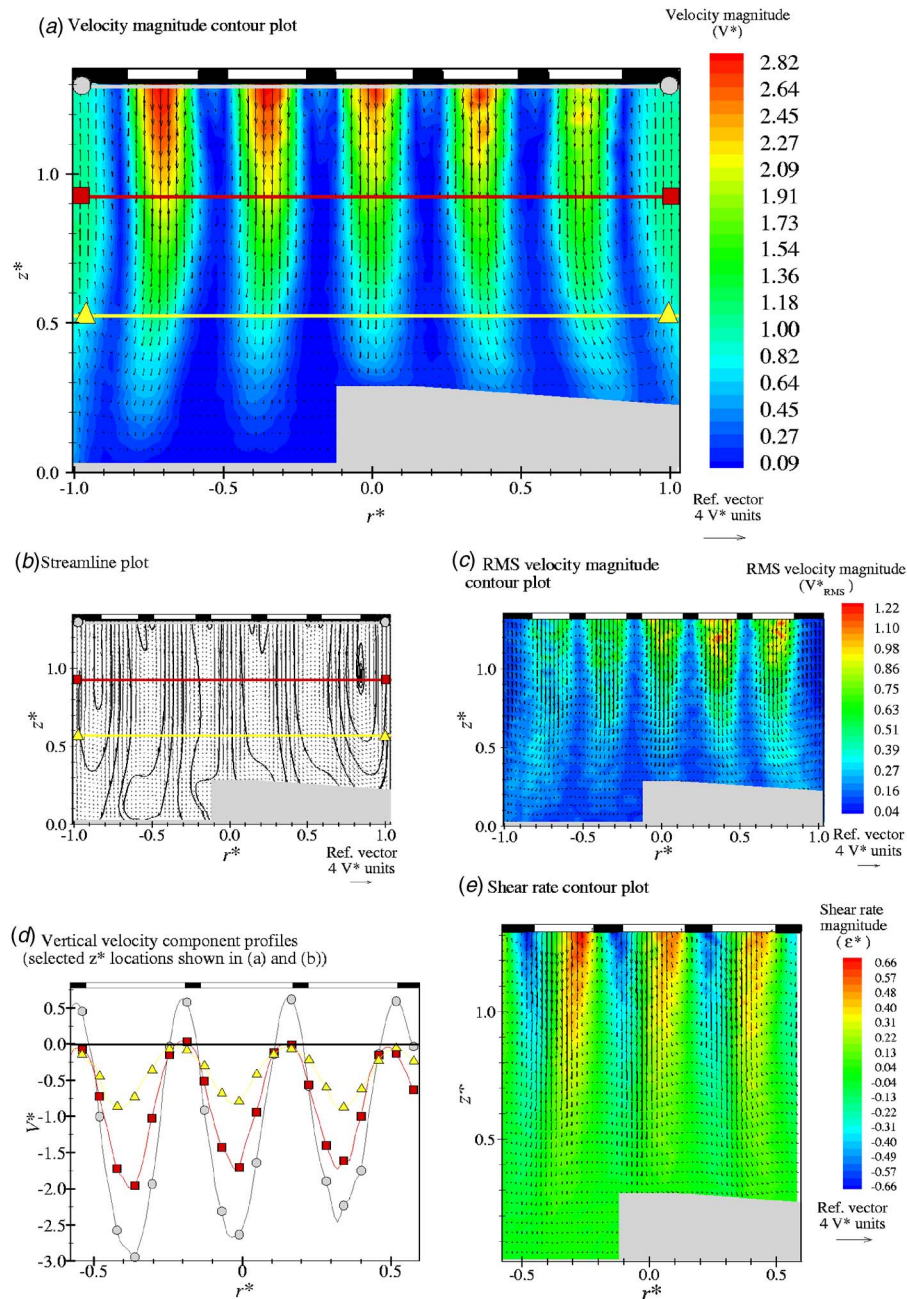


Fig. 5 Velocity magnitude, streamlines, rms velocity, vertical velocity profiles, and shear rate for $Re=76$

plots; (d) velocity profiles across the central three septum holes; and (e) shear rate contours. Figures 4–6 clearly illustrate the three flow regimes: creeping, laminar, and turbulent, respectively. The septum is located just above the upper edge of each plot. For convenience, a rough depiction of open and closed portions of the septum is provided at the top of each plot. The Re ranges presented here for the different flow regimes agree closely with those given by Komoda et al. [6] and to a lesser degree with those given by Idelchik [11]. It was also noted that, in general, peak velocity scaled well with septum speed, although there were important variations (discussed below). Shear rate values also scaled well with septum speed, although the high fluid viscosity cases (resulting in a lower Re) produced somewhat lower shear rate values as explained below. In all cases, the scaled shear values were less than unity, indicating that the measured shear was less than what would be predicted for laminar flow. This result can be explained

by data smoothing and inadequate spatial resolution.

Creeping Flow: $4 < Re < 15$. The creeping flow regime depicted in Fig. 4 is evidenced by several characteristics. As can be seen in Figs. 4(a) and 4(e) and as noted in Table 1, the jet penetration depth, measured by L_{JP}^* and L_{EP}^* are very small. In the limit of true creeping flow, one would expect flow streamlines to be perfectly symmetric upstream and downstream of the septum. This would imply that the flow streamlines (see Fig. 4(b)) would converge rapidly as the fluid entered the septum hole, and diverge equally rapidly upon exiting the septum hole, leading to a rapid reduction of velocity away from the septum. The streamline plot depicted in Fig. 4(b), and the small velocity and strain penetration lengths shown in Figs. 4(a) and 4(e) suggest that the flow is indeed behaving in a manner that approaches creeping flow.

The vector field and vertical velocity profile plots (Figs. 4(a)

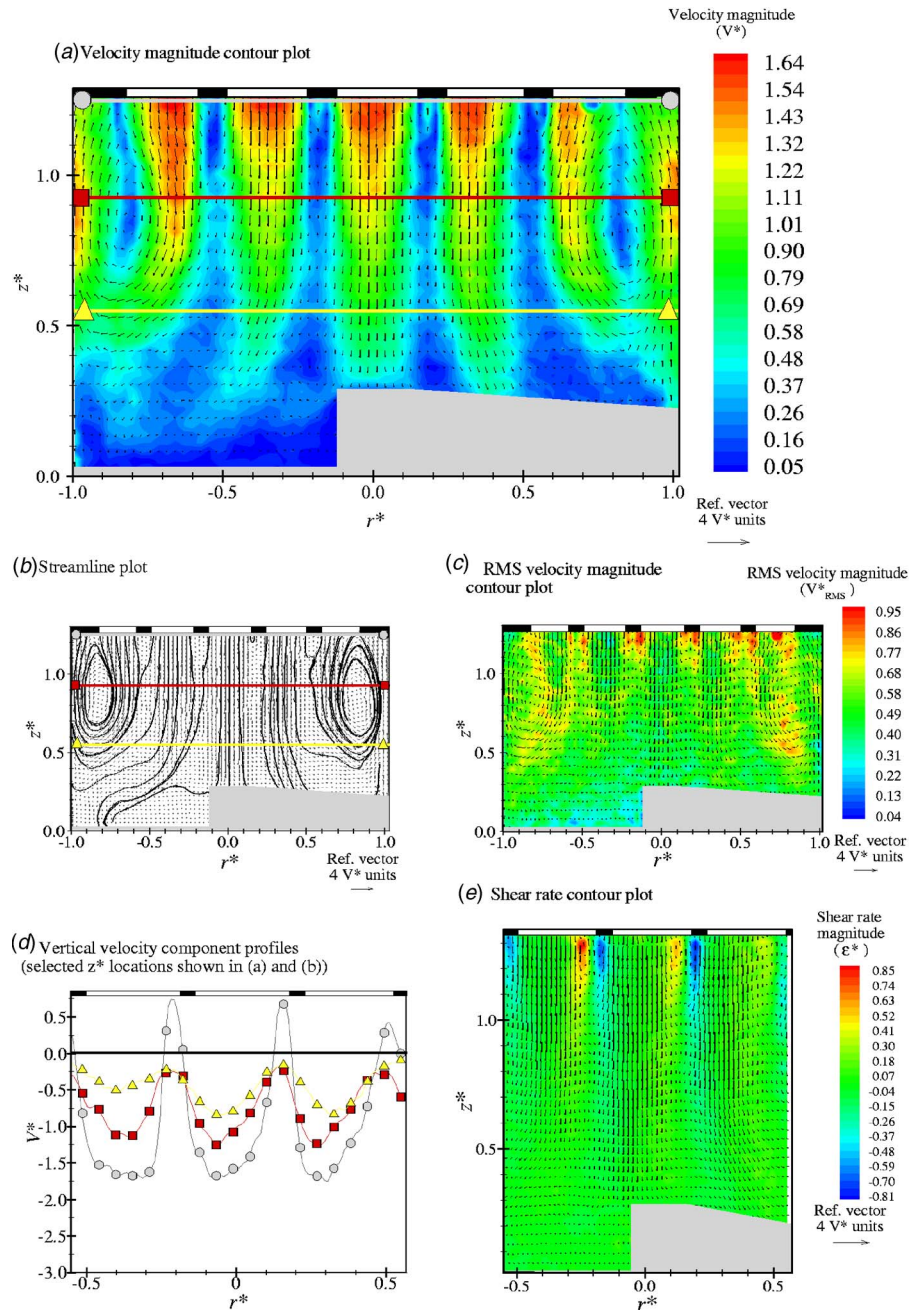


Fig. 6 Velocity magnitude, streamlines, rms velocity, vertical velocity profiles, and shear rate for $Re=23,000$

and 4(d)) indicate that the fluid emerging from the septum hole is surrounded by upward moving fluid. The upward movement is due to fluid being dragged upward by the closed portion of the septum. Additionally, a large volume of fluid was observed moving upward adjacent to the wall of the mixing chamber ($r^* = \pm 1$), as can be seen to some degree in Fig. 4(a). This is expected because the cylindrical wall of the mixing chamber is translating vertically during the upstroke and also because septum holes are absent at the septum circumference.

In the creeping flow case, ε_{MAX}^* should equal unity. However, strain rates depicted in Fig. 4(e) and in Table 1 were lower than expected for fully developed flow. It is suspected that lower than ideal spatial resolution, the presence of septum jitter, and the fact that the streamlines diverge rapidly downstream of the septum relaxing the velocity gradients will reduce the computed peak

shear values. The low strain rates away from the septum (Fig. 4(e)) correlate with a lack of fluid movement in those regions, as can clearly be seen in Figs. 4(a) and 4(d).

Upon examination of V_{F-MAX}^* and experimentally determined C values (a measure of fluid development, see Eq. (3b)) summarized in Table 1, one can see that the flow is indeed significantly developed ($C \approx 1.5$). Referring to well known correlations [12], the entrance length for our creeping flow cases should range from about 11 mm to 36 mm, all of which are less than the septum thickness. The reason C is not equal to 2.0 (the predicted value for fully developed laminar flow) in these cases lies in the rapid divergence of the streamlines away from the septum and a concomitant reduction in the maximum velocity. Due to experimental limitations, it was not possible to compute C based on velocity data

inside, or right at the edge of the septum.

Returning to Table 1, it is also apparent that, with the exception of the lowest Re case (Re=4) K is equal to or larger than unity as expected (see discussion following Eq. (2)). The discrepancy with Re=4 indicates that the average fluid velocity through the central hole is *less* than that predicted by mass conservation, and can be explained by asymmetric flow through the septum, which can be clearly seen in Fig. 4(a) by noting that the peak through-hole velocities are greater on the right side holes than the left. Asymmetry of the flow for this case may be due to bag folding. Additionally, shading effects are less pronounced in the true limit of creeping flow. Nonetheless, the deviation of K from unity is small.

A final characteristic of the creeping regime was the near absence of rms velocity away from the septum (Fig. 4(c)) and the low far-field strain values (Fig. 4(e)). Low $V_{\text{RMS-FF}}^*$ values are simply a consequence of the fact that the flow is highly repeatable in the creeping flow regime from cycle to cycle. High V_{RMS}^* values near the septum can be explained by the presence of septum jitter, which would result in local variations in the measured velocity near the septum. Were the septum jitter to be removed, it is expected that V_{RMS}^* near the septum would also be low.

Laminar Flow: Re=76. Between Re=15 and Re=76 several key changes take place. At Re=76, both the jet length L_{JP}^* and strain penetration length L_{EP}^* (Figs. 5(a) and 5(e)) become significantly larger than that seen in the Re=4 results, as is also noted in Table 1. Additionally, the jets have significantly higher peak through-hole velocity ($V_{\text{F-MAX}}^*=2.7$), C , and $V_{\text{F-AVG}}^*$ (equal to K) values. In the Re=76 case, the entrance length for fully developed flow increases to roughly 160 mm, which would suggest that the flow should not be fully developed (resulting in $C < 2$). As is noted in Table 1, C is nonetheless equal to 1.7, indicating significant development. Upon further examination of Figs. 5(a) and 5(b), one can see a lack of jet spread, strong upward fluid velocities directly adjacent to the downward jet, and a flow profile that is clearly parabolic. As was also seen in the creeping flow case, $\varepsilon_{\text{MAX}}^*$ remained lower than that predicted by laminar flow theory. The explanation for this is the same as that discussed in the creeping flow case.

Additionally, the value of $V_{\text{F-AVG}}^*$ (equal to K) reported in Table 1 clearly exceeds the expected value of unity. The explanation lies in the slight bulging of the lower bag, and folding of the flexible material that constitutes the walls of the upper bag. The former effect causes deviations from the ideal case wherein the mixing chamber is modeled as a cylinder that stretches axially while maintaining a constant diameter. Bulging of the lower bag during actual operation causes its cross-sectional area to increase and consequently, the amount of fluid required to pass through the septum holes also increases. Additionally, folding of the upper bag can shade the outermost ring of septum holes (for $V^* \rightarrow \pm 1$). Note that the outermost ring of holes contributes 63% of the total open area, therefore any shading effect there will significantly reduce the total open area and increase through-hole velocity further. During our experiments, uneven bag folding was observed on the right side, and is evidenced by reduced jet velocities on the right-hand side of each plot.

Although the V_{RMS}^* values near the septum increase significantly from the creeping flow case, $V_{\text{RMS-FF}}^*$ remains low. The high V_{RMS}^* near the septum can be explained by the septum jitter described in the experimental procedure section. It was also noted that most of the V_{RMS}^* comes from the vertical component. The horizontal rms component (not plotted here) remains very low throughout the view field.

Turbulent Flow: $460 < \text{Re} < 23,000$. All four high Re cases revealed similar patterns for velocity, shear, jet penetration, and general flow behavior. PIV plots for Re=23,000 are shown in Fig. 6. Both strain and velocity (ε^* , $V_{\text{F-MAX}}^*$, and $V_{\text{F-AVG}}^*$) scale roughly

linearly with increasing septum speed, as can be seen in Table 1. Additionally, L_{JP}^* and L_{EP}^* remained virtually constant throughout the entire regime, which is explained by Eq. (6) (penetration depth is not dependent on V_S). The transition from laminar to turbulent flow was clearly evidenced by a sharp increase in $V_{\text{RMS-FF}}^*$, which rose from negligible values to about 0.6, indicating significant fluid turbulence throughout the entire mixing volume. Additionally, the vertical velocity profile shows significant signs of blunting, as was expected for turbulent flow. This blunting can be seen by comparing Figs. 5(b) and 6(b), and by noting the lower C value (Table 1).

The flow showed evidence of development for the turbulent case, as can be seen in Figs. 6(a)–6(d), and by C values ranging from 1.3 for Re=460 down to 1.2 for the highest three Re (Table 1). As discussed previously, fully developed turbulent flow should yield a C value of about 1.23 [12]. The experimentally determined C values are somewhat high based on correlations for entrance length [12], which predict distances between 430 mm and 830 mm. We hypothesize that the high C values may be due to the interactions between adjacent jets in a jet array. We are conducting additional experiments to explore this issue. The impact of this anomaly is evidenced in lower than expected peak shear values, as discussed below.

Although the peak shear value $\varepsilon_{\text{MAX}}^*$ increased to between 0.7 and 0.9, it did not exceed unity as expected for turbulent flow. The reasons for this have been discussed earlier. The impacts of bag bulging and folding also evidenced themselves in the turbulent cases, as evidenced by higher than unity $V_{\text{F-AVG}}^*$ values shown in Table 1.

Comparison With Existing Mixing Technology

As discussed in the Introduction, there is a wide range of mixing tasks requiring different mixer characteristics. One key characteristic of a mixer is the ability to produce the desired shear rate values. Tatterson [14] provides several correlations for predicting shear rates in an impeller-driven mixer based on impeller speed, along with a plot relating shear levels to impeller speeds for various distances from the impeller for a particular test case. For the impeller-driven test case considered by Tatterson [14], a rotational speed of 100 rpm produces a shear rate of approximately 70 s^{-1} at the impeller tip. Increasing impeller speed to 400 rpm results in a shear rate of approximately 230 s^{-1} . However, as one moves away from the impeller, shear rates drop enormously. For example, at a distance of 2.5 mm from the impeller tip, the corresponding shear rates for 100 and 400 rpm are about 35 s^{-1} and 135 s^{-1} , respectively. High shear rates can either be desirable or detrimental depending on the mixing application. The results from cases presented in this paper show that the FCM can produce a wide range of shear rates from 0.7 s^{-1} to 111 s^{-1} (Table 1), although peak shear at the microscopic scale is likely higher. Ni et al.'s [1] shear rates for oscillatory baffled columns (0.7 s^{-1} for Re=251 and 21.4 s^{-1} for Re=4021) are in a similar range to ours. Even more extreme (low or high) shear rates can be attained in the FCM by changing the hole pattern, hole diameter, and percentage open area A_O . For example, a septum with a single large hole (comparable to the baffled column used by Ni et al. [1]) would increase A_O , and so reduce the peak fluid velocity and shear rate. In the case where high shear is desirable, decreasing A_O could produce tremendously higher fluid velocities, and proportionately higher shear rate levels. Importantly, it must be noted that the FCM produces high shear rates in an extended annular column downstream of *each* hole, implying that the high shear regions are more uniformly distributed throughout the mixing volume. In contrast, the impeller-driven mixer experiences high shear only in the immediate vicinity of the mixer. Likewise, for low shear mixing as well, the FCM ensures that the entire fluid volume is gently stirred due to the even distribution of septum holes and

the fact that the septum interacts with the full column of fluid during each oscillatory cycle.

Summary

A novel oscillatory flexible chamber mixer has been demonstrated in this study, and its flow characteristics have been investigated. The results presented here clearly demarcated three major flow regimes: creeping, laminar, and turbulent flow. For $4 < Re < 15$, the flow exhibited creeping characteristics, with minimal flow activity away from the septum. This regime would be appropriate for continuous stirring at low shear levels, for example, in certain biological mixing applications. As the Reynolds number increased to $Re=76$, the flow became laminar and clear, strong jets issued from the septum plate, while the rms velocity away from the septum remained quite low. As the Reynolds number was increased beyond 460, the flow transitioned to turbulent, as evidenced by a marked increase in rms velocity throughout the mixing region. A model was also presented and verified relating the jet penetration length to septum speed for both laminar and turbulent regimes. Analysis of shear rates show the potential of the FCM to produce a wide range of shear values for different applications, and are comparable to shear rates produced by other designs [1,14]. The major difference between the current mixer and other impeller-driven mixers is that the entire fluid volume in the FCM is exposed to the desired shear level in contrast to the small region of high shear in the vicinity of the impeller in an impeller-driven mixer. Finally, recommendations for design refinement and customization for different mixing scenarios were presented.

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Nomenclature

A_O	= fractional open area of the perforated plate septum (-)
C	= constant that accounts for flow development (-)
D_H	= hole diameter (in the perforated septum) (mm)
D_S	= septum diameter (mm)
K	= constant that accounts for fluid velocity deviations from $V_{F-NOM/L}$ (-)
L_C	= working chamber length (mm)
L_{eP}	= strain penetration length (mm)
L_{eP}^*	= nondimensionalized strain penetration length (-)
L_{JP}	= jet penetration length (mm)
L_{JP}^*	= nondimensionalized jet penetration length (-)
L_S	= stroke length (mm)
N	= number of holes in the septum (-)
Re	= Reynolds number (-)
r	= radial position (mm)
r^*	= nondimensionalized radial position (-)
St	= Strouhal number (-)
t	= time (s)
V_F	= fluid velocity (mm/s)
$V_{F-AVG/L}$	= average through-hole fluid velocity with respect to the lab frame L (mm/s)
V_{AVG}^*	= nondimensionalized average through-hole velocity with respect to the lab frame L (-)

$V_{F-AVG/S}$	= average through-hole fluid velocity with respect to the septum S (mm/s)
$V_{F-MAX/L}$	= maximum through-hole fluid velocity with respect to the lab frame L (mm/s)
V_{MAX}^*	= nondimensionalized maximum through-hole velocity with respect to the lab frame L (-)
$V_{F-MAX/S}$	= maximum through-hole fluid velocity with respect to the septum S (mm/s)
$V_{F-NOM/L}$	= nominal (predicted average) through-hole fluid velocity with respect to the lab frame L (mm/s)
$V_{F-NOM/S}$	= nominal (predicted average) through-hole fluid velocity with respect to the septum S (mm/s)
V_{RMS-FF}^*	= non-dimensionalized far field rms velocity (-)
$V_{S/L}$	= velocity of the septum with respect to the lab frame L (mm/s)
V^*	= nondimensionalized fluid velocity with respect to the lab frame (-)
z	= vertical position (mm)
z^*	= nondimensionalized vertical position (-)
ε	= local shear rate (1/s)
ε^*	= nondimensionalized shear (-)
$\varepsilon_{MAX-LAM}$	= maximum laminar shear rate for laminar pipe flow (1/s)
ε_{MAX}^*	= nondimensionalized maximum shear (-)
ν	= kinematic viscosity (mm ² /s)
ω	= oscillation frequency (1/s)

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