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Experimental investigation of thermal and flow mixing enhancement induced by Rayleigh-like Streaming in a milli-mixer

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Abstract

In milli/microchannel, fluid flows are essentially laminar and, as a consequence, heat transfer is limited. An important application of millichannels is mixing of several flows. In this article we present mixing of two fluid flows at two different temperatures with the objective of strongly decreasing the time needed to obtain a mixture at a [homogeneous](#) temperature. To increase heat and mass transfer, we propose an active enhancement technique by generating secondary flows by using ultrasonic waves. [A mixer](#) has been realized consisting of a millichannel fed by two fluids coupled to a piezoelectric transducer with a vibrating frequency (37.7 kHz) adapted to the channel width. A test bench has been realized to measure mixing properties of [the mixer](#) with and without ultrasound for specific equivalent Reynolds number ($Re_{eq} \leq 23$). At this frequency, vortices were formed to break the flow laminarity by generating a velocity field with significant transverse components. The observed patterns revealed vortices parallel with the transducer surface corresponding to modal Rayleigh-like streaming. To characterize the mixing performance a thermal mixing criterion (C_M) based on input/output temperatures was defined which showed [a significant increase in the presence of Rayleigh-like streaming patterns](#).

Key words: [Transfer enhancement](#), Rayleigh-like streaming, Mixing criterion.

1. Introduction

Small-scale devices are essentially used in microelectronics for heat transfer purposes and in bio- and chemical analyses for lab-on-chips [1]. Mixing two or more fluids is a classic step in process engineering. Mixtures are often realized in static mixers in which the fluids are continuously mixed by flowing inside a tube or more generally a channel. A rather complete description of applications of micromixing technology has been made by Nguyen in the chemical industry and in chemical and biochemical analysis

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[2]. In milli- or micro-devices, due to geometrical confinement, turbulence induced by inertial forces cannot develop and Newtonian fluid flows are generally in the laminar regime. In this case both heat transfer and mixing are limited and finding the adapted residence time, needed for chemical reaction or other transformations, can be problematic. To increase the thermal and flow mixing rate, two types of enhancement techniques are generally distinguished: passive and/or active [3, 4, 5, 6]. Passive techniques are usually based on the energy provided by the flow itself (e.g. mass transport provided by molecular diffusion and chaotic advection). In active techniques, an external power source is required.

There are many studies concerning species concentration measurements in mixing while little work has been carried out to study thermal mixing. The latter was analyzed by Xu et al.[7] for two miscible fluids in a T-shaped microchannel. They found that in the mixing channel, the heat transfer process is dominated by both thermal diffusion and convection. Glawdel et al. [8] have reported a technique, which employed a photobleaching method by channel wall absorption of a fluorescent dye (Rhodamine B) embedded in fluids to accurately determine the temperature field at the intersection of two fluids in a Y-shaped channel.

Static mixing promoters are specific to a given device and generally, the enhancement is obtained by modifying the flow paths and/or the surface state. The chosen geometry cannot be applied to others. This limitation has led to the search for active systems in order to create a more efficient flow. Such systems necessitate an external power source to provoke flow disturbances (secondary flow) which induce rapid mixing. Among these, the use of ultrasound has become a common way to provoke flow disturbances associated or not with specific geometries. The disturbances can be directly created by streams due to ultrasonic waves or through an intermediate system or medium reacting to ultrasound and modifying the streamlines of the main flows.

For example, in this context, microbubble surface vibrations induced by ultrasonic waves have been considered [9]. However, there is some inconvenience due to bubble instabilities and mechanical promoters which create vibrations by means of piezoelectric transducers have been tested [10]. To take advantage of streams created by ultrasonic waves in rectangular channels without any specific surface geometry, several researchers have studied mixing inside simple channels without promoters. Bengtsson & Laurell [11] have used ultrasound to induce Rayleigh vortices to improve mixing of two laminar flows. Sugano et al. [12] have developed a Y-shaped microreactor for gold nanoparticle synthesis via a pulsed mixing

method in order to obtaining rapid mixing using two piezoelectric valveless micropumps. In all the experiments, it is important to characterize the degree of mixing. Manickam [13] has defined the quality of mixing based on concentrations. In our case, we have proposed another type of criterion based on temperatures.

The work presented here is within the framework of active techniques and uses acoustic waves to modify the fluid flow, via a phenomenon called *acoustic streaming*. Streaming flows have applications in fluid homogenization and mixing especially in microfluidics [14], in heat transfer enhancement [15, 16], in separation [17], in particle sorting [18] or in fluid pumping [19]. This phenomenon is denoted as *Rayleigh streaming*, from the pioneering study of Rayleigh on acoustically generated flows in pipes [20], and is distinct from the Eckart streaming flow originating from bulk acoustic dissipation by viscosity [21]. In both cases, a secondary flow is produced perpendicular to the ultrasound emitter surface. Recently, Lei et al. [22] have shown that, considering three-dimensional cavity modes of rectangular channels, a wider family of streaming patterns, parallel to the transducer surface, could be found.

The mixing rate is a crucial parameter for chemical reaction however thermal residence time also plays an important role for some process in which the mixing is not efficient enough and is not controlled when fluid flows are not at the same temperature. This aspect is very important when mixing fluids whose state (liquid, gel, ...) is strongly dependent on temperature. Taking these two findings into consideration, we propose to study the thermal and flow mixing of two miscible fluids with different temperatures in a milli-channel by generating some vorticity via acoustic waves. These are produced by a piezoelectric transducer placed perpendicular to the channel wall. A mixing criterion based on input/output temperatures is proposed. The objective is to obtain a mixture at a given temperature during the shortest time.

2. Rayleigh-like streaming

In a confined space in the presence of a plane standing wave, energy dissipation in the viscous boundary layer and other solid surfaces leads to a distribution of vortices. Rayleigh has shown that for an isothermal fluid in an infinite parallel-plate channel with a standing wave of wavelength (λ) much larger than the plate separation, two streaming vortices are formed per quarter wavelength ($\lambda/4$) of the acoustic wave which are symmetric about the channel centerline [20]. This theory stands for a

two-dimensional configuration in which streaming patterns (counter-rotating longitudinal roll cells) are perpendicular to the face of the acoustic transducer (xy plane in Fig. 1). However, it is possible to find transducer-plane streaming patterns (xz plane in Fig. 1) in which vortices circulate parallel to the surface driving the streaming.

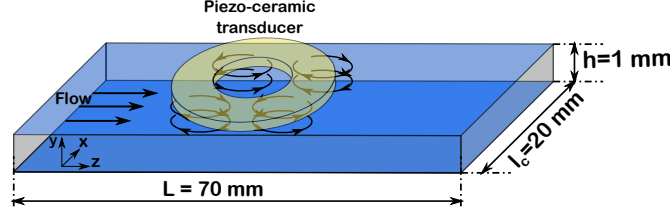


Figure 1: Sketch of Rayleigh-like streaming field in a fluid channel with a transducer placed thereon.

This flow pattern can be called Rayleigh-like streaming and has also been observed by Lei et al. [22, 23]. The authors have conducted experimental and theoretical investigations. They concluded that combinations of traveling waves in the direction of the main flow with standing modes in the x direction lead to streaming vortices in the same plane as the transducer surface. They have given conditions for the occurrence of different types of streaming patterns. When $h/l_c \leq 1/20$, they have concluded that transducer-plane streaming occurs. This condition is met in our experiment ($h=1$ mm and $l_c = 20$ mm).

3. Experimental set-up and measurements

3.1. Experimental procedure

A single millichannel, (70 mm long, 20 mm wide and 1 mm high) was built in plexiglas. A cold fluid and a hot fluid were separately introduced in the channel through distinct inlets. In addition two distinct outlets were realized to measure the degree of mixing. Such a geometrical structure has already been used in another context by Xiong et al. [24] to study liquid-liquid extraction by real-time fluorescent detection by adding auxiliary microstructure to increase the extraction efficiency [23]. The upper side of the millichannel is made of pyrex to make the visualization easier (Fig. 2b).

A schematic of the experimental set-up is given in (Fig. 2a). The hot and cold inlets of the channel are supplied with distilled water, the temperature of which is controlled by thermostatic baths set at 55 °C and 22 °C, respectively. The flow rate was controlled by a Syringe Pump that was calibrated for a low Reynolds number flow range ($Re \leq 23$). Four K-type thermocouples are placed at the inlet and outlet of each fluid during the experiment. Temperatures were sampled every second until achieving steady

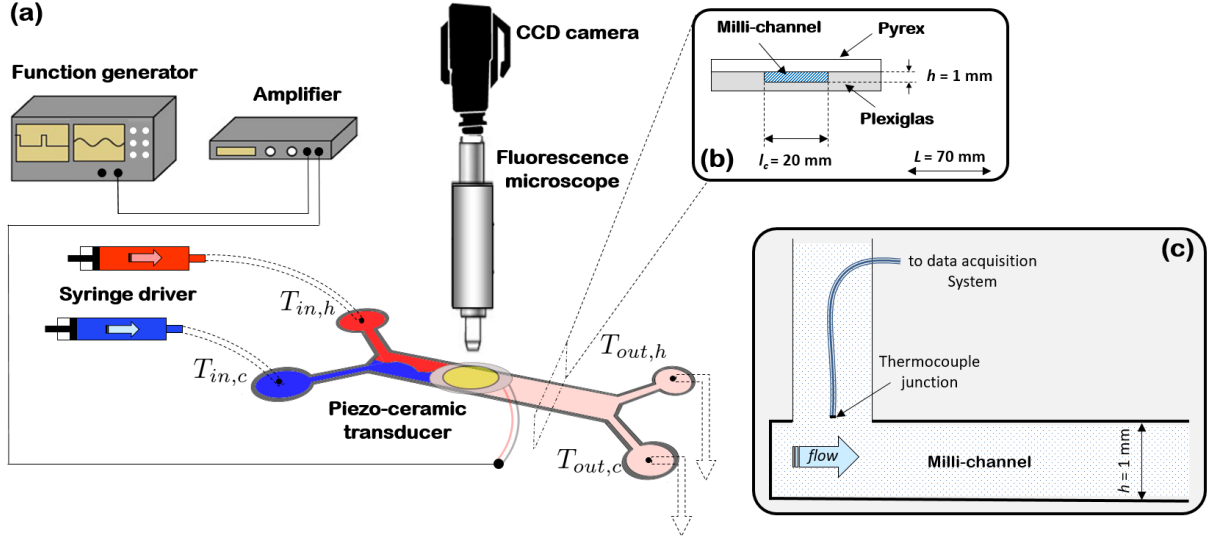


Figure 2: Experimental set-up and close-up of the test section.

state. The thermocouples are fixed inside the flexible pipe water parallel to the flow direction over a length of 2 cm as shown in figure 2c. By doing that, the end of the thermocouple reaches a thermal equilibrium with the fluid. A numerical simulation using COMSOL Multiphysics has shown that, for an inlet temperature of 45 °C and similar experimental flow rates the temperature at the junction located at the end of the thermocouple was the same as that of the neighboring fluid within 0.3 °C.

A piezo-ceramic transducer (UCE-45155, UCE ultrasonic co. China) was fixed by applying shear-wave coupling to the surface of the pyrex. A sinusoidal signal of frequency 37.7 kHz was generated by a function generator ($V_{pp} = 30$ V), and transmitted via a power amplifier to the acoustic transducer whose vibrations propagated into the channel. The device assembly was mounted on a fluorescence stereomicroscope (Leica MZ16 F, Heerbrugg, Switzerland). The fluid was seeded with fluorescent particles of 10 μm in order to visualize and characterize the streaming flow inside the channel using a CCD camera (Imaging Source, DFK 31AF03, Germany). The typical bead trajectories observed in experiments are shown in Figure 4.

3.2. Estimation of the ultrasonic power

A preliminary calorimetric test, based on the first law of thermodynamics, was carried out to estimate the ultrasound power dissipated into fluids. For this purpose, we only injected the cold fluid and then, we measured the temperature difference (ΔT) of the fluid between inlet and outlet at different mass flow rates (\dot{m}). The thermal losses of the system due to insignificant differences in temperatures between

104 ambient and injected cold liquid were neglected. Then, the magnitude of the dissipated ultrasound power
 105 (P_{ac}) can be estimated as follows:

$$P_{ac} \equiv P_{cal} = \dot{m}C_p(\Delta T) \quad (1)$$

106 where P_{cal} represents the calorimetric power dissipation and C_p the specific heat of cold liquid
 107 ($J.kg^{-1}.K^{-1}$). The power delivered by ultrasonic waves is reported in figure 3 as a function of an
 108 equivalent Reynolds number Re_{eq} defined later in Section 4 (eq.10).

109 We measured the heat flow rate in the presence ($Q_{c,ac}$, $Q_{h,ac}$) and absence (Q_c , Q_h) of ultrasound
 110 for the hot and cold fluid injection in the millichannel as:

$$Q_c \quad \text{and} \quad Q_{c,ac} = \dot{m}C_p(T_{c,out} - T_{c,in}) \quad (2)$$

$$Q_h \quad \text{and} \quad Q_{h,ac} = \dot{m}C_p(T_{h,out} - T_{h,in}) \quad (3)$$

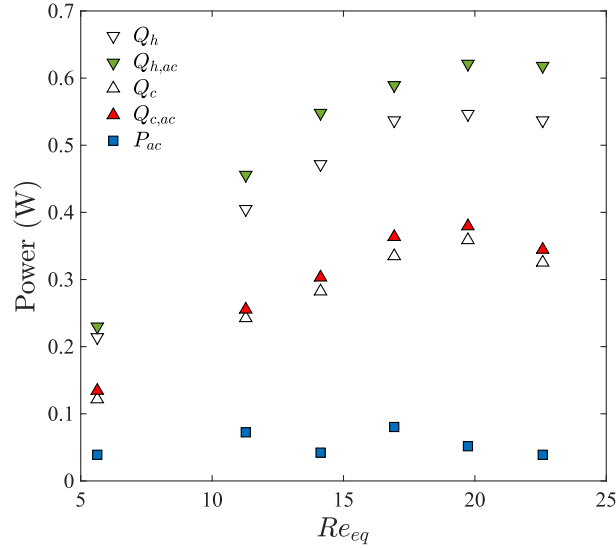


Figure 3: Dissipated ultrasound power (P_{ac}), heat flow rate in the presence ($Q_{c,ac}$, $Q_{h,ac}$) and absence (Q_c , Q_h) of ultrasound as a function of equivalent Reynolds number Re_{eq}

111 The energy balance to determine the real heat flow rates transmitted from one fluid to the other is
 112 given as follows:

$$P_{ac} + Q_c \equiv Q_{c,ac} + Q_{tl} \quad (4)$$

$$P_{ac} + Q_h \equiv Q_{h,ac} + Q_{tl} \quad (5)$$

Where Q_{tl} represents the thermal losses which can be neglected. As can be seen in Figure 3 the differences between $Q_{c,ac}$ and Q_c are less than 8% and less than 14 % between $Q_{h,ac}$ and Q_h .

4. Results and discussion

The first part of this work consisted in coupling both acoustic waves and hydrodynamics to characterize the steady-state laminar flow conditions. For this objective, one of the injected fluids was diluted in blue color dye to perform the mixing experiment. As can be seen in Figure 4c, we observe a distinct boundary between the two fluids for $Re \simeq 2$ whose value is characteristic of a laminar flow regime. Such a clear distinction between the two flows has already been observed [8]. When the transducer is turned on for a similar Reynolds number (Fig. 4d), the stable boundary is disrupted by vortices. For the same exchanger length, this behavior enhances the mixing quality. In order to characterize this more accurately, we performed a second experiment in which the fluid was seeded with fluorescent particles.

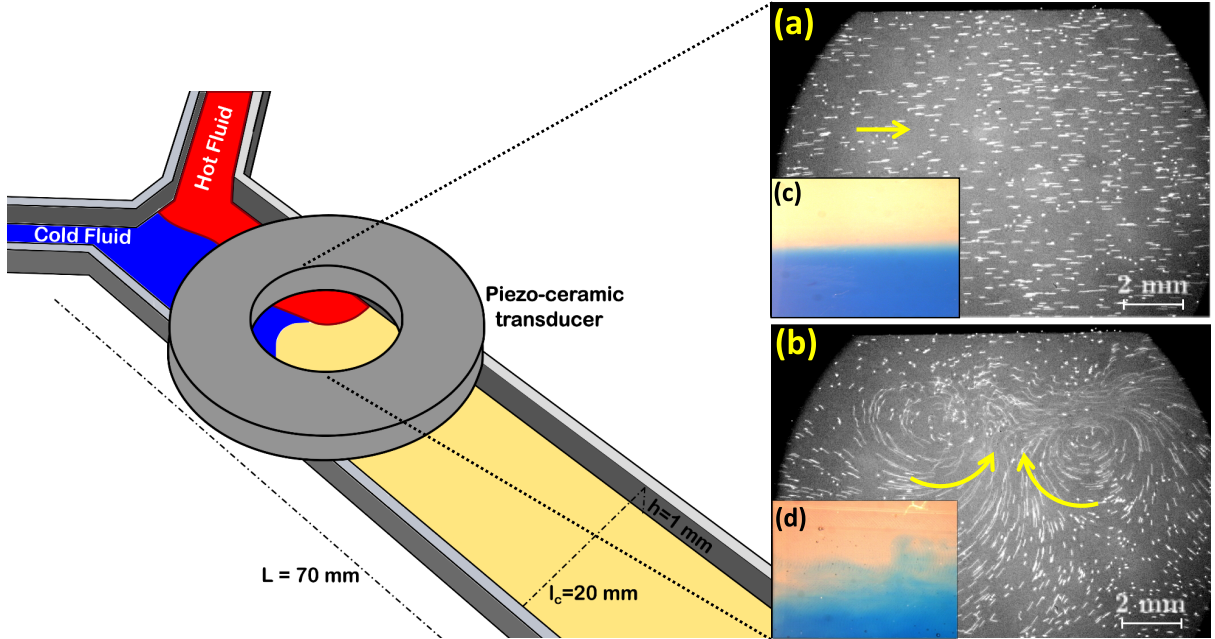


Figure 4: Flow pattern and mixing snapshots without (a, c) and with (b, d) Rayleigh-like streaming flow for $Re \simeq 2$. On the left side is presented the device allowing the visualization through the transducer aperture. On the right side are shown visualization results.

The local velocity v_l measurements are performed with an exposure time of 0.33 s. This is long enough for particle displacement to leave a light trail behind, allowing visualization of its trajectory and local

velocity v_l , as can be seen in Figure 4a for $Re \simeq 2$ and $v_l = 0.96 \text{ mm.s}^{-1}$. In the presence of ultrasonic waves (Fig. 4b), we observe the appearance of counter-rotating vortices parallel to the transducer surface. The observed structure contrasts with the classic Rayleigh-type patterns. The roll cells have a diameter of about 4 mm each and were able to induce a local velocity of $v_{l,ac} = 2.2 \text{ mm.s}^{-1}$. where subscripts l and ac are represent the local and acoustic states in our experiment. This flow ($v_{l,ac} > 2v_l$), called Rayleigh-like streaming, [can enhance the mass transport](#) between the two fluids by perturbing the bulk flow and breaking the interface of the two laminar flows, thereby enabling faster and more homogeneous mixing.

The second part of this study focuses on the energetic aspect in trying to thermally quantify the mixing efficiency. The same fluid was used in the inlet channels but with two different temperatures. Both cold and hot fluids flows were mixed in the millichannel. The outlet temperatures were measured to evaluate the degree of mixing. In noting the mass flow rates of hot \dot{m}_h and cold \dot{m}_c fluids, the specific heat capacity $c_{p,h}$ and $c_{p,c}$, the inlet temperatures of hot $T_{in,h}$ and cold $T_{in,c}$ fluids and the outlet temperatures $T_{out,h}$ and $T_{out,c}$, for a perfect mixing, the outlet common temperature of both fluids is given by:

$$T_{out,h} = T_{out,c} = T_s \quad (6)$$

where c and h refer to the cold and hot fluids respectively, and T_s is the temperature value reached for an infinite length exchanger, defined by:

$$T_s = \frac{\dot{m}_c c_{p,c} T_{in,c} + \dot{m}_h c_{p,h} T_{in,h}}{\dot{m}_c c_{p,c} + \dot{m}_h c_{p,h}} \quad (7)$$

In our experiment, results are presented as a function of the Reynolds number. For a fluid whose average temperature can be defined, it is determined by

$$Re = \frac{\dot{m} D_{hy}}{\mu S} \quad (8)$$

where \dot{m} is the total mass flow rate, D_{hy} the hydraulic diameter, μ the dynamic viscosity and S the channel cross section $S = l_c h$.

However, the two fluid flows enter the channel with different temperatures but with the same volume flow rates. Due to the values of the mass densities, the mass flow rates of each flow are different. It

is difficult to define a Reynolds number for the mixture because of the large difference between the viscosity of each fluid. To overcome this problem, we have defined an equivalent Reynolds number. We have followed the same approach as that used in two-phase flow analysis where only one Reynolds number is defined with characteristics of both liquid and vapor [13]. By defining the mass flow rate densities as:

$$G_h = \frac{\dot{m}_h}{S} \quad , \quad G_c = \frac{\dot{m}_c}{S} \quad (9)$$

The equivalent Reynolds number becomes

$$Re_{eq} = \frac{G_c D_{hy}}{\mu_c} + \frac{G_h D_{hy}}{\mu_c} \left(\frac{\rho_c}{\rho_h} \right)^{0.5} \left(\frac{\mu_h}{\mu_c} \right) \quad (10)$$

When the fluid temperatures are identical, Re_{eq} is equal to the usual Reynolds number in which

$$G = \frac{\dot{m}}{S} = G_c + G_h \quad (11)$$

Results are presented for $T_{in,h} = 45^\circ\text{C}$ and $T_{in,c} = 23.5^\circ\text{C}$ through the difference of temperature ΔT (in absolute value) between inlet and outlet for each fluid.

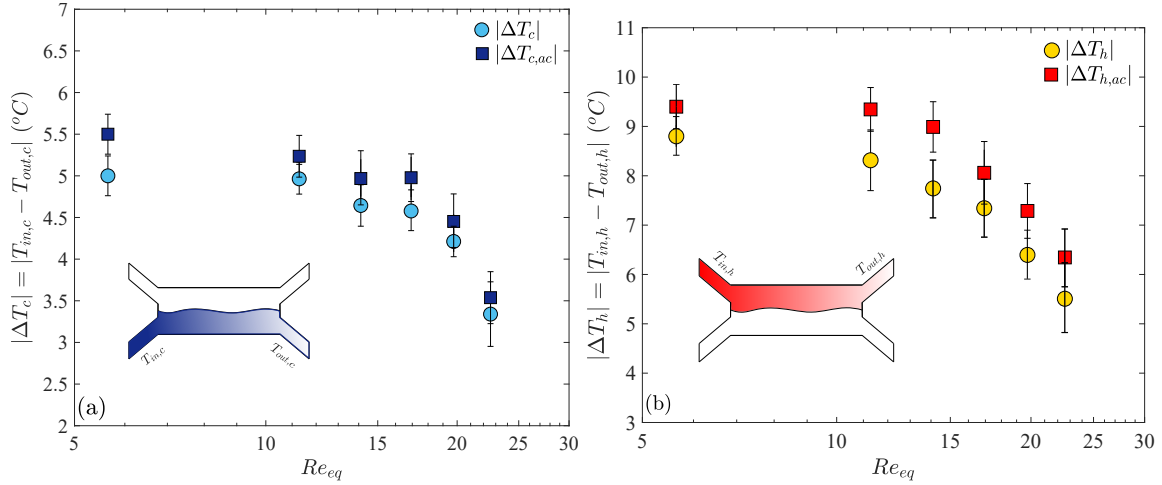


Figure 5: Temperature difference ΔT with and without ultrasound as a function of the equivalent Reynolds number (a) Cold side $\Delta T_c = T_{out,c} - T_{in,c}$ (b) Hot side $\Delta T_h = T_{out,h} - T_{in,h}$.

In Figure 5 the temperature difference is presented as a function of the equivalent Reynolds number for the cold (Fig. 5a) and hot fluids (Fig. 5b), with (denoted by subscript *ac*) and without acoustic waves.

These differences decrease with the Reynolds number due to the corresponding decrease in residence time. For all equivalent Reynolds numbers, the temperature difference is greater with ultrasound than

without. However, for the cold fluid the change in ΔT is smaller than for the hot fluid. This difference is due to the thermal losses through the walls which are greater for the hot fluid. In fact, our milli-channel was not thermally insulated enough due to the fact that the pyrex wall is not insulated to allow the visualization to be done. For high Reynolds numbers, ultrasound seems to be less efficient.

When the flow rates are equal, we can characterize the mixing by a thermal mixing criterion C_M :

$$C_M = 1 - \left(\frac{T_{out,h} - T_{out,c}}{T_{in,h} - T_{in,c}} \right) \quad (12)$$

for perfect mixing $T_{out,c} = T_{out,h}$ and $C_M = 1$.

As can be seen in Figure 6, the thermal mixing criterion C_M is shown as a function of Re_{eq} in the presence ($C_{M,ac}$) and absence (C_M) of ultrasound. The results show that for all conditions the mixing criterion decreases as Re_{eq} increases. This can be explained by the residence time at which the mixing occurs in the channel.

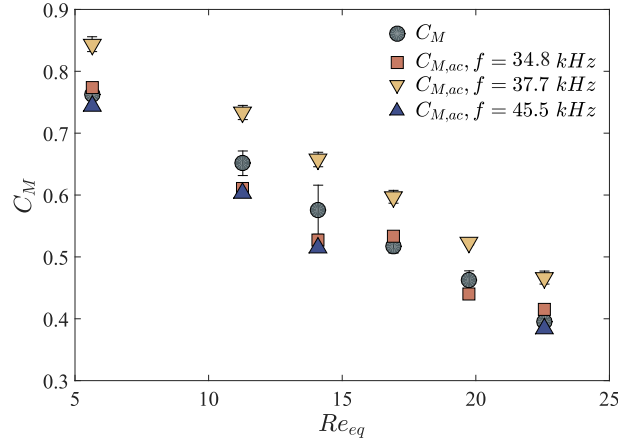


Figure 6: Thermal mixing criterion C_M vs Re_{eq} , without ultrasound and with three ultrasound frequencies.

In addition, the frequency has been varied in the vicinity of 37.7 kHz with two other piezoelectric transducers (at frequencies of about 34.8 & 45.5 kHz) and in this case no improvement of C_M has been observed. This is due to resonance between the acoustic wave and the channel width. The acoustic wavelength is defined as $\lambda = c/f$. As the speed of water, c , is approximately 1480 m/s, the half-wavelength can be established for frequency of 37.7 kHz. The $\lambda/2$ obtained is about 20 mm and is similar to the channel width.

To quantify the impact of acoustic waves, Figure 7 represents the difference of $C_{M,ac}$ and C_M as a function of Re_{eq} . As can be seen, the mixing enhancement tends to decrease with increasing Re_{eq} .

This behavior can be caused by the competition between straming vortex intensity and main channel flow.

Indeed, the influence of straming vortex intensity seems to be greater for small flow rates.

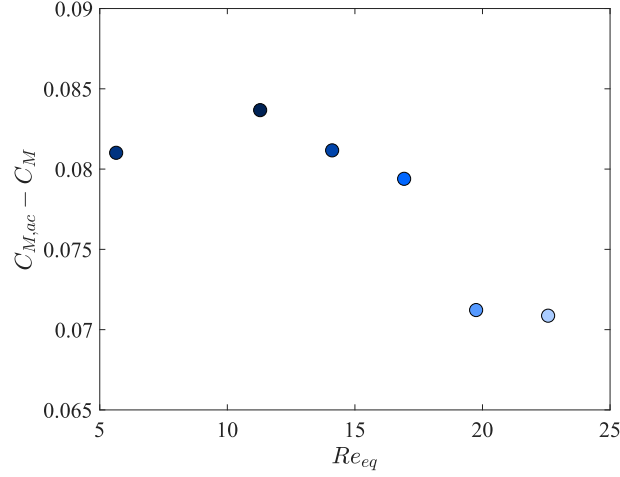


Figure 7: The mixing enhancement ($C_{M,ac} - C_M$) vs Re_{eq} .

5. Conclusions and Outlook

In numerous chemical or biological applications especially in microfluidic systems, regulating the fluid temperature is very important. When a microcrochannel is fed with two fluid flows at different temperatures this becomes more difficult. This study aimed at characterizing the behavior of the flow resulting of mixing two inlet fluid flows and at enhancing mixing in trying to know and to improve the resulting averaged temperatures. In this objective we have used ultrasound to homogeneize the flow and obtain better temperature control. First a fluid flow not submitted to ultrasound was characterized, then the effect of ultrasonic waves was evaluated. Ultrasounds were produced by a piezo-electric transducer and resulted in vortices which allow better mixing of the inlet fluids. These vortices correspond to transducer-plane streaming also called modal Rayleigh-like streaming.

To analyze the results we have defined a specific equivalent Reynolds number, Re_{eq} , and a new type of criterion to characterize the degree of mixing on outlet temperatures. This thermal mixing criterion (C_M) has been determined from the inlet and outlet temperatures as a function of the equivalent Reynolds number Re_{eq} . This criterion shows a significant increase when ultrasound is applied, indicative of an improvement of mixing.

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Highlights

- Thermal and flow mixing of two fluids were studied in presence of 37 kHz ultrasound
- A new type of acoustic streaming called *Rayleigh-like streaming* was identified
- Thermal and mixing enhancement induced by *Rayleigh-like streaming* was measured
- A new type of thermal criterion to characterize the degree of mixing is proposed

Graphical abstract

