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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.

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## 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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7 [2]. In milli- or micro-devices, due to geometrical confinement, turbulence induced by inertial forces  
8 cannot develop and Newtonian fluid flows are generally in the laminar regime. In this case both heat  
9 transfer and mixing are limited and finding the adapted residence time, needed for chemical reaction or  
10 other transformations, can be problematic. To increase the thermal and flow mixing rate, two types of  
11 enhancement techniques are generally distinguished: passive and/or active [3, 4, 5, 6]. Passive techniques  
12 are usually based on the energy provided by the flow itself (e.g. mass transport provided by molecular  
13 diffusion and chaotic advection). In active techniques, an external power source is required.

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

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

29 For example, in this context, microbubble surface vibrations induced by ultrasonic waves have been  
30 considered [9]. However, there is some inconvenience due to bubble instabilities and mechanical promoters  
31 which create vibrations by means of piezoelectric transducers have been tested [10]. To take advantage  
32 of streams created by ultrasonic waves in rectangular channels without any specific surface geometry,  
33 several researchers have studied mixing inside simple channels without promoters. Bengtsson & Laurell  
34 [11] have used ultrasound to induce Rayleigh vortices to improve mixing of two laminar flows. Sugano  
35 et al. [12] have developed a Y-shaped microreactor for gold nanoparticle synthesis via a pulsed mixing

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

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

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

## 58 **2. Rayleigh-like streaming**

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

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

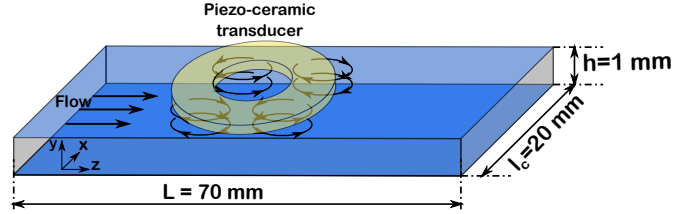


Figure 1: Sketch of Rayleigh-like streaming field in a fluid channel with a transducer placed thereon.

68 This flow pattern can be called Rayleigh-like streaming and has also been observed by Lei et al.  
 69 [22, 23]. The authors have conducted experimental and theoretical investigations. They concluded that  
 70 combinations of traveling waves in the direction of the main flow with standing modes in the  $x$  direction  
 71 lead to streaming vortices in the same plane as the transducer surface. They have given conditions for  
 72 the occurrence of different types of streaming patterns. When  $h/l_c \leq 1/20$ , they have concluded that  
 73 transducer-plane streaming occurs. This condition is met in our experiment ( $h=1$  mm and  $l_c = 20$  mm).

### 74 3. Experimental set-up and measurements

#### 75 3.1. Experimental procedure

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

82 A schematic of the experimental set-up is given in (Fig. 2a). The hot and cold inlets of the channel  
 83 are supplied with distilled water, the temperature of which is controlled by thermostatic baths set at 55  
 84 °C and 22 °C, respectively. The flow rate was controlled by a Syringe Pump that was calibrated for a low  
 85 Reynolds number flow range ( $Re \leq 23$ ). Four K-type thermocouples are placed at the inlet and outlet  
 86 of each fluid during the experiment. Temperatures were sampled every second until achieving steady

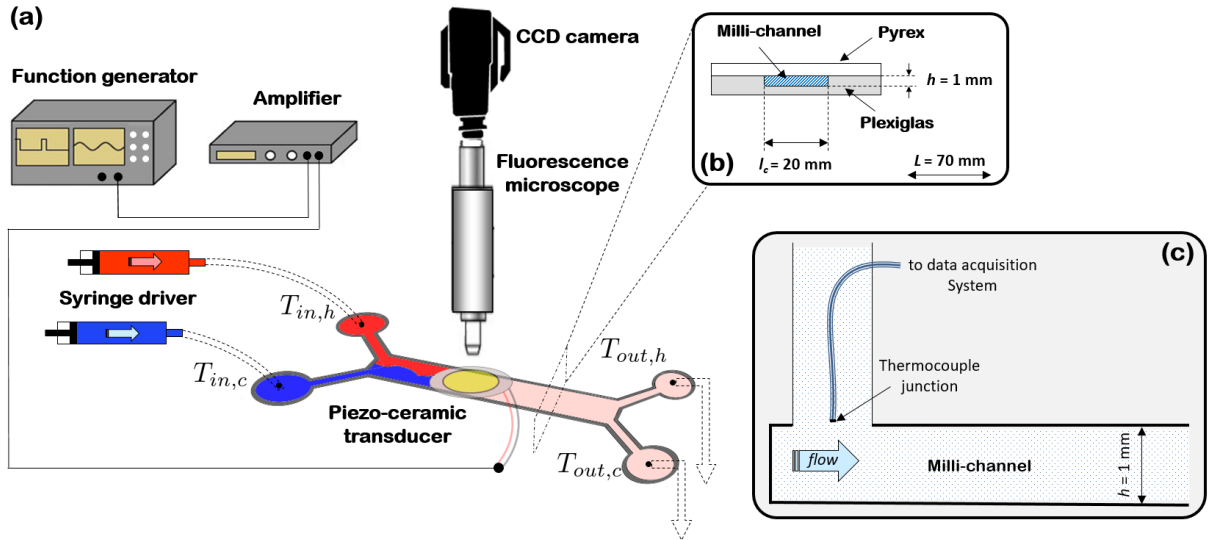


Figure 2: Experimental set-up and close-up of the test section.

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

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

### 99 3.2. Estimation of the ultrasonic power

100 A preliminary calorimetric test, based on the first law of thermodynamics, was carried out to estimate  
 101 the ultrasound power dissipated into fluids. For this purpose, we only injected the cold fluid and then,  
 102 we measured the temperature difference ( $\Delta T$ ) of the fluid between inlet and outlet at different mass  
 103 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:

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

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

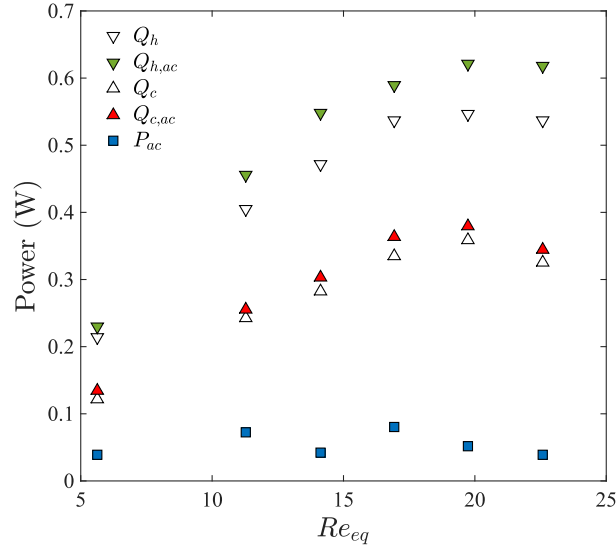


Figure 3: Dissipated ultrasound power ( $P_{ac}$ ), heat flow rate in the presence ( $Q_{c,ac}$ ,  $Q_{h,ac}$ ) and absence ( $Q_c$ ,  $Q_h$ ) of ultrasound as a function of equivalent Reynolds number  $Re_{eq}$

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

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

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

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

#### 115 4. Results and discussion

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

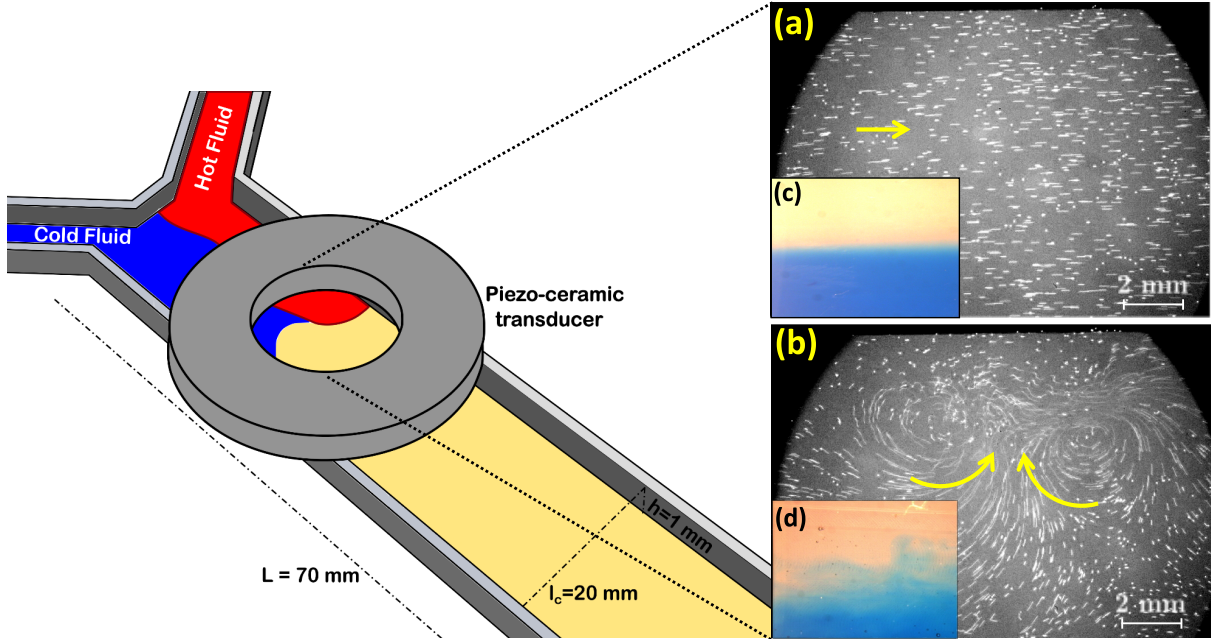


Figure 4: Flow pattern and mixing snapshots without (a, c) and with (b, d) Rayleigh-like streaming flow for  $Re \simeq 2$ . On the left side is presented the device allowing the visualization through the transducer aperture. On the right side are shown visualization results.

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

126 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  
 127 waves (Fig. 4b), we observe the appearance of counter-rotating vortices parallel to the transducer surface.  
 128 The observed structure contrasts with the classic Rayleigh-type patterns. The roll cells have a diameter  
 129 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  
 130  $l$  and  $ac$  are represent the local and acoustic states in our experiment. This flow ( $v_{l,ac} > 2v_l$ ), called  
 131 Rayleigh-like streaming, [can enhance the mass transport](#) between the two fluids by perturbing the bulk  
 132 flow and breaking the interface of the two laminar flows, thereby enabling faster and more homogeneous  
 133 mixing.

134 The second part of this study focuses on the energetic aspect in trying to thermally quantify the  
 135 mixing efficiency. The same fluid was used in the inlet channels but with two different temperatures.  
 136 Both cold and hot fluids flows were mixed in the millichannel. The outlet temperatures were measured  
 137 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  
 138 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  
 139 temperatures  $T_{out,h}$  and  $T_{out,c}$ , for a perfect mixing, the outlet common temperature of both fluids is  
 140 given by:

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

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

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

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

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

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

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

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

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

153 The equivalent Reynolds number becomes

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

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

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

155 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  
 156  $\Delta T$  (in absolute value) between inlet and outlet for each fluid.

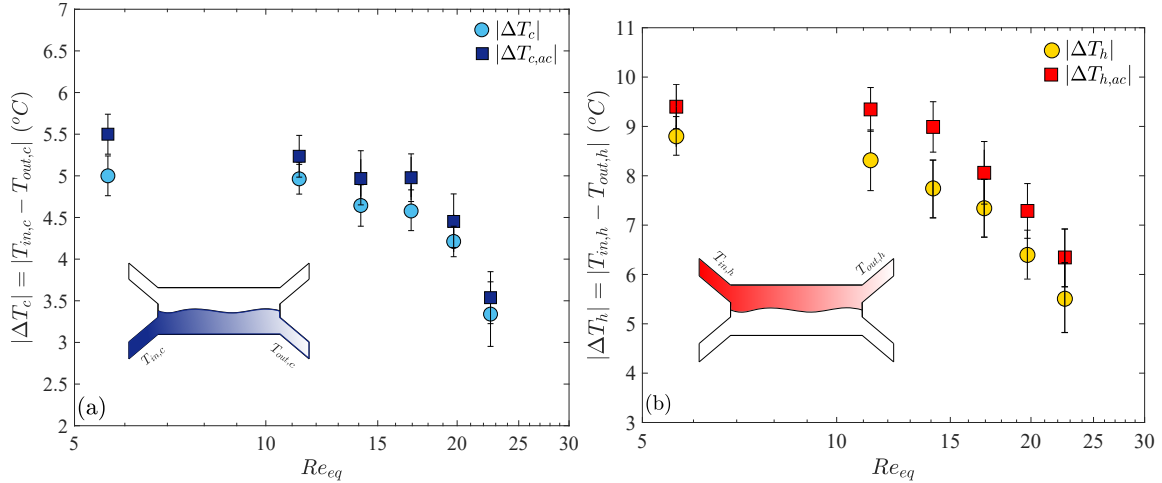


Figure 5: Temperature difference  $\Delta T$  with and without ultrasound as a function of the equivalent Reynolds number (a) Cold side  $\Delta T_c = T_{out,c} - T_{in,c}$  (b) Hot side  $\Delta T_h = T_{out,h} - T_{in,h}$ .

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

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

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

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

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

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

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

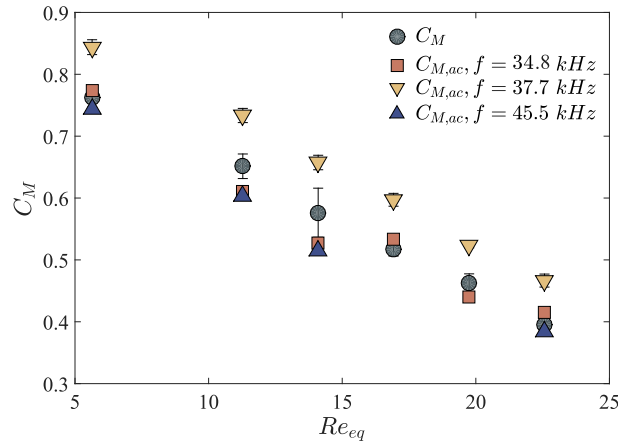


Figure 6: Thermal mixing criterion  $C_M$  vs  $Re_{eq}$ , without ultrasound and with three ultrasound frequencies.

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

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

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

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

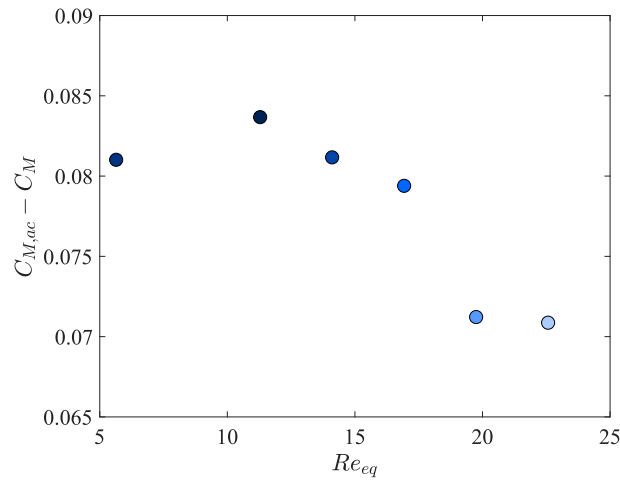


Figure 7: The mixing enhancement ( $C_{M,ac} - C_M$ ) vs  $Re_{eq}$ .

## 182 5. Conclusions and Outlook

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

192 To analyze the results we have defined a specific equivalent Reynolds number,  $Re_{eq}$ , and a new type of  
193 criterion to characterize the degree of mixing on outlet temperatures. This thermal mixing criterion ( $C_M$ )  
194 has been determined from the inlet and outlet temperatures as a function of the equivalent Reynolds  
195 number  $Re_{eq}$ . This criterion shows a significant increase when ultrasound is applied, indicative of an  
196 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

