



HAL
open science

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

S.A. Bahrani, R. Herbaut, L. Royon, K. Azzouz

► **To cite this version:**

S.A. Bahrani, R. Herbaut, L. Royon, K. Azzouz. Experimental investigation of thermal and flow mixing enhancement induced by Rayleigh-like streaming in a milli-mixer. *Thermal Science and Engineering Progress*, 2019, 14, 10.1016/j.tsep.2019.100434 . hal-03314801

HAL Id: hal-03314801

<https://hal.science/hal-03314801v1>

Submitted on 20 Jul 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

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

S. Amir Bahrani^{a,c}, Rémy Herbaut^a, Laurent Royon^b, Kamel Azzouz^d, André Bontemps^b

^a *Université Paris Diderot, Sorbonne Paris Cité, MSC, UMR 7057 CNRS, 75013, Paris, France.*

^b *Université Paris Diderot, Sorbonne Paris Cité, LIED, UMR 8236 CNRS, 75013, Paris, France.*

^c *IMT Lille Douai, Univ. Lille, Energy Engineering Department, F-59000 Lille, France.*

^d *Valeo Thermal Systems, 78321 La Verrière, France.*

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

Email addresses: amir.bahrani@imt-lille-douai.fr (S. Amir Bahrani)

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 (λ) 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.

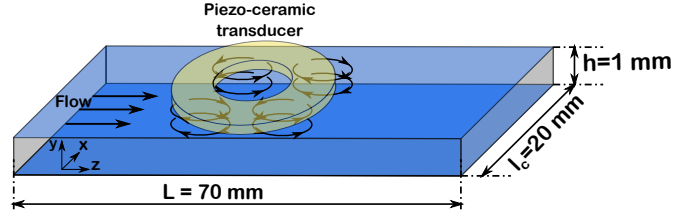


Figure 1: Sketch of Rayleigh-like streaming field in a fluid channel with a transducer placed thereon.

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

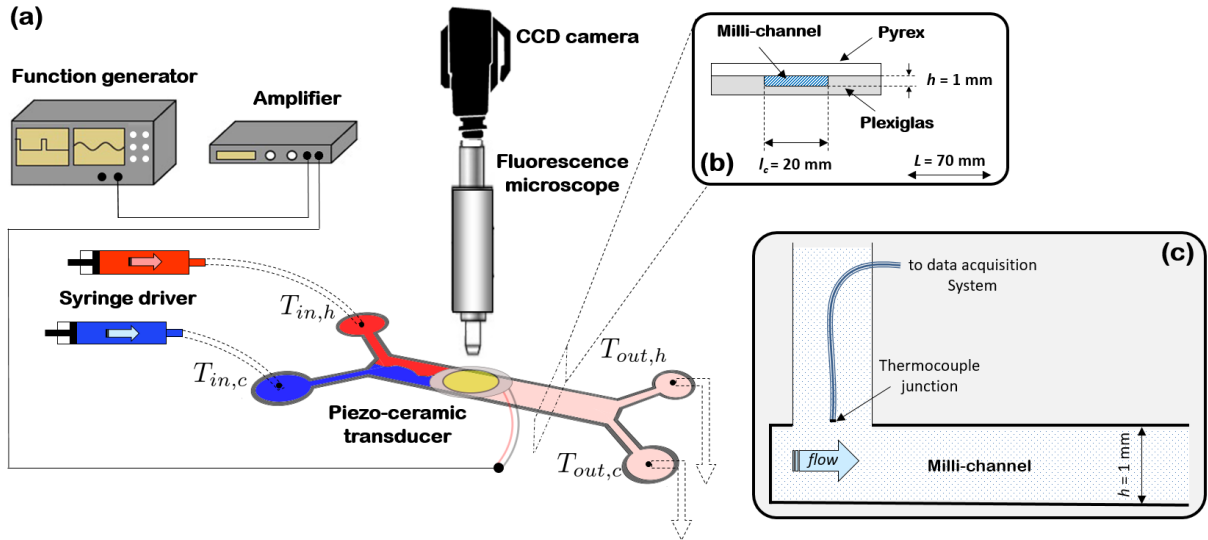


Figure 2: Experimental set-up and close-up of the test section.

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 μm 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 (ΔT) 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:

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

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

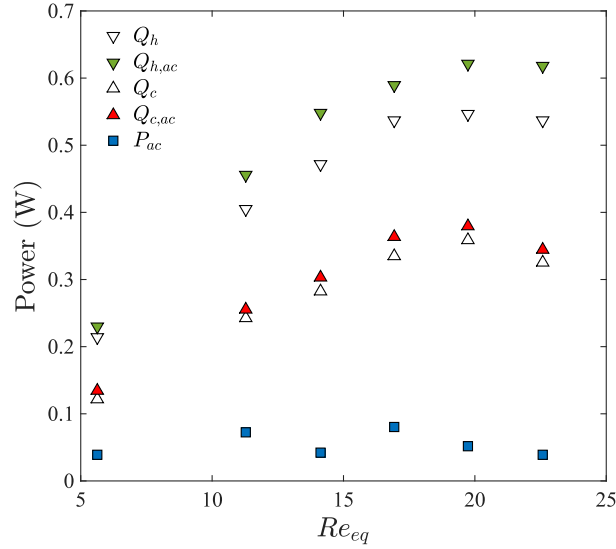


Figure 3: Dissipated ultrasound power (P_{ac}), heat flow rate in the presence ($Q_{c,ac}$, $Q_{h,ac}$) and absence (Q_c , Q_h) of ultrasound as a function of equivalent Reynolds number Re_{eq}

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.

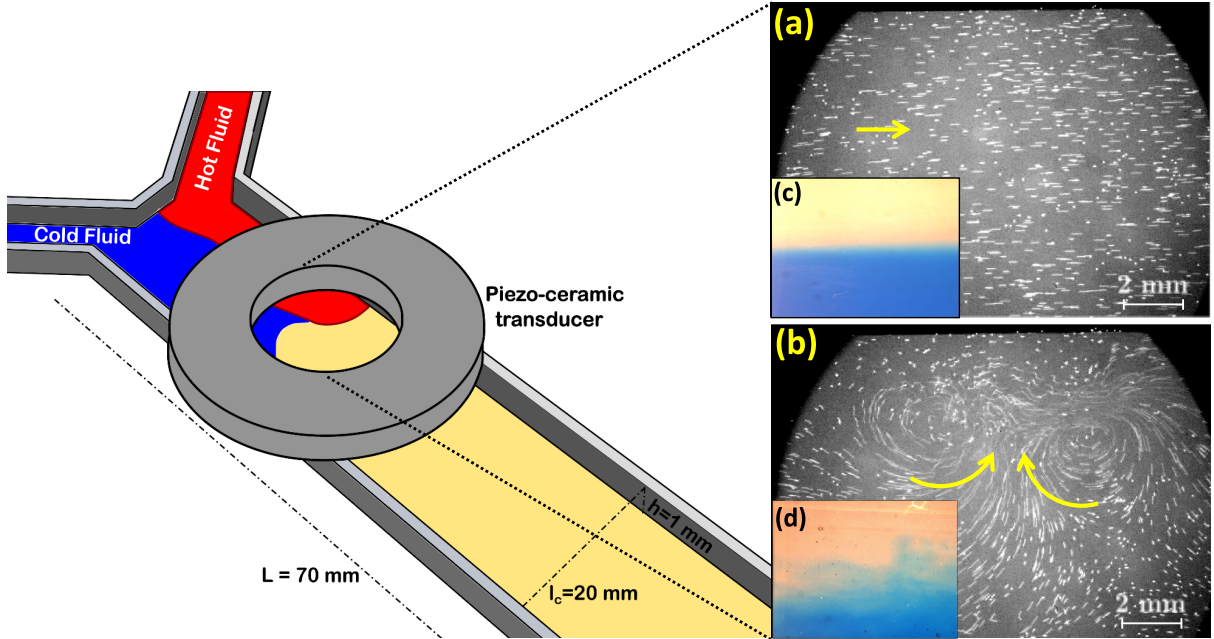


Figure 4: Flow pattern and mixing snapshots without (a, c) and with (b, d) Rayleigh-like streaming flow for $Re \simeq 2$. On the left side is presented the device allowing the visualization through the transducer aperture. On the right side are shown visualization results.

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, μ 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 ΔT (in absolute value) between inlet and outlet for each fluid.

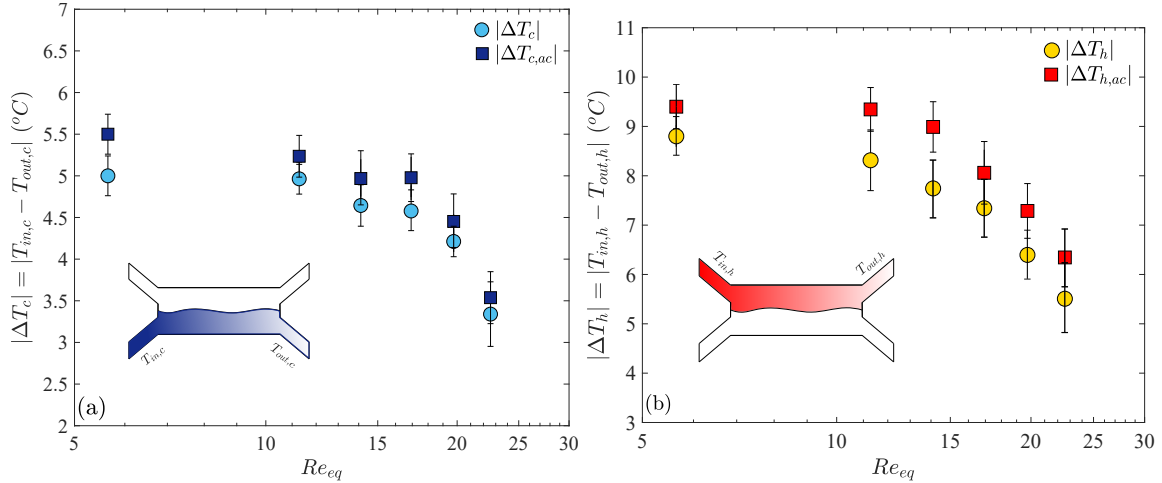


Figure 5: Temperature difference ΔT with and without ultrasound as a function of the equivalent Reynolds number (a) Cold side $\Delta T_c = T_{out,c} - T_{in,c}$ (b) Hot side $\Delta T_h = T_{out,h} - T_{in,h}$.

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 ΔT 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.

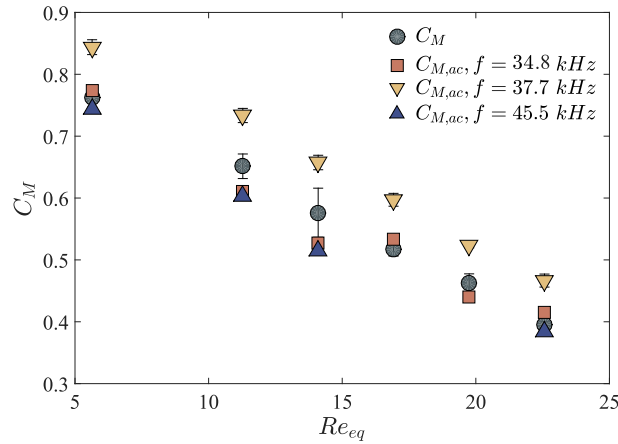


Figure 6: Thermal mixing criterion C_M vs Re_{eq} , without ultrasound and with three ultrasound frequencies.

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.

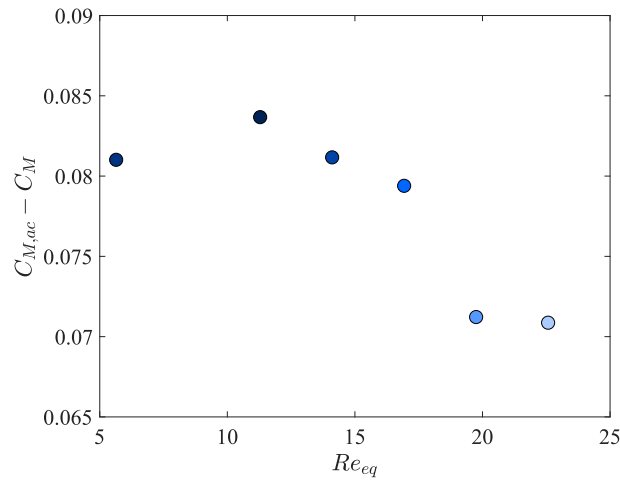


Figure 7: The mixing enhancement ($C_{M,ac} - C_M$) vs Re_{eq} .

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.

197 **Acknowledgements**

198 The authors are grateful to Dr. Martin Hendel for fruitful discussions.

199 **References**

- 200 [1] T. M. Squires and S. R. Quake, Microfluidics: Fluid physics at the nanoliter scale, *Rev. Mod. Phys.*,
201 **77** (2005) 977–1026.
- 202 [2] N.-T. Nguyen, *Micromixers. Fundamentals, Design and Fabrication*, Elsevier Science, 2012.
- 203 [3] S. A. Bahrani, L. Humberset, R. Osipiana, L. Royon, K. Azzouz and A. Bontemps, How thermally
204 efficient are chaotic advection mixers? An experimental assessment, *Int. J Therm. Sci.*, **145** (2019)
205 106046.
- 206 [4] V. Hessel, H. Lowe and F. Schonfeld, Micromixers—a review on passive and active mixing principles,
207 *Chem. Eng. Sci.*, **60** (2005) 2479–2501.
- 208 [5] N.-T. Nguyen, Z. Wu, Micromixers—A review, *J. Micromech. Microeng.*, **15** (2005) R1–R16.
- 209 [6] Y. K. Suh, S. Kang, A review on mixing in Microfluidics, *Micromachines*, **1** (2010) 82–111.
- 210 [7] B. Xu, T. N. Wong, N.-T. Nguyen, Z. Z. Che and J. C. K. Chai, Thermal mixing of two miscible
211 fluids in a T-shaped microchannel, *Biomicrofluidics* **4** (2010) 044102.
- 212 [8] T. Glawdel, Z. Almutairi, S. Wang, and C. Ren, Photobleaching absorbed Rhodamine B to improve
213 temperature measurements in PDMS microchannels, *Lab Chip* **9** (2009) 171–174.
- 214 [9] D. Ahmed, X. Mao, J. Shi, B. K. Juluri and T. J. Huang, A millisecond micromixer via single-bubble-
215 based acoustic streaming, *Lab Chip* **9** (2009) 2738–2741.
- 216 [10] P. H. Huang, Y. L. Xie, D. Ahmed, J. Rufo, N. Nama, Y. C. Chen, C. Y. Chan and T. J. Huang, An
217 acoustofluidic micromixer based on oscillating sidewall sharp-edges *Lab Chip* **13** (2013) 3847–3852.
- 218 [11] M. Bengtsson, T. Laurell, Ultrasonic agitation in microchannels, *Anal. Bioanal. Chem.* **378** (2004)
219 1716–1721.

- 220 [12] K. Sugano, Y. Uchida, O. Ichihashi, H. Yamada, T. Tsuchiya and O. Tabata, Mixing speed-
221 controlled gold nanoparticle synthesis with pulsed mixing microfluidic system, *Microfluid. Nanofluid.*
222 **9** (2010) 1165–1174.
- 223 [13] V. Manickam, I. B. Celik, J. Mason, and Y. Liu, Assessment of the Degree of Mixing in Microchannel
224 Two-Fluid Flows, ASME 2012 10th International Conference on Nanochannels, Microchannels, and
225 minichannels Volume 1: Symposia, Parts A and B, Rio Grande, Puerto Rico, (2012).
- 226 [14] C. Suri, K. Takenaka, H. Yanagida, Y. Kojima, K. Koyama, Chaotic mixing generated by acoustic
227 streaming, *Ultrasonics***40** (2002) 393–396.
- 228 [15] B-G. Loh, S. Hyun, P.I. Ro, C. Kleinstreuer, Acoustic streaming induced by ultrasonic flexural
229 vibrations and associated enhancement of convective heat transfer, *J. Acoust. Soc. Am.* **111** (2002)
230 875–883.
- 231 [16] B. Tajik, A. Abbassi, M. Saffar-Avval, A. Abdullah, H. Mohammad-Abadi, Heat transfer enhance-
232 ment by acoustic streaming in a closed cylindrical enclosure filled with water, *Int. J. Heat Mass*
233 *Transf.* **60** (2013) 230–235.
- 234 [17] J. T. Karlsen and H. Bruus, Acoustic Tweezing and Patterning of Concentration Fields in Microflu-
235 idics, *Phys. Rev. Applied* **7** (2017) 034017.
- 236 [18] C. Devendran, I. Gralinski, A. Neild, Separation of particles using acoustic streaming and radiation
237 forces in an open microfluidic channel, *Microfluid. Nanofluid.* **17** (2014) 879–890.
- 238 [19] L. Schmid, A. Wixforth, D. A. Weitz, T. Franke, Novel surface acoustic wave (SAW)-driven closed
239 PDMS flow chamber, *Microfluid Nanofluid* **12** (2012) 229–235.
- 240 [20] Lord Rayleigh, On the circulation of air observed in Kundt’s tubes, and on some allied acoustical
241 problems, *Philos. Trans. R. Soc. London* **175** (1884) 1–21.
- 242 [21] C. Eckart, Vortices and streams created by sound waves, *Phys. Rev.* **73** (1948) 68–76.
- 243 [22] J. Lei, M. Hill and P. Glynne-Jones, Transducer-Plane Streaming Patterns in Thin-Layer Acoustoflu-
244 idic Devices, *Phys. Rev. Applied* **8** (2017) 014018.

- 245 [23] J. Lei, P. Glynne-Jones, and M. Hill, Modal Rayleigh-like streaming in layered acoustofluidic devices,
246 *Phys. Fluids*, **28** (2016) 012004.
- 247 [24] P. Xiong, X. Chen, Y. Xiong, G.Liu, Y. Tian, Microstructure enhanced liquid-liquid extraction in
248 a real-time fluorescence detection microfluidic chip, *Micromachines*, **7** (2016) 46.

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

