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1 ***Heat transfer intensification by low or high frequency ultrasound:***  
2 ***thermal and hydrodynamic phenomenological analysis***

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10 **Abstract**

11 The aim of this work is to quantitatively demonstrate the intensification of heat transfer in  
12 forced convection by mean of ultrasonic irradiation at low (25 kHz) or high (2 MHz)  
13 frequency. High frequency ultrasound induces convective acoustic streaming while low  
14 frequency ultrasonic waves produce mainly cavitation effects. These hydrodynamic  
15 phenomena are at the origin of strongly different observations in terms of flow pattern  
16 modification and thereby in Nusselt number values. A link is tentatively established between  
17 hydrodynamic behaviors at both ultrasonic frequencies and corresponding thermal results.  
18 Hydrodynamic approach was performed with a 2D-2C PIV device while thermal one was  
19 carried out under uniform heat flux conditions. It seems that thermal enhancement effect of  
20 acoustic streaming (2 MHz) decreases as flow rate increases. This behavior is consistent with  
21 the decrease of turbulent kinetic energy produced by acoustic streaming in the same

22 conditions. In the contrary, thermal enhancement effect produced by acoustic cavitation (25  
23 kHz), increases as flow rate increases. This result could be due to the increase of relative size  
24 of acoustic bubbles with respect to laminar boundary layer thickness as flow rate increases. In  
25 conclusion, the two different ultrasound frequencies, which lead to two different  
26 hydrodynamic effects, also lead to two different thermal and turbulence trend with respect to  
27 flow rate modifications.

## 28 **Keywords**

29 Heat transfer enhancement; ultrasound; forced convection, turbulence

## 30 **Highlights:**

31 Hydrodynamic effects of low and high frequency ultrasound within a flow are studied

32 Thermal enhancement effect produced by both low and high frequency ultrasound is studied

33 A link is established between thermal and hydrodynamic behaviours with respect to frequency

34 A phenomenological explanation is proposed for the different behaviors observed

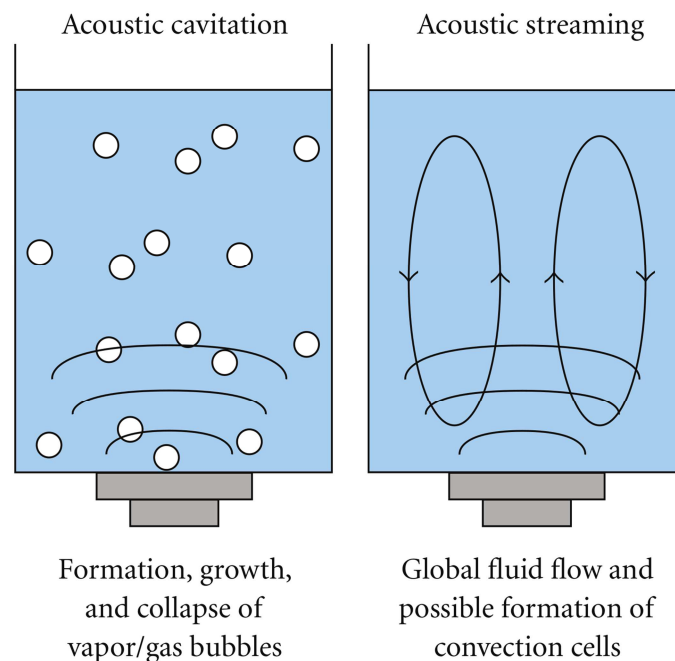
## 35 **1. Introduction**

36 This study compares heat transfer enhancement induced by low and high  
37 frequency ultrasound. A link is proposed between the observed intensification to the  
38 hydrodynamic behavior produced by ultrasound in flowing fluid. Low and high frequency  
39 ultrasound are at the origin of hydrodynamic phenomena of different nature. In addition, it is  
40 investigated to what extent heat transfer intensification by ultrasound can be linked to the  
41 nature of this induced effect. It is therefore expected to give recommendations on the choice

42 of ultrasonic frequency in the design of future vibrating heat exchangers depending on  
43 parameters such as flow regime, Reynolds number and erosion issues.

#### 44 1.1 State of the art

45 Ultrasound is a mechanical wave with frequencies above 18 – 20 kHz. Acoustic cavitation  
46 and acoustic streaming are two hydrodynamic effects induced by the ultrasonic irradiation of  
47 a liquid [1]. Their intrinsic characteristics are strongly dependent on the frequency of the  
48 irradiative waves. A schematic description of these both effects is shown in figure 1.



49

50 Fig. 1: Illustration of ultrasonic cavitation and acoustic streaming effects as presented in [19]

51 Acoustic cavitation can be defined as a growing, oscillating and collapsing phenomenon of  
52 gas and vapor cavities induced by ultrasound propagation within a liquid. Potential uses of  
53 acoustic cavitation for industrial process intensification are wide [1] (heat exchangers,  
54 chemical reactors, antifouling/defrosting system...). Nevertheless, strong technological  
55 development is still required in terms of reactors design and optimization [2]. Acoustic

56 cavitation is able to disturb strongly fluid environment from a hydrodynamic point of view [3]  
57 thanks to three different mechanisms:

58 - At first, micro-streaming, induced by the oscillation of the cavitation bubble wall,  
59 produces fluid recirculation around it on a distance scale known as acoustic  
60 boundary layer. The thickness of this layer relies on both the kinematic viscosity  
61 of the medium and the pulsation of the acoustic wave [4]. As an example, in water  
62 at 20 °C, acoustic boundary layer ranges from 8 microns with 2 MHz ultrasound to  
63 90 microns with 20 kHz ultrasound [5].

64 - The second hydrodynamic phenomenon is the acoustic bubbles displacement.  
65 Indeed, these latter can be displaced across the fluid by radiation strength because  
66 of the absorption and scattering of incident acoustic waves. This is true for both  
67 progressive and stationary waves fields. In the second case, the time averaged  
68 radiation pressure is equal to zero only at nodes or anti-nodes, driving then bubbles  
69 to stable locations [5]. For strong acoustic intensity, void ratio of the liquid  
70 increases because of the growing number of bubbles producing an impedance wall  
71 which attenuates the acoustic intensity and then the acoustic driven bubbles  
72 phenomenon [5-6].

73 - The third phenomenon is linked to the collapse of the acoustic bubbles which  
74 produces strong shock waves within the fluid leading to liquid micro-jets when  
75 occurring near a solid wall [5]. In this latter case, collapse leads generally to  
76 surface erosion issues, advantageously used in cleaning processes [7-8].  
77 Nevertheless, the erosion phenomenon is an issue to be solved in order to avoid  
78 material damage.

79 For all these reasons, it has been widely shown that acoustic cavitation is able to trigger or to  
80 increase turbulence rate within a liquid flow under laminar or transitional hydrodynamic  
81 conditions [9-11].

82 Acoustic streaming is a generic term defining a liquid or a gas flow driven by acoustic waves.  
83 There are two kinds of acoustic streaming depending on conditions at which it is enabled.  
84 Thanks to a null net mass flow characteristic, acoustic streaming is able to produce  
85 recirculating flows with strong global mixing properties.

86 - The first one is named Eckart's streaming [12] and appears because of the spatial  
87 attenuation of acoustic wave intensity due to liquid absorption, diffraction of the  
88 wave leading to energy spreading, or because of the acoustic beam enlargement. In  
89 anyway, all these phenomena lead to energy attenuation in the direction of the  
90 acoustic wave propagation inducing pressure gradient and then fluid movement.  
91 Eckart's streaming usually occurs under propagative wave conditions.

92 - The second type of acoustic streaming occurs under stationary wave conditions  
93 [13]. In this case, the streaming is governed by the dissipation phenomenon  
94 occurring within the acoustic boundary layer, i.e. near the oscillating wall of the  
95 transducer or near a solid wall exposed to an acoustic wave. Such as for oscillating  
96 acoustic bubbles, this leads to recirculating flows within the acoustic boundary  
97 layer giving rise to others recirculation modes into the bulk by propagating the  
98 movement from one cell to the next one. Near the walls, mixing effects combined  
99 with strong shearing strength, are able to lyse cells walls [14].

100 Both types of streaming are able to induce turbulent flows [15-16]. Mixing properties of  
101 ultrasound were evidenced within sonochemical reactors by Residence Time Distribution  
102 (RTD) measurements [17-18]. According to the literature, acoustic streaming observed at

103 500 kHz ultrasound results in strong stirring effects leading to RTD results classically  
104 observed with mechanically full-stirred reactors [17].

105 The main effect limiting the convective heat transfer is the presence of a laminar boundary  
106 layer (also called viscous sub-layer) near the wall. This is usually defined as a flow region  
107 where the thermal diffusion is predominant, contrary to thermal convective effects that prevail  
108 in the bulk. A decrease of its thickness allows to reduce the thermal resistance of this interface  
109 and thereby to increase heat transfer rate. **Stirring**, mixing and turbulence properties of both  
110 acoustic cavitation and acoustic streaming **render consequently** ultrasound **as** an attractive and  
111 active method to enhance heat transfer. By this way, heat transfer intensification could also  
112 help to achieve two main objectives:

- 113 - thermal transfer increase between two fluids separated by a solid interface with  
114 fixed parameters (case of heat exchangers)
- 115 - **temperature difference decrease** keeping the same heat flux when sensitive fluids  
116 are processed **(case of liquid food pasteurization)**

117 Studies on heat transfer enhancement by ultrasound began in the middle of the 20<sup>th</sup> century. It  
118 can be noticed that most of these studies **are** focused on phase change, like boiling [20-21], or  
119 on natural convection [22]. Some studies dealt also with heat transfer in forced convection or  
120 in the field of heat exchangers but in a less extend. Most of the recent studies have for main  
121 purpose fouling reduction [23]. **However, some works since 2000 are devoted to heat transfer**  
122 **enhancement in forced convection by using ultrasound:**

- 123 - **Most of them use low frequency ultrasound (20 kHz to 100 kHz [19, 24-25]).**  
124 **Intensification of heat transfer up to 270 % has been reported using a 35 kHz**  
125 **vibrating shell and tube heat exchanger [26].**

126 - High frequency effect of ultrasound on heat transfer has also been highlighted  
127 through recent works showing how acoustically induced streaming can enhance  
128 convective heat transfer coefficients [27].

129 - Studies on cooling process have also been successfully performed [28-30] leading  
130 to a 27% heat transfer enhancement.

131 One might here consider that a positive effect on heat transfer has always been reported in all  
132 studies involving ultrasound. A comprehensive overview can be found in two publications  
133 [24, 31]. However, it appears that most of the studies deal with heat transfer enhancement by  
134 using ultrasound in a very general way. Only a few of them have been carried out in a  
135 phenomenological way especially with the impact of ultrasound on the boundary layer or on  
136 the turbulence rate within the liquid flow [3,7,9,27,32].

137 According to the literature, it is reasonable to identify four main parameters that clearly  
138 influence heat transfer enhancement by ultrasound. Whereas two of them do concern  
139 geometry configuration and fluid properties, the two others relate to ultrasonic wave  
140 characteristics:

141 - Geometry of the system: the distance between the exchange surface and the  
142 ultrasonic transducer is an important parameter to be taken into account as it acts  
143 directly on acoustic intensity especially in the presence of cavitation [33-34].  
144 Moreover, the angle of radiation has a significant impact on thermal results for  
145 natural convection in the presence of acoustic cavitation [35].

146 - Fluid used may have different physicochemical properties affecting ultrasonic  
147 effects previously described. For example, bubble behavior is driven by saturation  
148 pressure and surface tension [5]. Viscous fluids are less sensitive to cavitation [5].  
149 On the other hand, increasing the fluid viscosity (bulk and dynamic) leads to an

150 increase of the acoustic absorption coefficient. As an example, this coefficient is of  
151 prime importance into acoustic forces induced by a plane acoustic wave  
152 responsible for acoustic streaming phenomenon [36].

153 - Ultrasound frequency appears to be a very important parameter that determines the  
154 nature of induced-hydrodynamic phenomena and thereby the heat transfer  
155 intensification trend [10]. Indeed, hydrodynamics phenomena produced by  
156 ultrasound (cavitation or streaming) are different with respect to frequency leading  
157 to different thermal behaviors.

158 - Ultrasonic power: thermal transfer enhancement caused by ultrasound seems to be  
159 interrelated with delivered ultrasonic powers [19]. As an example, Nusselt number  
160 is directly linked to the supplied ultrasonic power in the case of heat transfer  
161 intensification due to the presence of acoustic streaming at high frequency [27].

162 As aforesaid, very few articles deal with enhancement of heat transfer in forced convection  
163 using ultrasound. Main experimental set-ups use shell and tube heat exchanger geometry and  
164 low ultrasound frequency (20 kHz to 100 kHz). Furthermore, most of them were limited to  
165 cavitation effect on heat transfer intensification and reported the influence of liquid flow rate  
166 on enhancement values [24, 30, 37].

167 Modeling of thermo-hydraulic effects generated by ultrasound is of prime importance for the  
168 integration of this technology to optimize many industrial processes using heat exchangers.  
169 Some mathematical [38] and numerical [39-41] models dealing with hydrodynamic effects of  
170 ultrasound have been released. These models have been designed for low [39-41] and high  
171 [38] frequency range and specific conditions of use of ultrasound. It is therefore necessary to  
172 investigate, identify and qualify parameters involved on thermo-hydraulic effects induced by  
173 ultrasound in a larger way in order to feed these models. Over all, it is still

174 phenomenologically unclear how ultrasonically induced phenomena (cavitation and  
175 streaming) can modify a flow.

## 176 **1.2 Objectives**

177 The objectives of this work are thus to carry out both hydrodynamic and thermal approaches  
178 in the presence of intense acoustic cavitation (25 kHz) or strong acoustic streaming (2 MHz)  
179 in order to propose a relevant phenomenological explanation of the frequency effect.  
180 Motivation for using high frequency ultrasound comes from strong erosion issues that could  
181 occur in heat exchangers by using low frequency ultrasound even if antifouling action at this  
182 frequency has been proved [42]. In the aim of designing future optimized vibrating heat  
183 exchangers, it is highly desired to compare thermal performances in relation with phenomena  
184 implied at low and high frequency ultrasound. Benefits and drawbacks for both frequencies  
185 with respect to specific requirements and operating conditions of these future heat exchangers  
186 will then be analyzed.

## 187 **2. Experimental apparatus and data reduction**

### 188 **2.1 General presentation of the test section**

189 An experimental setup was designed and built (Fig. 2) in order to investigate heat transfer  
190 intensification in forced convection by ultrasound. An overall description of the bench test  
191 used for this study has been detailed in a previous article in which preliminary results of heat  
192 transfer enhancement using 2 MHz ultrasound were exposed [27].

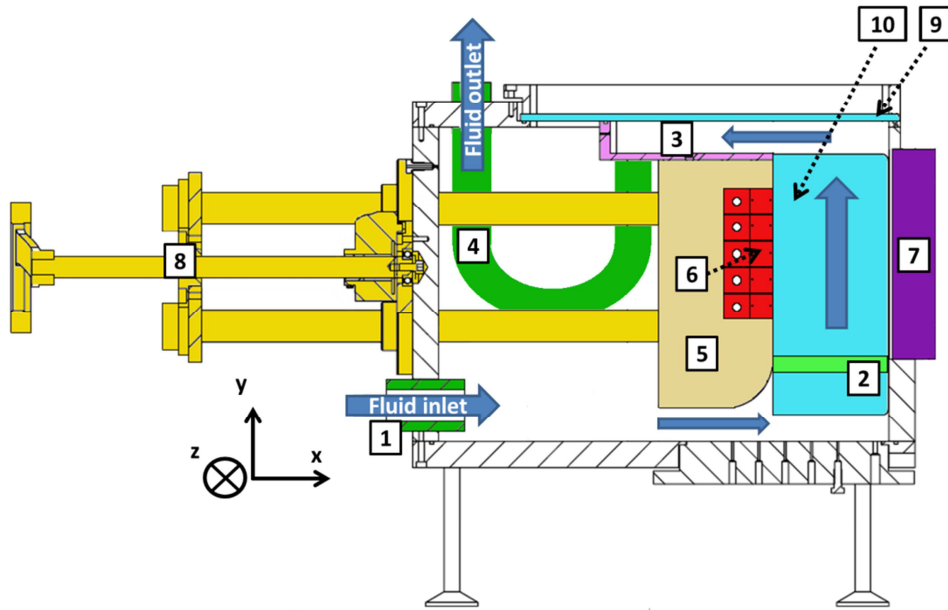


Fig. 2: Side view of the test section ALTO used for this study.

193 The fluid enters into the test section in **1** and follows blue arrows on Fig. 2. It passes then  
 194 through a porous media **2** in order to ensure a flat velocity profile. The fluid flows throughout  
 195 a rectangular canal and is then collected at the top of this canal in **3**. It exits the test section by  
 196 a pipe in **4**. The canal is made of a block composed of an insulating material that encompass  
 197 five heating plate blocks (respectively **5** and **6**) and by the ultrasonic transducer (**7**). The  
 198 heating plate (**6**) is made of five stacked heating elements, thermally insulated from each other  
 199 and individually power supplied [27]. Each element is equipped with temperature sensors in  
 200 order to determine local convective heat transfer coefficients. The thickness of the canal (x-  
 201 axis) can be changed by using the device **8**. In this present study, the canal size is  
 202 30 \* 100 mm (x-z plan) and the total heat plate (**6**) length is 100 mm (y axis). Finally, two  
 203 perpendicular visualization windows (**9** and **10**) allow measuring velocity and turbulent fields  
 204 in the x-y plan thanks to a 2D-2C Particle Image Velocimetry (PIV) method.  
 205 Local heat transfer coefficients in front of each heating element can be determined following  
 206 the procedure described in [27]. It is thereby possible to calculate Nusselt number as follows:  
 207

$$Nu = \frac{h_i d_h}{\lambda} \quad (1)$$

208 with  $h_i$  [W/m<sup>2</sup>/K] the local convective heat transfer coefficient in front of the  $i^{\text{th}}$  heating  
209 element,  $d_h$  [m] the hydraulic diameter and  $\lambda$  [W/m/K] the thermal conductivity of the fluid.  
210 Heat Transfer Enhancement Factor (**HTEF**) can then be defined as:

$$HTEF = \frac{Nu_{us} - Nu_{silent}}{Nu_{silent}} \quad (2)$$

212  
213 where  $Nu_{us}$  and  $Nu_{silent}$  [-] are the Nusselt numbers with and without ultrasound  
214 respectively.

## 215 2.2 Characterization of ultrasound transducers

216 In this work, two different ultrasonic frequencies were used. in order to compare specific  
217 effects of acoustic streaming and of acoustic cavitation on convective heat transfer in forced  
218 convection. To ensure comparison, **the** ultrasonic power delivered to the liquid flowing  
219 throughout the canal was estimated by means of a classical calorimetric method **and** kept  
220 identical for both transducers. The 25 kHz transducer was specifically designed by Sinaptec  
221 with an active surface size identical to that of **the** 2 MHz Sonosys transducer. **Both**  
222 **transducers were purposely characterized in order to evaluate the presence or not of acoustic**  
223 **cavitation and of acoustic streaming using 25 kHz or 2 MHz. It was confirmed that 2 MHz**  
224 **ultrasound irradiation mainly results in strong acoustic streaming. Acoustic cavitation was not**  
225 **revealed by chemical (iodide oxidation) and aluminum foil tests for this frequency (2 MHz).**  
226 **On the other hand, none significant chemical activity was observed using iodide oxidation test**  
227 **at 25 kHz. Nevertheless, strong mechanical effects due to intense cavitation were clearly**  
228 **illustrated by the aluminum foil erosion test [35] as it can be observed in Fig. 3.**

229 According to these results, it was assumed that the low-frequency transducer (25 kHz) only  
230 produces acoustic cavitation with strong mechanical effects whereas the high frequency one  
231 (2 MHz) only induces acoustic streaming. The great difference in the nature of the  
232 ultrasonically-induced effects depends exclusively on frequency. Therefore, a clear  
233 comparison of the action of cavitation and acoustic streaming on heat transfer is possible. In  
234 this study identical transducers in terms of geometric parameters and ultrasonic power are  
235 used.

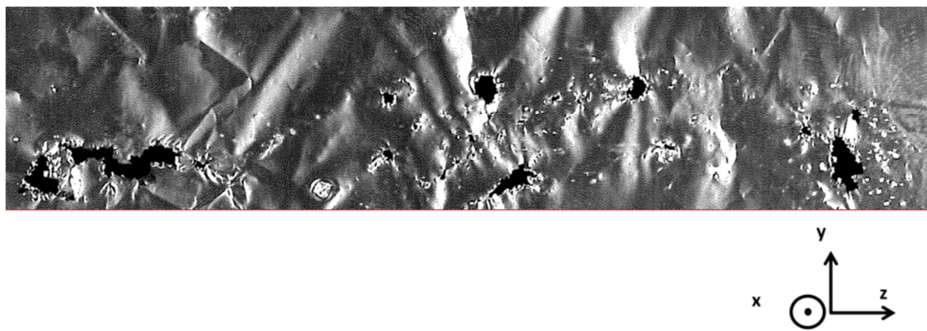


Fig. 3: Erosion pit clustering (black part) of the aluminum foil covering the entire 5<sup>th</sup> heating element facing the 25 kHz transducer. Total ultrasonic power = 110 W, distance from the transducer = 30 mm, exposure time = 60 seconds.

### 236 2.3 Particle Image Velocimetry (PIV) set-up

237 Hydrodynamic modifications in the flow induced by ultrasound were investigated by PIV  
238 technique using the set-up described in [27]. The laser is a Nd-Yag (Litron provided by  
239 Dantec Dynamics) with two cavities generating 200 mJ of maximum energy for 6-9 ns pulse  
240 time. The camera is an ImagerProX2 M (provided by LaVision) with a 1600 \* 1200 pixels  
241 spatial resolution. Each of the pixels of the camera measures  $7.4 * 7.4 \mu\text{m}^2$ . Average fields are  
242 obtained from 2000 instantaneous fields.

243 The measurement field size is equal to the size of the canal in front of the  $i^{\text{th}}$  heating block  
244 (30 mm thick by 20 mm high on x-y plan). The camera lens is a Nikon 150 mm, leading to

245 PIV field pixels equals to  $16.5 * 16.5 \mu\text{m}^2$ . Interrogation windows are  $16 * 16$  pixels leading  
246 to a square of  $0.264 * 0.264 \text{ mm}^2$ . Consequently, PIV measurement provides measurement  
247 fields of the entire canal thickness (x-axis) on the entire  $i^{\text{th}}$  heating block height (y-axis).  
248 These PIV measurements allow us to link thermal phenomenon to hydrodynamic ones that  
249 take place in front of this  $i^{\text{th}}$  heating block.

250 PIV device gives instantaneous velocity fields from which it is possible to calculate average  
251 velocity fields from 2000 instantaneous velocity fields. RMS velocity [m/s] fields and  
252 turbulent kinetic energy (TKE) [ $\text{m}^2/\text{s}^2$ ] on the two dimensions x-y plan for the 2000  
253 instantaneous velocity fields can then be calculated thanks to the following equation:

$$TKE = \frac{3}{4} V_{RMS}^2 \quad (3)$$

254 with  $V_{RMS}$  [m/s] the root mean square velocity as calculated by the following equation:

$$V_{RMS} = \sqrt{\frac{\sum_{i=1}^N (V_i - \bar{V})^2}{(N - 1)}} \quad (4)$$

255  
256 where  $V_i$  [m/s] is the value of the modulus of the instantaneous velocity of the  $i^{\text{th}}$  image on a  
257 total of 2000 images and  $\bar{V}$  [m/s] is the modulus of the average velocity. It is assumed that the  
258 velocity component  $V_z$ , which is not measured because of the x-y plan orientation of the laser  
259 sheet, contains a similar contribution as the one contained within the values of  $V_x$  and  $V_y$  [43].  
260 This assumption implies isotropy of the turbulence even if it is questionable near the heating  
261 plate. Nevertheless, the correction of  $^{3/4}$  instead of  $^{1/2}$ , classically used for turbulence  
262 calculated from planar velocity fields, does not change the observed phenomenology. It only  
263 affects the absolute values. Since this study is mainly phenomenological and aims at

264 **comparing** the effects at two different ultrasonic frequencies, the bias will therefore be  
265 identical for all measurements **without being** detrimental to the analysis.

## 266 **2.4 Operating parameters and experimental protocol**

267 Operating hydrodynamic parameters used in this study are displayed in Tab.1. Flowrates  
268 range from 215 up to 1315 L/h with respect to technical abilities of the test bench resulting in  
269 Reynolds numbers from 900 (laminar) to 5500 (transitional/turbulent). Properties of the water  
270 are those at the inlet temperature (20°C).

Flowrate [L/h]	215	358	600	835	1074	1315
Reynolds number	900	1500	2500	3500	4500	5500
Flow Velocity [m/s]	0.020	0.033	0.056	0.077	0.099	0.122

Tab. 1 : Operating parameters

271 Canal thickness (x-axis) was kept constant at 30 mm in this study whereas canal width (z-  
272 axis) and canal height (y-axis) were both set at 100 mm. Thermal measurements reported in  
273 this paper were done in front of the fifth heating block, i.e. the upper block of the heating  
274 plate, which is 20 mm height (see Fig. 1). This choice was made because of the fully  
275 developed hydrodynamic and thermal conditions in front of the fifth block as previously  
276 shown [27]. The hydraulic diameter is equal to 0.046 m for this series of measurements. To  
277 ensure a fair comparison, the ultrasonic power was kept constant to 110 W for both 25 kHz  
278 and 2 MHz with the assumption of uniform distribution of 22 W per heating element.  
279 Moreover, the total heating power being equal to 450 W, each heating element is assumed to  
280 deliver uniformly 90 W.

## 281 **3. Results and discussions**

### 282 3.1 Thermal results for 25 kHz and 2 MHz sonication

283 Thermal results obtained in silent conditions and for both ultrasound configurations (25 kHz  
284 and 2 MHz) are plotted on Fig. 4. Nusselt numbers are given with respect to **the** fluid flow  
285 velocity and **corresponding** Reynolds number (constant canal thickness). Experimental results  
286 clearly demonstrate the thermal enhancement induced by ultrasound when Nusselt numbers  
287 are compared to those of silent regime, whatever the incident irradiative frequency. On silent  
288 mode, the evolution of the Nusselt number is consistent with the fact **that the** heat transfer  
289 coefficient increases when **the** liquid flow rate increases and thereby corresponding flow  
290 velocity. These results confirm classical results in forced convection for silent regime, i.e.  
291 Nusselt increases as Reynolds increases. This can be **fully** explained by the decrease of the  
292 laminar boundary layer thickness near the heating wall leading thereby to the decrease of the  
293 corresponding thermal resistance [44]. However, it is important to note that the  
294 laminar/turbulent transition classically observed for Reynolds numbers between 2000 and  
295 3000 in internal forced convection is not experimentally observed here. This can be explained  
296 by the presence of a 90° turn at the fluid inlet. **This unusual configuration seems to generate**  
297 **hydrodynamic disturbances, causing a gradual enhancement of heat transfer for Reynolds**  
298 **numbers lower than 2000. This behavior is contrary to theory, which predicts constant Nusselt**  
299 **in laminar regime.**

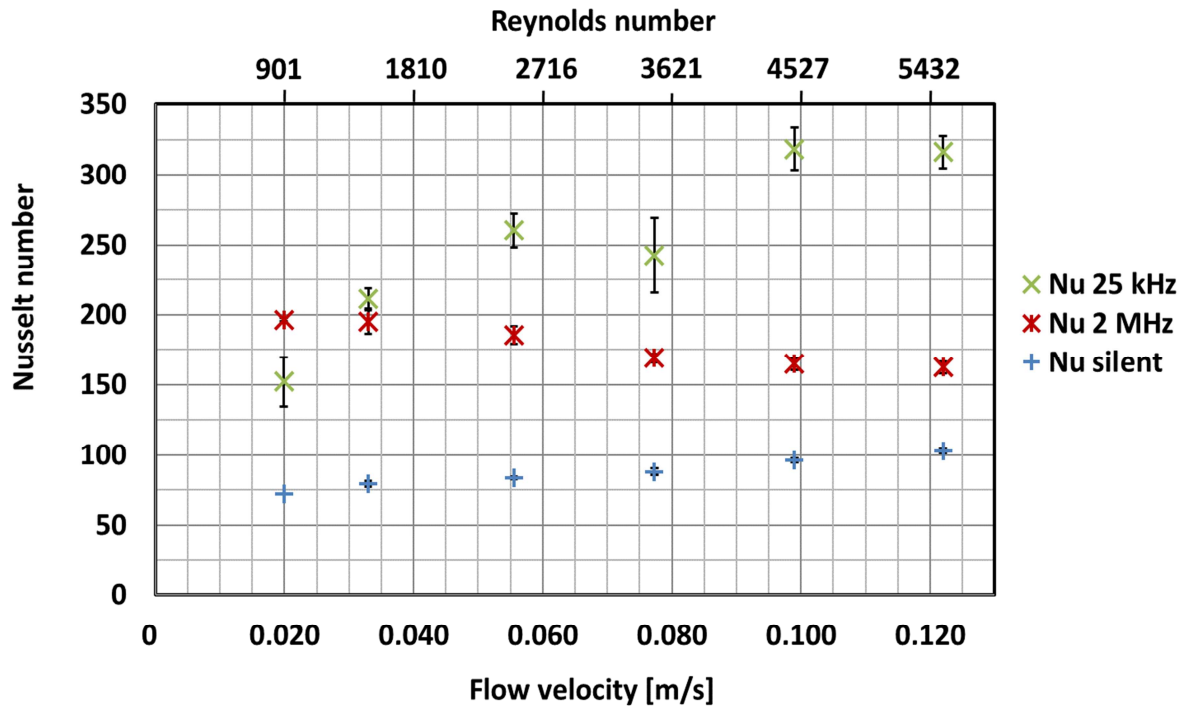


Fig. 4: Nusselt number vs mean flow velocity and Reynolds number for silent conditions, 25 kHz and 2 MHz ultrasound. Heating element n°5, total ultrasound power 110 W, total heating power 450 W. The uncertainty bars are drawn in black for all points on the graph.

300 As stated before, the presence of an ultrasonic field enhances heat transfer but more  
 301 interestingly, these results highlight its dependency towards the ultrasonic frequency. Indeed,  
 302 at high frequency (2 MHz), an increase of the flow velocity leads to a slow decrease of the  
 303 observed heat transfer intensification. The reverse occurs at 25 kHz where an increase of flow  
 304 velocity leads to an increase of the Nusselt number reaching a plateau for the highest tried  
 305 flow velocities and Reynolds numbers. Surprisingly, at the lowest investigated flow velocity  
 306 in this study, the intensification of heat transfer is stronger at 2 MHz than at 25 kHz; whereas  
 307 beyond flow velocities of 0.033 m/s (i.e.  $Re = 1500$ ) heat transfer enhancement is higher  
 308 using low frequency ultrasound. In order to understand and to propose relevant explanations  
 309 for the difference highlighted by thermal results despite the same supplied ultrasonic and  
 310 thermal power, a hydrodynamic study using PIV was then performed.

311 **3.2 Hydrodynamic study results under 25 kHz and 2 MHz sonication**

312 **3.2.1 Preliminary observations without ultrasound**

313 The average velocity field observed without ultrasound is given in Fig. 5 for mean flow  
314 velocities of 0.020 m/s (a) and 0.122 m/s (b) corresponding to Reynolds numbers of 900 (a)  
315 and 5500 (b). As expected, the found pattern illustrates a fluid flowing classically within a  
316 rectangular canal from bottom to top along y-axis direction. As clearly shown, there is none  
317 velocity component along x-axis. Although these results were expected, it was useful to  
318 validate them experimentally before comparison with flow patterns recorded under ultrasound  
319 at 25 kHz or 2 MHz.

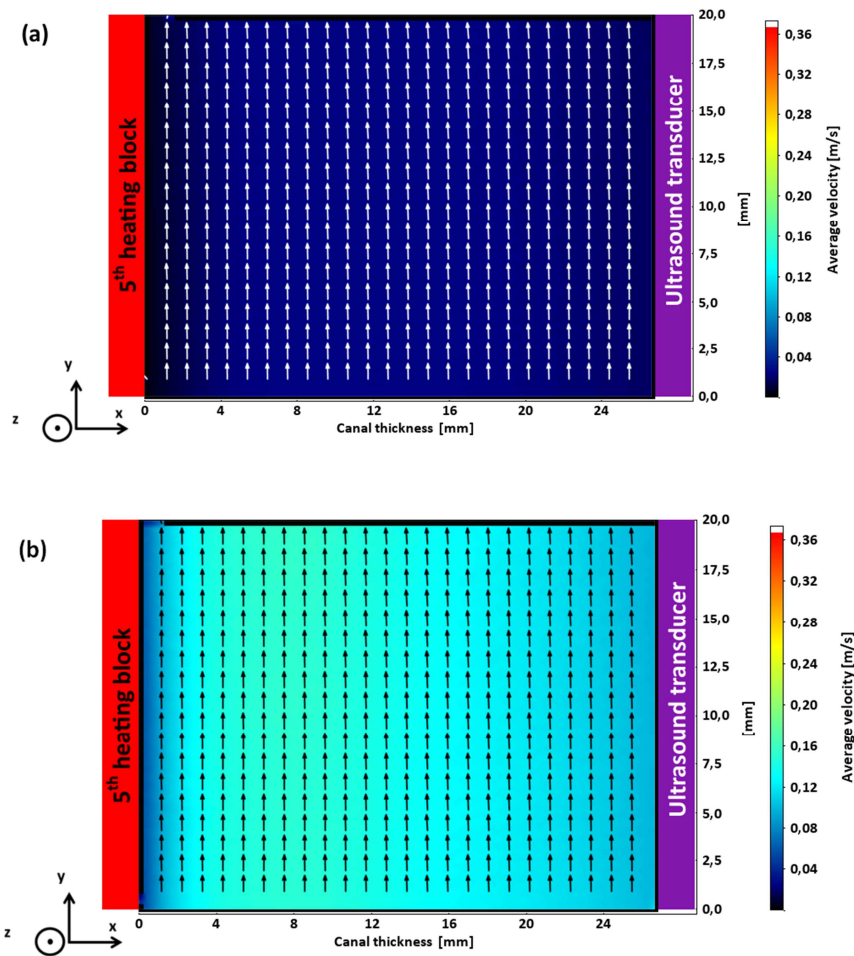


Fig. 5: Average velocity fields observed under silent conditions, heating block n°5, canal

thickness 30 mm, hydraulic diameter = 0.046 m. Mean flow velocity = 0.020 (a) and 0.122 (b) m/s corresponding to Reynolds number = 900 (a) and 5500 (b), Vectors give flow direction and color scale gives velocity values.

### 320 **3.2.2 Experimental results in the presence of 2 MHz ultrasound**

321 For a mean flow velocity equal to 0.020 m/s (i.e. Reynolds = 900), the flow pattern is strongly  
322 disturbed by sonication at 2 MHz, resulting in local velocity value increase and flow direction  
323 modifications as clearly shown in Fig. 6.a. The canal filled with water induces a resonating  
324 cavity for 2 MHz ultrasound waves equal to 40 wavelengths. This number is verified  
325 experimentally and corresponds to the number of ridges **visible on Fig 6.a**. Higher velocity  
326 values (around 0.240 m/s) can be also spotted out in the vicinity of the heating wall. The  
327 Schlichting streaming, classically occurring around vibrating walls or solid walls submitted to  
328 stationary waves, is probably at the origin of this phenomenon. Velocity value increases also  
329 into the bulk to reach 0.160 m/s. For a higher mean flow velocity (0.122 m/s, Reynolds =  
330 5500), changes in the flow pattern are not so marked as shown in Fig. 6 b. Some weak flow  
331 direction modifications are still visible, but the 2 MHz velocity field (Fig 6.b) is very close to  
332 **the one measured** in silent conditions (Fig 5.b). Hydrodynamic effects due to the secondary  
333 flow produced by 2 MHz ultrasound on the x-axis direction are strongly affected by the mean  
334 flow velocity. **It is demonstrated here that modifications of flow pattern, due to the presence**  
335 **of high frequency ultrasound, sharply depends on the value of the mean flow velocity in this**  
336 **experimental configuration.**

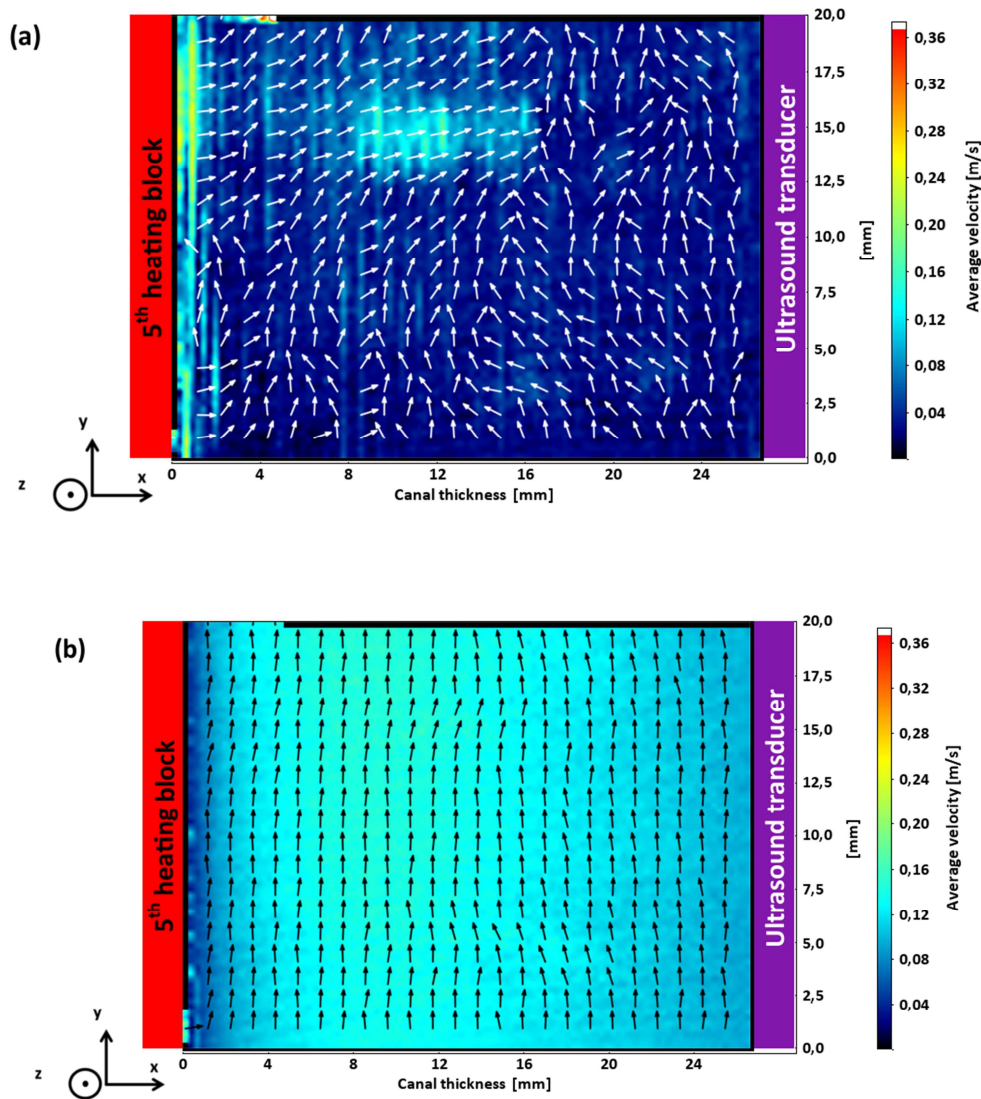


Fig. 6: Average velocity field observed with 2 MHz irradiation, heating block n°5, canal thickness 30 mm, hydraulic diameter = 0.046 m. Mean flow velocity = 0.020 (a) and 0.122 (b) m/s corresponding to Reynolds = 900 (a) and 5500 (b), Vectors give flow direction and color scale gives velocity values.

337 As mentioned in the state of the art, the relationship between acoustic streaming and induced  
 338 turbulences within a liquid or a flow has been already established [16]. The hydrodynamic  
 339 behavior analysis of the average velocity fields presented in Fig. 6 can thus explain those  
 340 presented in Fig. 7 wherein turbulent kinetic energy fields are reported. Turbulent kinetic  
 341 energy (TKE) field with a mean flow velocity of  $0.020 \text{ m}\cdot\text{s}^{-1}$  ( $\text{Re} = 900$ ) reveals that positions

342 of TKE highest values ( $12.5 \text{ mm} < y < 20 \text{ mm}$ ) do correspond to the ones where the average  
343 velocity field is the most disturbed. Attenuation of velocity field modification by 2 MHz  
344 ultrasound, with respect to the mean flow velocity increase (and corresponding Reynolds  
345 number) illustrated in Fig.6, can be directly correlated to the decrease of the TKE values in  
346 the same experimental conditions as reported in Fig.7. Similarly, the decrease of Turbulent  
347 Kinetic Energy produced by 2 MHz ultrasound with respect to the mean flow velocity  
348 increase can be linked to the decrease of Nusselt number as detailed in Fig. 4 under the same  
349 conditions.

350 The present study is not able to determine real causes of this extinguishing phenomenon of the  
351 streaming strength when liquid flowrate is increased. Nevertheless, two hypotheses can be  
352 drawn at this point. At first, the flow observed within the canal for 2 MHz sonication may be  
353 produced by the combination of the pumping pressure due to the mean flow on the y-axis  
354 direction and radiation pressure due to the secondary flow on the x-axis direction (acoustic  
355 streaming). Consequently, the higher the pumping pressure in comparison with the radiation  
356 pressure (which is constant because of ultrasound power kept constant in this study), the  
357 lesser the influence of acoustic streaming is. The second hypothesis could be that the pressure  
358 field within the canal is disturbed when the flow becomes more turbulent because of pressure  
359 fluctuations induced by turbulences leading possibly to a masking effect, thus hindering  
360 acoustic wave propagation and then acoustic streaming production. A future Reynolds  
361 similarity study could be helpful to answer to this question.

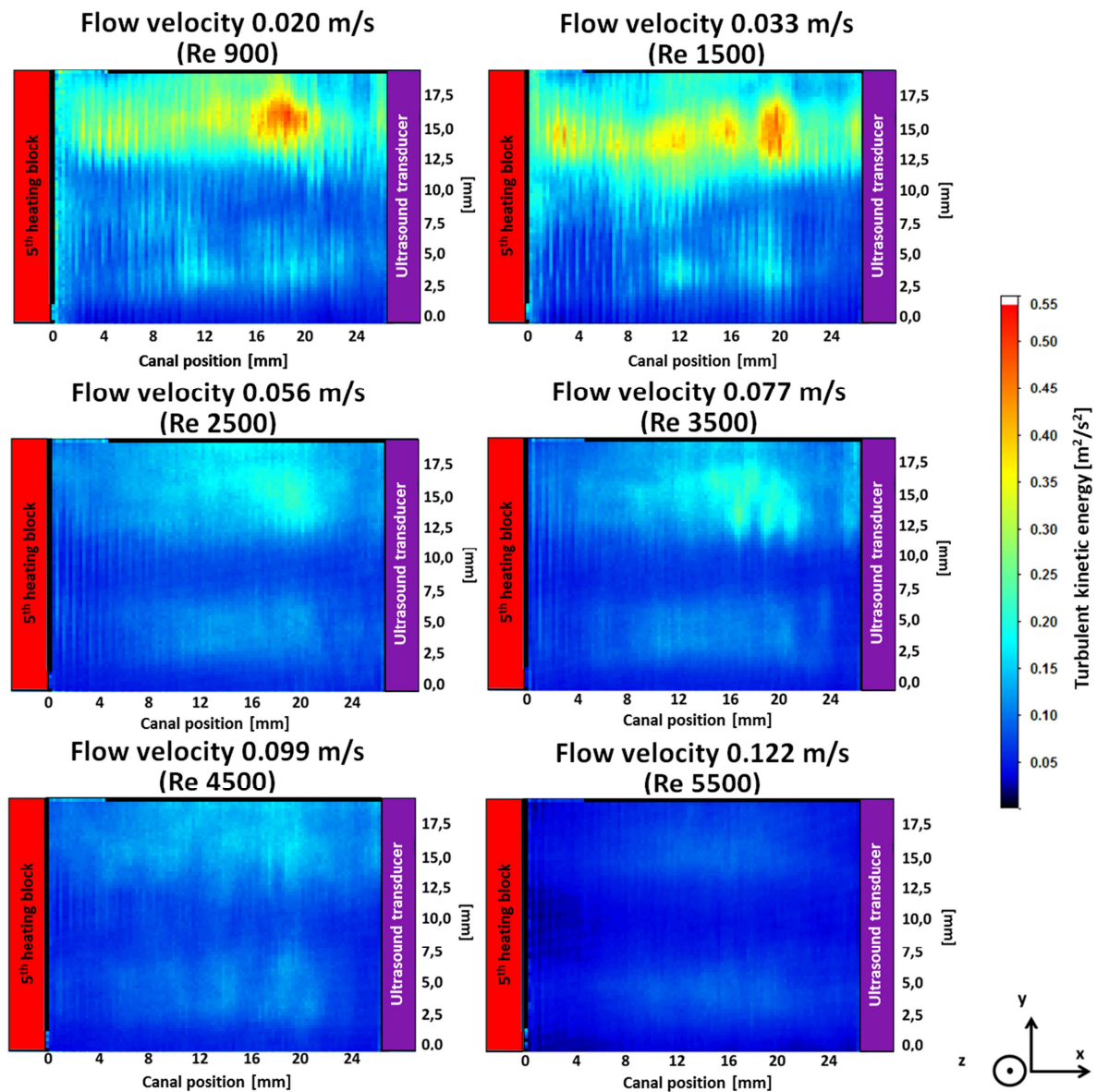


Fig. 7: Turbulent kinetic energy fields estimated in front of the 5<sup>th</sup> heating block for 6 mean flow velocities. Ultrasound frequency = 2 MHz, canal thickness = 30 mm, hydraulic diameter = 0.046 m, total ultrasound power = 110 W.

### 362 3.2.3 Experimental results in the presence of 25 kHz ultrasound

363 Average velocity fields for 25 kHz sonication are displayed in Fig. 8. Their comparison with  
 364 those of the Fig. 5 (silent regime) highlights that direction and values of the velocity are quite  
 365 similar in both ultrasonic and silent modes. Few vectors deviations are visible only nearby the

366 heating wall for mean flow velocity equal to 0.020 m/s (Fig. 8.a). These velocity deviations  
367 totally vanish when the mean flow velocity reaches 0.122 m/s (Fig. 8.b).

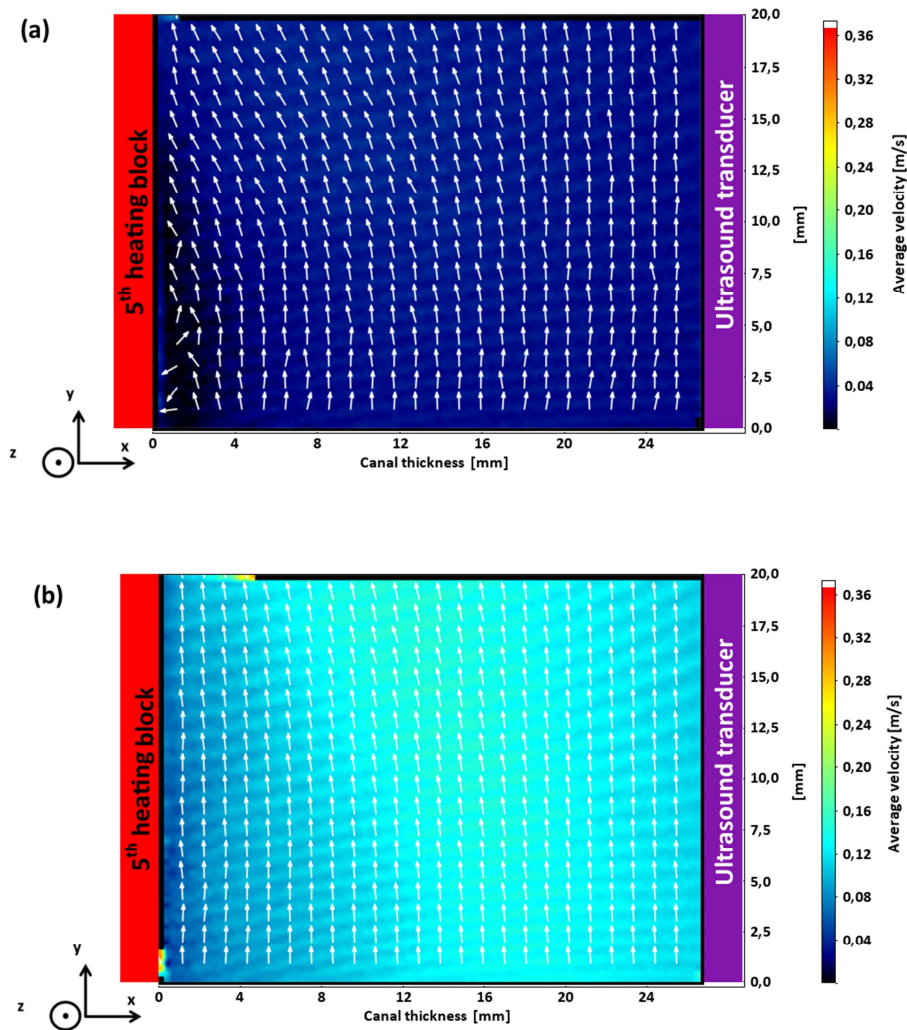


Fig. 8: Average velocity fields observed with 25 kHz ultrasound sonication, mean flow velocity = 0.020 (a) and 0.122 (b) m/s corresponding to Reynolds = 900 (a) and 5500 (b), hydraulic diameter = 0.046 m. Vectors give flow direction and color scale gives velocity values.

368 Fig. 9 compares instantaneous velocity fields under both silent (a) and 25 kHz (b) regimes for  
369 a Reynolds number equal to 900. Ultrasonic cavitation is a temporal stochastic but spatially  
370 homogeneous distributed phenomenon as shown on Fig. 9 (b) for the lowest mean flow

371 velocity (0.020 m/s and Reynolds = 900). Fig. 9(b) shows high velocity spots, reaching up to  
372 over 0.36 m/s.

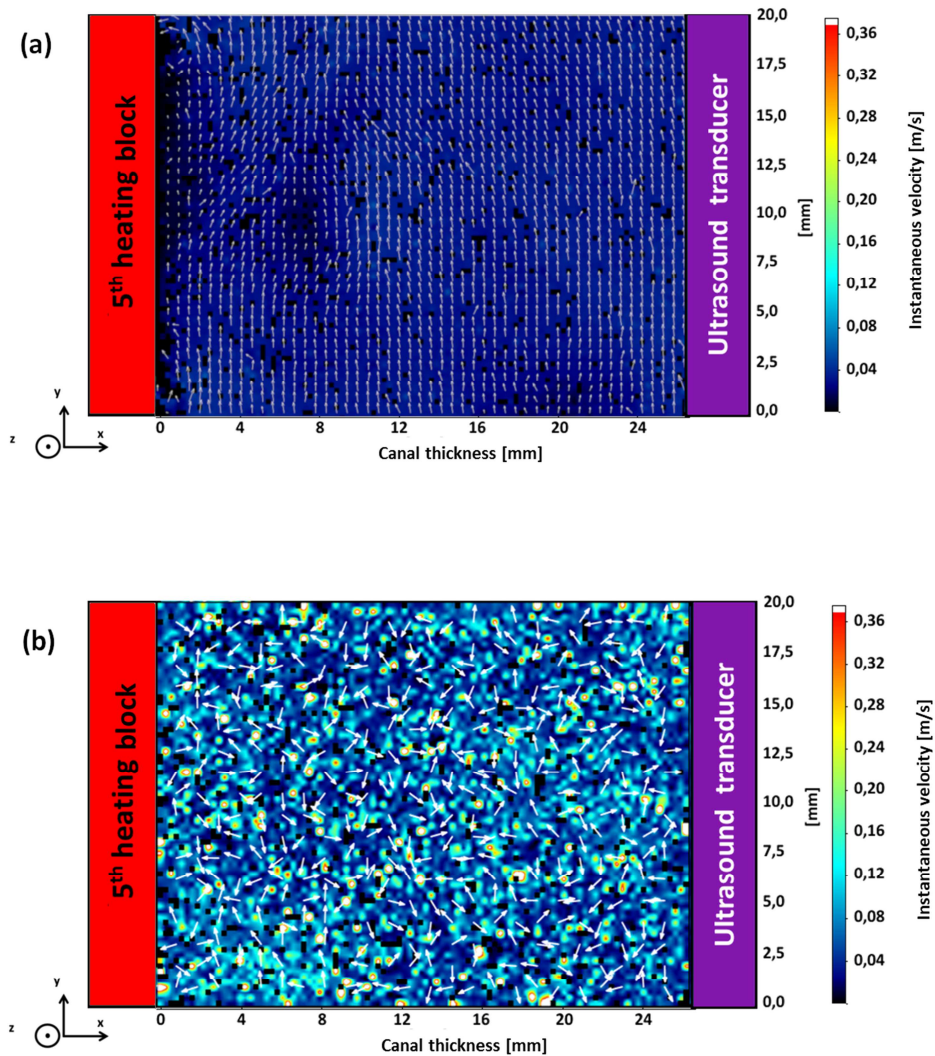


Fig. 9: Instantaneous velocity fields observed under silent regime (a) and under 25 kHz sonication (b). Mean flow velocity = 0.020 m/s corresponding Reynolds = 900, hydraulic diameter = 0.046 m. Vectors give instantaneous velocity directions and color scale gives velocity values.

373 Both acoustic bubble oscillations and collapses probably induce jointly these high velocity  
374 spots within the fluid as illustrated in Fig. 10. This figure shows one of the 2000 PIV doublet  
375 image zoomed on a collapsing cluster bubble (high color level pixels on images (a) and (b))

376 recorded by the camera for a mean flow velocity of 0.020 m/s. The collapse induces a  
377 reduction of the area occupied by bubbles as shown with added double dotted arrows on  
378 images (a) and (b) of Fig. 10. This PIV doublet subsequently gives the instantaneous velocity  
379 field (image (c)). The maximum velocity induced by the cluster collapse reach 0.100 m/s. Its  
380 position corresponds to one of the collapsing cluster areas. Consequently, bubbles strongly  
381 disturb the flow velocity within a disturbance area, which is of bigger size than the cluster  
382 bubble itself (black dotted arrow on image (c) of Fig. 10). Two hypotheses can be drawn to  
383 explain this phenomenon. In the one hand, the violent bubble wall move induces fluid  
384 entrainment away from it. This may be supported by the fact that interrogation windows all  
385 around the cluster area display also higher velocity values than 0.020 m/s, which is the mean  
386 flow velocity. The second hypothesis is a bias of the velocity calculation. Indeed, the velocity  
387 is calculated on a  $16 * 16$  pixel interrogation window whose each pixel measures  
388  $16.5 * 16.5 \mu\text{m}^2$ . Consequently, PIV measurements are not able to clearly distinguish  
389 phenomena inducing effects within an area smaller than  $264 * 264 \mu\text{m}^2$ . In this study, the used  
390 interrogation window size gives the most accurate measurement technically possible.

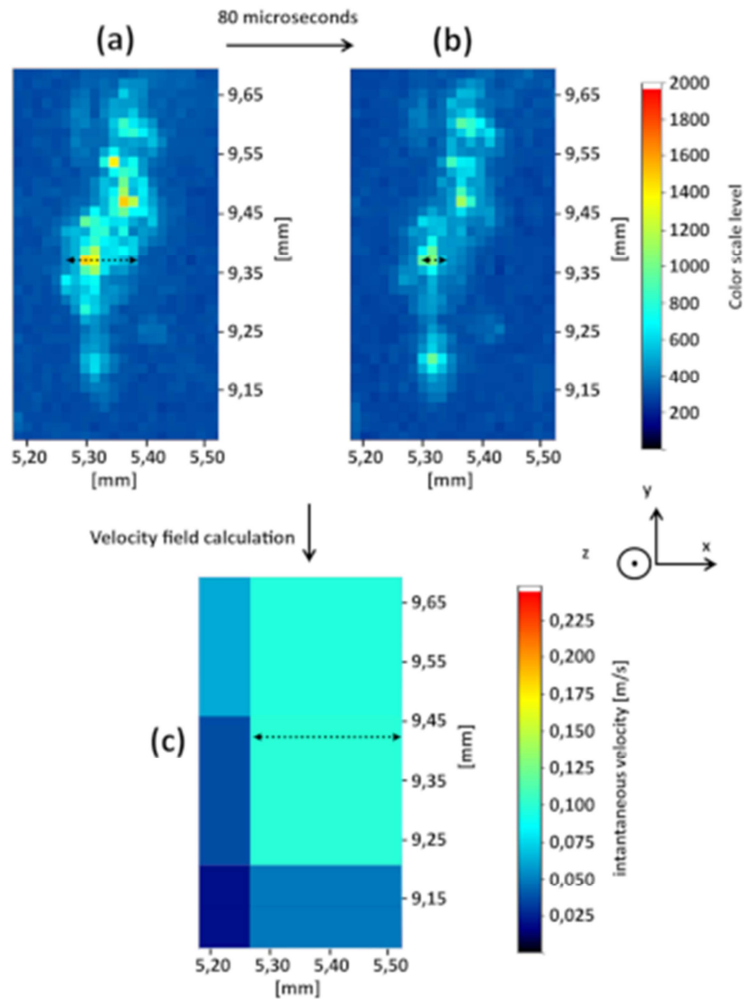


Fig. 10: PIV doublet recording a bubble cluster collapse and resulting instantaneous velocity field within the canal. Reynolds = 900, flow velocity = 0.020 m/s, time between two images of a doublet = 80 microseconds. Pixel size on doublet images =  $16.5 * 16.5 \mu\text{m}^2$  and interrogation window size on velocity field =  $264 * 264 \mu\text{m}^2$ .

391 As already aforementioned, some previous studies have established a clear relationship not  
 392 only between acoustic cavitation and turbulences increase [3, 10] but also between bubble  
 393 collapse and recirculation flows around bubbles walls [5]. **Consequently, it seems reasonable**  
 394 **to link the increase of turbulent kinetic energy in the presence of 25 kHz ultrasound (Fig. 11)**  
 395 **to the collapses and oscillations of bubbles and bubble clusters (Fig. 10).** Whatever the set  
 396 mean flow velocity in the presence of 25 kHz ultrasound, turbulent kinetic energy increases as  
 397 compared to silent regime. Nevertheless, highest values are measured close to the heating wall

398 and for the highest flow velocity where the turbulent kinetic energy can reach locally up to  
399  $0.15 \text{ m}^2/\text{s}^2$  (Fig. 11). Turbulent kinetic energy mean values within the bulk are overall similar  
400 for all experimental flow conditions and are equal to  $0.014 \text{ m}^2/\text{s}^2$  (see Fig. 11). This means  
401 that acoustic cavitation can induce strongest turbulence rates near the heating wall. This  
402 observation is consistent with the fact that acoustic cavitation bubble collapse is known to be  
403 more violent when occurring near a solid wall [5]. Bubbles behavior is driven by the  
404 ultrasonic frequency and power, liquid properties such as viscosity, surface tension and vapor  
405 pressure and by the presence or not of solid wall. Any change in these parameters leads to the  
406 modification of bubbles size and collapsing diameter, oscillating frequency and strength of the  
407 collapse. Consequently, turbulent kinetic energy within the bulk remains constant whatever  
408 mean flow velocity. This observation is consistent with the unchanged operating parameters  
409 influencing bubbles behaviors.

410 Fig. 11 also shows the increase of the turbulent kinetic energy values close to the heating wall  
411 as the flow velocity increases under 25 kHz ultrasonic field. This substantial increase can be  
412 explained by taking into account the laminar boundary layer thickness and the size of fluid  
413 area disturbed by cavitation bubbles. The disturbed fluid area size (linked to the one of  
414 collapsing bubbles and clusters as shown in Fig. 10) is estimated as an example by  $\chi$  in  
415 Fig. 12.  $\chi$  is dependent on several aforesaid parameters but not on the flow regime in contrary  
416 to the boundary layer thickness ( $\delta$  in Fig. 12) which decreases as mean flow velocity and  
417 Reynolds number increase. The velocity spots size ( $\chi$ ) distribution is ranging from 250  
418 micrometers to 500 micrometers, i.e. one or two PIV interrogation windows (squares in Fig.  
419 12). This size distribution was observed for all mean flow velocities tested in this study. The  
420 flow velocity within the canal does not influence the velocity spots size nor their spatial  
421 distribution. Because the boundary layer thickness decreases as flow velocity and associated  
422 Reynolds increase, the ratio  $\chi/\delta$  increases for the same conditions. Consequently, the

423 disturbance effect within the boundary layer due to bubbles collapse increases as mean flow  
 424 velocity and Reynolds number increase. Indeed, violent collapse of bubbles literally disrupts  
 425 the boundary layer, laminar flow being turned into a very turbulent one over a thickness  
 426 defined by  $\chi$ . This value is driven by the collapse strength of the bubble and by viscous  
 427 effects whose attenuate disturbance propagation. The smaller the thickness of the boundary  
 428 layer is (i.e. the higher flow velocity and Reynolds number are), the easier bubbles are able to  
 429 disrupt it over all its thickness. It seems relevant to say that this phenomenon leads to the  
 430 increase of the heat transfer enhancement with respect to flow rate increase.

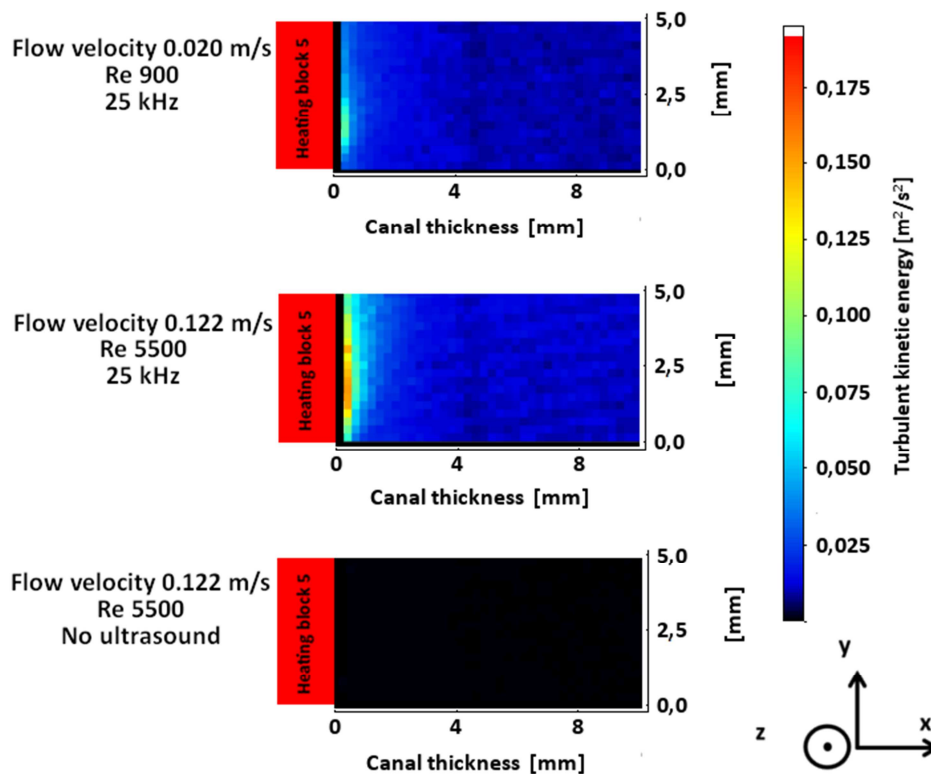


Fig. 11: Details of Turbulent Kinetic Energy (TKE) field near the 5<sup>th</sup> heating block from 0 to 10 mm from the heating wall to the bulk and on the first five millimeters in height under 25 kHz ultrasound sonication and silent regime for mean flow velocity = 0.020 and 0.122 m/s corresponding to Reynolds = 900 and 5500.

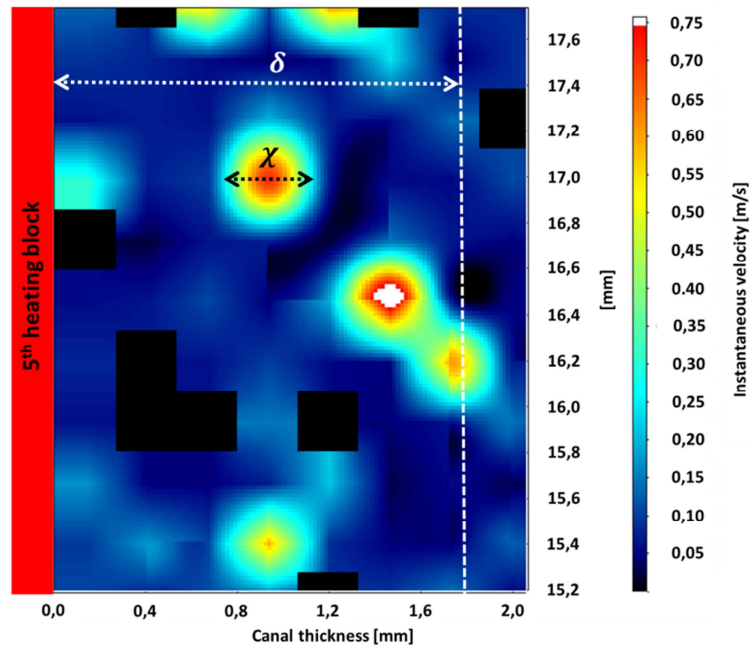


Fig. 12: Illustration of the influence area of cavitation bubbles on the laminar boundary layer. The theoretical viscous boundary layer  $\delta$  for silent regime is calculated from [45] ( $f = 25$  kHz,  $e = 30$  mm,  $Q_v = 1075$  L/h, Mean flow velocity =  $0.099$  m/s,  $Re = 4500$ ,  $\delta = 1.76$  mm,  $P_{us} = 110$  W).

### 431 3.3 Thermo-hydraulic study between 25 kHz and 2 MHz sonication

432 As already shown in this paper, thermal and hydrodynamic behaviors at 25 kHz and 2 MHz  
 433 sonication are different. Moreover, in Fig. 13, average turbulent kinetic energy values are  
 434 plotted for both frequencies with mean flow velocities equal to  $0.020$  and  $0.122$  m/s ( $Re = 900$   
 435 and  $5500$  respectively) as a function of canal position. These calculated values give the mean  
 436 value for each interrogation window column (y-axis) for a fixed row (x-axis) in order to  
 437 obtain an average turbulent kinetic energy profile with respect to canal thickness (x-axis).  
 438 This leads to **quantitative values required** to compare hydrodynamic effects for each  
 439 ultrasound frequency.

440 As illustrated in Fig. 13, for 2 MHz ultrasound the lower the mean flow velocity is, the higher  
441 the average turbulent kinetic energy is. This observation is in agreement with the Nusselt  
442 number behavior, which experiences a decrease when flow velocity and thereby Reynolds  
443 number increase (Fig. 4). This naturally leads to a decrease of the Heat Transfer Enhancement  
444 Factor (HTEF) as plotted in Fig. 14.

445 With 25 kHz sonication, average turbulent kinetic energy values of Fig. 13 are also in good  
446 agreement with TKE fields presented in Fig. 11. The highest values are obtained close to the  
447 heating wall whatever the mean flow velocity. The higher the mean flow velocity is, the  
448 higher the turbulent kinetic energy near the wall is. Nevertheless, whatever **the considered**  
449 **flow velocity**, the turbulent kinetic energy profile remains unchanged. Indeed, when going far  
450 from the heating **wall, i.e. at a distance** higher than 4 mm (**x-axis**), a **nearly** constant value of  
451 the average TKE is measured within the bulk. Consequently, 25 kHz ultrasound modifies **bulk**  
452 **turbulences whatever the mean flow velocity value**, allowing a constant mixing effect within  
453 the bulk of the liquid. This could be of great interest for processes that require constant  
454 mixing effects of the fluid within the bulk on large flow velocity range.

455 However, the thermal enhancement increase, with respect to the mean flow velocity increase  
456 observed for 25 kHz sonication (Fig. 14), **is also consistent with the  $\chi/\delta$  ratio increase with**  
457 **same operating** conditions. Indeed, the increase of the mean flow velocity and associated  
458 Reynolds number induces a decrease of the boundary layer thickness. This phenomenon  
459 increases the disruption effect due to cavitation bubbles on the laminar boundary layer. By  
460 consequence, heat transfer from the heating wall to the bulk increases leading to a Nusselt  
461 number increase. Therefore, it can be expected that when the ratio  $\chi/\delta$  tends towards one,  
462 Nusselt number would not increase anymore with respect **to the mean flow velocity**. This  
463 could explain the asymptotical behavior for experimental curves observed for both Nusselt  
464 number (see Fig. 4) and HTEF profiles (see Fig. 14). As a conclusion, it is of great importance

465 to highlight that using 25 kHz ultrasound will be preferable to enable optimum intensification  
 466 of the transfer process under transitory-turbulent flows for processes involving parietal  
 467 transfer such as heat exchangers or membrane processes.

468 One can remark that the laminar boundary layer thickness is also decreasing with respect to  
 469 Reynolds number increase for 2 MHz sonication. So why is this behavior different from the  
 470 one observed with 25 kHz sonication at high flow velocity? It is probable that increasing the  
 471 pressure fluctuations or the flow velocity can affect the wave propagation and then the  
 472 streaming production at 2 MHz. Thus, the acoustic streaming is weaker for high Reynolds  
 473 numbers. This induces less intense convective effects and turbulence kinetic energy values for  
 474 both bulk and laminar boundary layer.

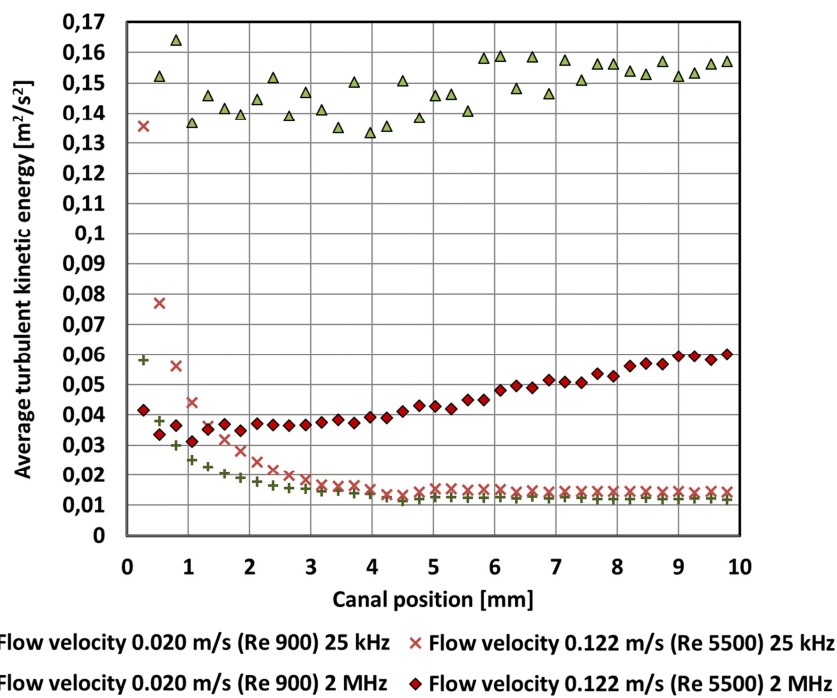


Fig. 13: Average turbulent kinetic energy profile vs canal position on the first 10 millimeters from the 5<sup>th</sup> heating block to the bulk (x-axis) under 25 kHz and 2 MHz sonication for mean flow velocity = 0.020 and 0.122 m/s corresponding to Re = 900 and 5500.

475 When average turbulent kinetic energy curves are compared with respect to frequency for  
 476 fixed hydrodynamic conditions, it appears that 2 MHz ultrasound produces a higher level of  
 477 turbulence at low mean flow velocities near the heating wall (Fig. 13). The contrary occurs at  
 478 high flow velocities. This observation is consistent with thermal results both expressed in  
 479 terms of Nusselt numbers (Fig. 4) or in terms of Heat Transfer Enhancement Factor (Fig. 14).  
 480 Indeed, the highest Nusselt Number and HTEF values at the lowest liquid flow rate are  
 481 obtained with 2 MHz ultrasound while the contrary is observed at highest flow velocity under  
 482 25 kHz sonication.

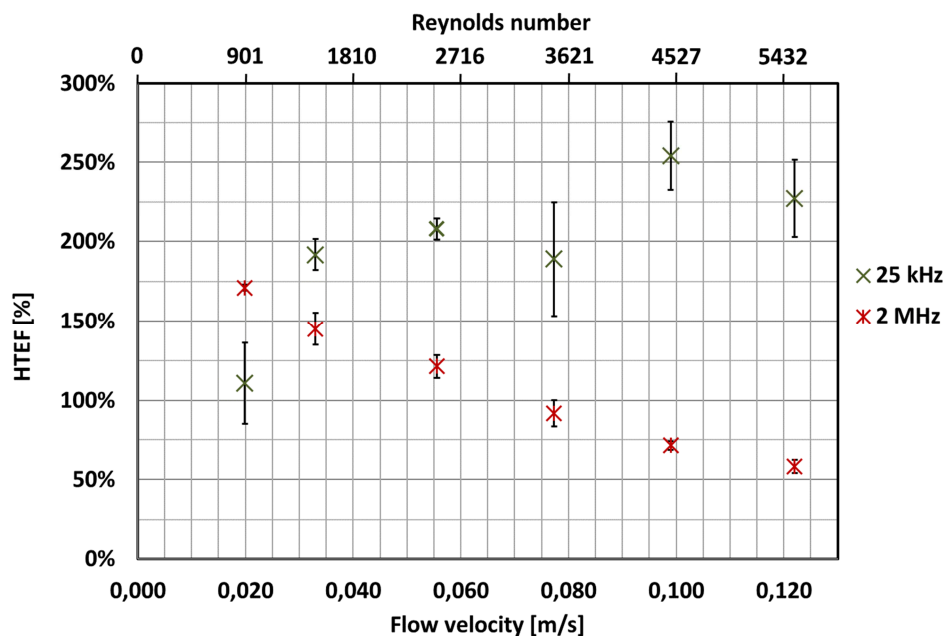


Fig. 14: Heat Transfer Enhancement Factor vs Reynolds number and mean flow velocity for 25 kHz and 2 MHz ultrasound. Total ultrasound power is equal to 110 W, total heating power is equal to 450 W.

483 Fig. 15 is finally suggested as a qualitative illustration of the relationship between  
 484 hydrodynamic and thermal behavior for each frequency investigated in this study. **For 2 MHz**  
 485 **sonication, an increase of mean flow velocity leads to a decrease of the turbulent kinetic**  
 486 **energy produced by 2 MHz ultrasound. This phenomenon is illustrated clearly by Nusselt**

487 number decrease with respect to the same conditions. For 25 kHz sonication, a decrease of the  
 488 boundary layer thickness, with respect to the mean flow velocity, induces an increase of the  
 489 disruption effect of the boundary layer produced by acoustic bubbles collapse. This leads to a  
 490 decrease of the thermal resistance and therefore in an increasing thermal enhancement as flow  
 491 velocity increases.

492 It is therefore reasonable to make the hypothesis that for a fixed ultrasonic power, acoustic  
 493 streaming is more efficient to enhance parietal transfer under laminar flow regimes while  
 494 acoustic cavitation is more relevant under transitory-turbulent flows.

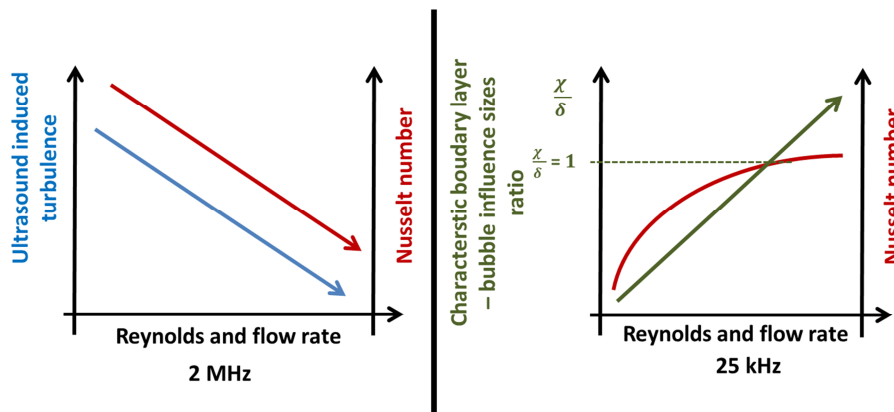


Fig. 15 : Illustration of the phenomenon involved in heat transfer enhancement by ultrasound in presence of acoustic streaming (2 MHz) and acoustic cavitation (25 kHz).

#### 495 4. Conclusions

496 The aim of this work, which belongs to a heat exchangers optimization project, was to study  
 497 mechanisms involved and responsible of the intensification of heat transfer with two different  
 498 ultrasound frequencies. One of the objectives was to establish a link between observed  
 499 acoustically induced heat transfer enhancements and related induced hydrodynamic  
 500 phenomena depending on the experimental conditions. This work focused on a comparison

501 between the differences highlighted using low (25 kHz) or high (2 MHz) frequency from both  
502 thermal and hydrodynamic points of view.

503 Thermal enhancement by ultrasound, i.e. Nusselt number increase compared to silent  
504 condition, is observed for both frequencies. On the one hand, 2 MHz ultrasound frequency  
505 produces strong convective effect usually named acoustic streaming that induces turbulence  
506 enhancement and global mixing effect. On the second hand, acoustic cavitation produced by  
507 25 kHz ultrasound leads to an increase of turbulences both in the bulk and within the  
508 boundary layer. Highest values on turbulent kinetic energy are obtained near the heating wall  
509 (i.e. within the boundary layer) which is consistent with the fact that acoustic bubble collapse  
510 is more violent near a solid wall. The higher the mean flow velocity is, the higher the thermal  
511 enhancement is. This stronger action of 25 kHz ultrasound at high flow velocity could be  
512 explained by the enhancement of the effect of cavitation bubbles collapse on the boundary  
513 layer. Indeed, as mean flow velocity increases, laminar boundary layer thickness decreases.  
514 This leads to an easier and a more efficient disruption of the boundary layer by bubble  
515 collapse and a reduction of the thermal resistance. In order to quantify this influence, a ratio  
516 defined as the size of the fluid disturbance area  $\chi$  [m] on the laminar boundary layer thickness  
517  $\delta$  [m] can be estimated. When this ratio  $\chi/\delta$  is equal to 1, it means that the length of  
518 disturbance area produced by bubbles collapse is equal to boundary layer thickness. This  
519 allows to directly transfer physical quantities (heat, concentration...) from the wall to the bulk  
520 flow. It is then expected that when the ratio  $\chi/\delta$  is equal or superior to 1, Nusselt number may  
521 stop to increase with respect to mean flow velocity for 25 kHz ultrasound regime.

522 Further studies will prospect the boundary layer disruption explanation proposed here with  
523 experiments performed for higher flow velocities and Reynolds numbers. Additional work  
524 will aim at determining causes of the turbulence attenuation with respect to flow velocity and

525 Reynolds number increase in presence of 2 MHz ultrasound observed in this study. The  
526 objective would be to determine if this phenomenon is reliable to the increase of the Reynolds  
527 number, i.e. to the natural turbulence in the flow in silent regime, or to the increase of the  
528 mean flow velocity. A Reynolds similarity study, including canal thickness modification for  
529 fixed Reynolds values, and then different flow velocities should help to answer to this  
530 question. Finally, a study dealing with global energy balance of thermal enhancement by  
531 ultrasound should be done. A comparison between energy efficiency of such a device and  
532 passive methods could be of great interest. Nevertheless, this kind of study needs an  
533 optimization of the ultrasound technology in accordance with thermal enhancement goals.

534 At least, results reported in this paper provide a better understanding of thermal intensification  
535 by using low (25 kHz) or high (2 MHz) frequency ultrasound according to main  
536 hydrodynamic phenomena induced by acoustic cavitation and acoustic streaming. It is hoped  
537 that this work will be helpful to the way to the design of future vibrating heat exchangers.

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