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Water disinfection by orifice-induced hydrodynamic cavitation*

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Abstract

Hydrodynamic Cavitation (HC) is considered as a promising water-disinfection technique. Due to the enormous complexity of the physical and chemical processes at play, research on HC reactors is usually carried out following an empirical approach. Surprisingly, past experimental studies have never been designed on dimensional-analysis principles, which makes it difficult to identify the key processes controlling the problem, isolate their effects and scale up the results from laboratory to full-scale scenarios.

The present paper overcomes this issue and applies the principles of dimensional analysis to identify the major non-dimensional parameters controlling disinfection efficacy in classical HC reactors, namely orifice plates. On the basis of this this analysis, it presents results from a new set of experiments, which were designed to isolate mainly the effects of the so-called cavitation number (σ_v). Experimental data confirm that the disinfection efficacy of orifice plates increases with decreasing σ_v . Finally, in order to discuss the significance of the results presented herein and frame the scope of future research, the present paper provides an overview of the drawbacks associated with dimensional analysis within the context of HC.

Keywords: hydrodynamic cavitation; water disinfection; E. Coli; dimensional

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1. Introduction

The lack of safe water in developing countries is affecting millions of people causing major sanitation and economic issues. Prohibitive costs and difficult access to chemicals (as well as qualified staff) [1] [2] prevent the implementation of water-disinfection technologies routinely adopted in developed countries. Such technologies also present shortcomings, the main one being associated with the fact that all chemicals used in the disinfection process may produce, under certain conditions, unhealthy and carcinogenic by-products (DBPs), such as trihalomethanes, haloacetic acids, bromate, and chlorite [3]. As a result, in the ongoing review of drinking water quality guidelines, the World Health Organization is updating risk assessments for dissolved chemicals, setting new stricter limits for DBPs [4]. From this picture it appears that there is a clear need to implement chemical-free water disinfection techniques, which must also be simple to use, robust and low-cost, especially to meet the demands of low-income countries.

In this context, techniques based on cavitation seem to be promising. Cavitation exploits the phenomenon of formation, growth, and collapse of vapour/gas bubbles triggered by pressure variations [5]. When the fluid experiences a critical pressure (i.e., lower than vapour pressure), the formation of cavities begins, and the maximum size of the cavities is typically reached under isothermal expansion. Subsequently, when higher pressure is recovered, bubbles undergo adiabatic collapse. Such a collapse leads to the formation of pressure-waves and micro-jets that instantly release a large amount of energy while generating intense normal and shear fluid stresses [6] [7] [8]. In the scientific literature, these severe conditions are considered as the main cause of cell membrane damage and consequently of microorganism death or inactivation [9] [10] [11]. Moreover, high temperature peaks promotes chemical reactions, such as the dissociation of water molecules into $\bullet\text{OH}$ radicals, which provide oxidizing power and increase the efficiency of disinfection [12].

Cavitation can be generated in two main ways: by ultrasonic waves travelling through the liquid (i.e., acoustic cavitation, AC), or by forcing the fluid through a constriction (i.e., hydrodynamic cavitation, HC) [13]. AC is energy demanding, works on batch and is effective only for fluid volumes in close proximity to the acoustic source. Thus, AC is deemed unsuitable for the treatment of large volumes of water [14] [15]. In the case of HC (which has been investigated considerably less than AC [16]), cavitation is typically obtained by a pressure drop, e.g. generated by an orifice plate or a Venturi tube. In contrast to AC, HC is deemed as an energetically more efficient process [17] [18] and allows for the treatment of large volumes of moving water; so it is suitable for implementation in drinking- and waste-water treatment plants [19] as well as in the food and beverage processing [20] [21] [22] and chemical synthesis [23] [24] [25] [26].

42 HC is induced by purely mechanical devices which can be used without
43 the presence of qualified staff and is therefore suitable for use in developing
44 countries. On the down side, HC is a more complex process than AC from
45 the fluid-dynamics prospective. AC involves bubbles growing and collapsing
46 in quiescent water, whereas HC commonly occurs in fast moving fluids whose
47 dynamics responds to complex (and currently poorly-understood) non-linear
48 interactions between bubbles and turbulence. As a consequence, the study of
49 fluid dynamics within HC reactors for water treatment is still in its infancy and
50 much more work is needed to identify governing parameters and quantifying
51 their role in the game of disinfection.

52 Recently, many research-works have focused on demonstrating the effective-
53 ness of HC as well as exploring the effects of different HC-reactor-geometries
54 on disinfection efficiencies. Orifice plates [27, 14], Venturi tubes [28, 29], and
55 rotor-stator reactors (e.g., high speed homogenizers) [30, 31] were the most in-
56 vestigated devices.. Other studies have focused on hybrid disinfection techniques
57 (i.e., the combination of cavitation with chemical disinfectants) in order to re-
58 duce the amount of chemicals in the water treatment processes [32, 33, 34, 35].
59 This interest in the topic witnesses the great potential of HC for water disin-
60 fection [36]. However, the scientific literature on HC currently lacks of a sound
61 methodological approach as well as sound theoretical grounds [37, 29]. In par-
62 ticular, due to its complexity, the study of HC for disinfection purposes has been
63 commonly addressed using an empirical approach, although numerical studies
64 have also been proposed (see, e.g., [38, 39, 40, 41]). However, to the best of
65 our knowledge, none of the existing studies in the literature has based the ex-
66 perimental work on dimensional analysis. This clearly makes it difficult to: (i)
67 identify all the relevant non-dimensional groups controlling the problem; (ii)
68 isolate their effects on the observed disinfection efficiencies; and ultimately (iii)
69 scale up from laboratory to full-scale HC reactors.

70 The objectives of the present paper are: (a) to identify, by means of dimen-
71 sional analysis, the non-dimensional parameters controlling disinfection efficien-
72 cies in classical HC reactors such as orifice plates; (b) in light of this dimen-
73 sional analysis, to provide a critical appraisal of the relevant literature (section
74 3) highlighting main results and knowledge gaps; (c) to present results from a
75 systematic set of experiments where the effects of the so-called cavitation num-
76 ber (defined in the next section), were isolated and assessed. This parameter
77 was chosen as the target of the present paper as it quantifies the intensity of
78 cavitation and is therefore considered key for the design of HC reactors.

79 2. Dimensional analysis

80 When a problem is as complex as HC, it is convenient to first attempt to
81 tackle it by adopting an empirical approach whose very first step should be di-
82 mensional analysis. Towards this end, let us consider the simple case of a HC
83 reactor where cavitation is induced by orifice-plates only. This is convenient
84 because: (i) the geometry of Venturi-tubes (i.e., the other commonly-employed
85 HC reactor) is much more complex than orifices as it is associated with many

86 more influencing variables, which make the analysis significantly more convo-
 87 luted; (ii) as Venturi tubes, orifice plates have been largely investigated in the
 88 literature and therefore the results of the present paper can be easily put into
 89 context; (iii) we present novel experiments involving orifice plates only.

90 Since most experimental studies deal with the case of HC reactors imple-
 91 mented in closed loop systems, we consider the case of a fixed volume of water
 92 V which goes through a HC reactor multiple times n_p . At these conditions it
 93 can be argued that the bacterial concentration C of a specific pathogen (mea-
 94 sured in Colony Forming Units, CFU, per unit volume of water) depends on the
 95 following set of parameters:

$$C = f(C_0, \mu, \rho, \gamma_s, v_h, P_2 - P_v, n_p, L_i), \quad (1)$$

96 where C_0 , is the initial pathogen concentration; μ , ρ and γ_s are the kinematic
 97 viscosity, the density and the surface tension of water, respectively; v_h is the
 98 mean fluid velocity at the downstream end of the constriction, P_2 is the abso-
 99 lute pressure recovered downstream of the orifice plate (see Figure 1), P_v is the
 100 absolute water-vapor pressure, L_i , in general terms, defines the set of variables
 101 characterizing the geometry of the reactor. In the simplest case of a circular
 102 orifice plate, which is the subject of the present paper, L_i includes: the charac-
 103 teristic diameter of the orifice (i.e., the constriction) d , the diameter of the pipe
 104 upstream and downstream of the plate D , the orifice-plate thickness b and the
 105 number of orifices n .

106 As far as equation (1) is concerned, a few comments are in order: (i) as
 107 in many other Fluid Dynamics problems, Equation (1) does not include simple
 108 pressures but pressure-differences with respect to a reference value, which, due to
 109 the importance of bubble formation and collapse, is here identified as the water-
 110 vapor pressure; (ii) the effects of temperature are indirectly taken into account
 111 through parameters μ , ρ , γ_s and P_v ; (iii) we did not consider the absolute water
 112 pressure upstream of the orifice plate (P_1) as this is a direct function of v_h and
 113 P_2 and is therefore redundant.

114 Relevant non-dimensional parameters can now be identified by application
 115 of the well-known Buckingham π theorem [42]. Towards this end ρ , v_h and d are
 116 chosen as the three repeating variables, which contain all the primary dimensions
 117 appearing in Equation (1), namely length [L], mass [M] and time [T] (CFU
 118 appearing in the definition of concentrations are dimensionless numbers and
 119 therefore cannot be accounted for as a primary dimension). Simple dimensional
 120 arguments lead to the following set of non-dimensional parameters:

$$Cd^3 = f_1 \left(C_0 d^3, \frac{\rho v_h d}{\mu}, \frac{\rho v_h^2 d}{\gamma_s}, \frac{P_2 - P_v}{\rho v_h^2}, n_p, \overbrace{\frac{D}{d}, \frac{b}{d}, n}^{L^*} \right). \quad (2)$$

121 The dependent parameter on the left hand of Equation (2), can be com-
 122 bined with the first independent parameter to form a dimensionless bacterial

123 concentration $\frac{C}{C_0}$, so that Equation (2) becomes:

$$\frac{C}{C_0} = f_2 \left(C_0 d^3, \frac{\rho v_h d}{\mu}, \frac{\rho v_h^2 d}{\gamma_s}, \frac{P_2 - P_v}{\rho v_h^2}, n_p, \frac{D}{d}, \frac{b}{d}, n \right), \quad (3)$$

124 where, C/C_0 is herein defined as a non-dimensional disinfection efficiency; $(\rho v_h d)/\mu$
125 is the Reynolds number of the jet forming at the downstream end of the ori-
126 fice, which regulates turbulence and flow development within the HC reactors;
127 $\rho v_h^2 d/\gamma_s$ is the so-called Weber number, which takes into account surface ten-
128 sion forces with respect to inertial forces and, presumably, strongly influences
129 the behaviour of bubbles [43]; D/d and b/d are geometrical parameters that,
130 together with the Reynolds number affect the flow characteristics of the orifice
131 and hence the fluid stresses bacteria may be subjected to (bacteria are strongly
132 sensitive to turbulence and fluid stresses, see e.g. [44]); $(P_2 - P_v)/(\rho v_h^2)$ is the
133 so-called cavitation number, which quantifies the intensity of cavitation so that,
134 for values above the one corresponding to the onset of supercavitation, the lower
135 is its value the more intense is the formation and collapse of bubbles. It is worth
136 mentioning that, in the current literature, the cavitation number σ_v is usually
137 formulated adding a scaling factor 2, irrelevant for dimensional analysis, see
138 Equation (4); $C_0 d^3$ is a dimensionless initial concentration, which, although ar-
139 bitrarily defined, indicates that the effectiveness of a HC reactor might depend
140 on initial conditions. In Equations (1), (2) and (3), f , f_1 and f_2 are functional
141 relations between dependent and independent variables.

142 The next section provides an appraisal of the existing literature contextually
143 to the dimensional analysis carried out above.

144 3. A critical appraisal of the literature

145 As hydrodynamic cavitation has attracted considerable research interest, the
146 number of experiments available in the scientific literature is large and growing
147 fast. In Table 1 we selected 12 works on the basis of the following criteria: (i)
148 they all deal with HC induced by orifice plates or similar reactors such as noz-
149 zles or partially closed valves; (ii) they all provide sufficient experimental details;
150 (iii) they all deal with disinfection of bacteria, except the work of Badve et al.
151 [45] that used zooplankton, included for the sake of completeness. It is worth
152 noting that *Escherichia Coli* is the most commonly adopted bacterium in these
153 experiments as it is often present in naturally-contaminated water. Moreover,
154 the microbiological quality of drinking water relies largely on examination of
155 indicator bacteria such as coliforms, in particular *E. Coli*. For this reason, the
156 procedures to measure its concentration is internationally regulated. In addi-
157 tion, *E. Coli* is simply cultivable in laboratory and is not particularly dangerous
158 to handle during the experiments. For the sake of completeness and to provide
159 an overall overview of the relevant literature, Table 1 provides information and
160 parameters that were reported by the authors of each referenced paper and
161 not only those already mentioned in the previous section. In order to interpret
162 Table 1 the following definitions apply:

- 163 • **reactor type** indicates the type of cavitating reactor used. OP refers
 164 to orifice plates; DynaJets[®], DynaSwirl[®] and StratoJets[®] are patented
 165 reactors with a configuration comparable to an orifice plate; "valve" refers
 166 to as partially closed valve in which cavitation occurs; "pump" refers to
 167 experiments where the bacterial reduction solely due to the action of the
 168 pump was assessed;
- 169 • **configuration** is the geometry of the orifice plate used, e.g. 25×2 mm
 170 indicates a plate with 25 holes of 2 mm of diameter. Additional infor-
 171 mation indicate the shape of the holes: squared (S), rectangular (R), if
 172 not specified otherwise, circular holes were adopted. Orifice plates put in
 173 series are indicated with the "+" sign;
- 174 • **holes area** is the total area of the holes in the plate;
- 175 • α is the ratio of perimeter of the holes to their total area;
- 176 • β is the ratio of holes-area to cross-sectional area of pipe;
- **cavitation number**. This is considered one of the most important pa-
 rameters to describe the intensity of cavitation. The literature, rather
 arbitrarily, introduced two types of cavitation numbers:

$$\sigma_v = \frac{P_2 - P_v}{1/2 \rho v_h^2}, \quad (4)$$

and,

$$\sigma_{v,\Delta P} = \frac{P_2 - P_v}{P_1 - P_2}, \quad (5)$$

- 177 • **t** is the total duration of the treatment;
- 178 • **initial/final CFU** are the initial and final concentration of bacteria used
 179 in the disinfection experiments;
- 180 • **disinfection efficiency** is the bacteria concentration reduction δC on
 181 percentage or in logarithmic unit, e.g. $3 \log$ corresponds to a reduction in
 182 the bacterial concentration of three orders of magnitude.

183 Empty cells (-) in Table 1 indicate data not provided by the authors. Data
 184 with an asterisk were non directly provided by the referenced papers, but were
 185 derived by the authors of the present paper. Appendix A provides details about
 186 experimental methods and results provided by papers referenced in Table 1.

187 Table 1 witnesses the remarkable experimental efforts made by researchers
 188 to investigate the influence of the main variables involved in orifice-shaped reac-
 189 tors, e.g. the pressure drop, the velocity of the constricted flow, etc.. However,
 190 the dimensional analysis developed in the previous section highlights that the
 191 single dimensional variables are not the key information, but it is instead their
 192 suitable combination in dimensionless groups that is informative. The values of

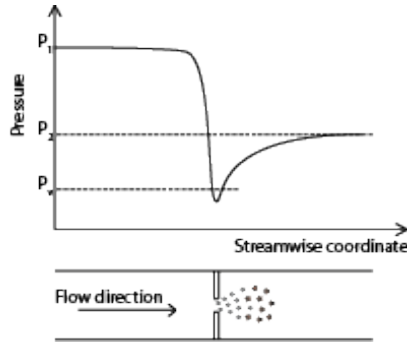


Figure 1: Upper panel reports the qualitative behaviours of the pressure along the centerline. Lower panel shows the formation and successive implosion of cavities.

193 those numbers therefore play the crucial role in determining reactor behavior
 194 and its effectiveness in inactivating bacteria. Aware of this fact, in Table 2 we
 195 report the dimensionless numbers used in the works reported in Table 1. In
 196 many of these studies, the experimental data necessary to calculate the dimen-
 197 sionless parameters were often not explicitly provided. Therefore, in Table 2 a
 198 qualitative comparison is made by simply reporting which non-dimensional param-
 199 eters, among those of Equation 3, were left to vary (“×” symbol) and those
 200 that were kept constant (“√” symbol) in a specific set of trials. Therefore,
 201 this table allows to assess whether the effects of one (or some) non-dimensional
 202 parameters were actually isolated.

203 Table 2 shows that past studies and experiments were designed to investi-
 204 gate/isolate the effects of dimensional, rather than non-dimensional parameters
 205 on disinfection efficiencies. The only non-dimensional group, whose effects were
 206 isolated (by three studies only [46, 12, 47]) is the one related to the initial
 207 concentration, which seems to be negatively correlated with the disinfection ef-
 208 ficiency of orifice-based HC reactors. Therefore, while the available literature
 209 plays a very important role in identifying and quantifying the effectiveness of
 210 HC and different HC reactors, it does not allow to understand and explore the
 211 physical mechanisms underpinning the disinfection efficiencies observed in the
 212 experiments as these could be the effect of multiple variables and associated
 213 physical processes. The authors believe that, in order to progress in this re-
 214 search field, future experimental work should be designed and carried out using
 215 the dimensional analysis framework herein proposed or, if required, different
 216 versions of it.

217 Consistently with this idea, the remaining part of the paper is dedicated to
 218 the presentation of a set of experiments that the authors have carried out in
 219 an orifice plate HC reactor to investigate mainly the effects of one of the afore-
 220 mentioned dimensionless parameter, namely, the cavitation number σ_v . This
 221 parameter is widely used to quantify the intensity of cavitation and is therefore
 222 commonly considered extremely important to characterize disinfection efficien-
 223 cies. In fact, since bubbles implosion is often considered the key physical process

224 responsible for bacterial inactivation (although this hypothesis has recently been
225 challenged, see [37, 29]), it is expected that disinfection efficiencies will be higher
226 for lower σ_v . Experiments were also designed to further investigate the effects
227 of initial bacterial concentration C_0 on disinfection efficiencies.

228 4. Experimental methods

229 All the experiments were carried out in the Water Engineering Laboratory
230 “Giorgio Bidone” at the Polytechnic of Turin (Italy) while bacteria preparation
231 and sample analysis was performed at the Research Centre of SMAT, which is
232 the Water Utility serving the city of Turin. The pilot plant used to induce cav-
233 itation is shown in the upper panel of Figure 2 and it consists in a closed loop
234 pipe (stainless steel, 32 mm internal diameter) including a cylindrical holding
235 tank of 35 l volume (300 x 500 mm). The water temperature was controlled by
236 two chiller-units connected to a cooling coil placed inside the tank. A centrif-
237 gal multistage pump (Lowara 3SV-11, 2900 rpm, 1 kW) was used to recirculate
238 the water and an electromagnetic flow meter (Endress Hauser PROline Promag
239 10) was employed to monitor the flowrate. Two manometers, named M1 and
240 M2 (lower-left panel of Figure 2) were used to monitor P_1 and P_2 , respectively.
241 A ball-valve was used to control P_2 and a transparent control section made of
242 glass (lower-right panel of Figure 2) was used to observe the occurrence of cavi-
243 tation. The cavitation unit was mounted between two flanges and was made of
244 a stainless steel-plate of 16 mm thickness (lower-left panel of Figure 2), where
245 4 holes of 2.5 mm diameter were drilled and arranged in a diamond pattern.
246 Each test consisted in the treatment of 21 l of Milli-Q[®] water contaminated by
247 *E. Coli* bacteria at different concentrations.

248 A reference sample was taken at the beginning of each test, after contam-
249 inated water was mixed within the whole hydraulic circuit for 10 minutes at
250 very low flow-rates that induced no cavitation. Successive samples were taken
251 at different times during each test. Each sample (300 ml), was then stored in
252 sterile plastic bottles that were kept at a constant temperature of 4 °C for a
253 period of maximum 24 hours. The samples were then brought to SMAT labs
254 for microbiological analysis to reconstruct the variation of the bacterial con-
255 centration C with time during each experiment. After each experiment, the
256 entire hydraulic circuit was sterilized by injecting 2 ml of sodium hypochlorite
257 and then rinsed three times. At the end of the procedure a sample was taken
258 to verify the absence of either chlorine- or bacteria-residuals to make sure that
259 following experiments were carried out at identical “circuit” conditions.

260 *E. Coli* was chosen as the reference bacterium for this study since it al-
261 lows a comparison with the works presented so far in the literature. *E. Coli*
262 (ATCC 8739, IELAB) was propagated on Chromogenic Coliform Agar (Oxoid)
263 overnight at 37 °C. Colonies were resuspended in Maximum Recovery Diluent
264 (Oxoid) and live bacteria concentration was measured through absolute ATP
265 quantification by Dendridiag SW reagents (GLBiocontrol) following the man-
266 ufacturer’s instructions. The desired amount of bacteria was then transferred
267 into 1 l of Milli-Q[®] water and further diluted to a final volume of 21 liters of

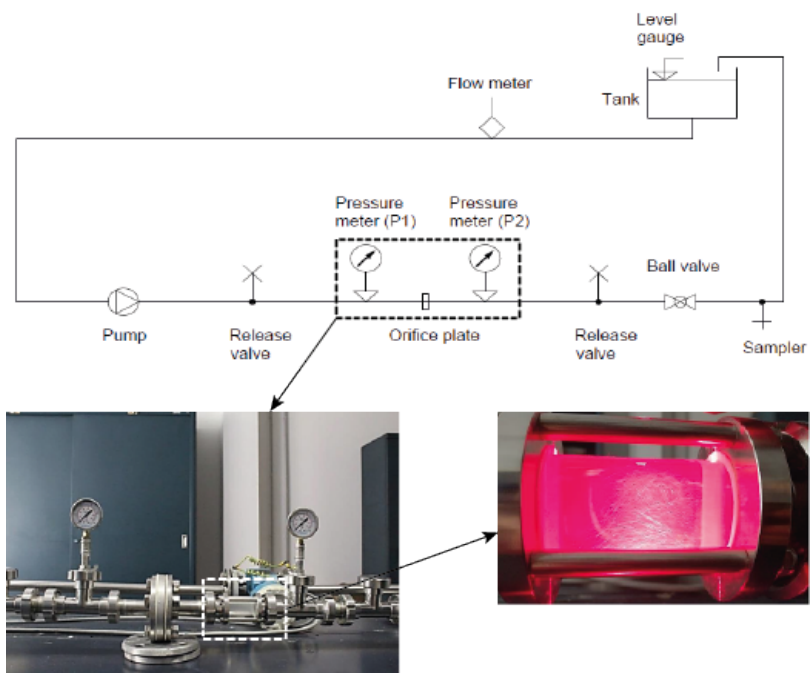


Figure 2: Experimental set-up: upper image shows the schematic representation of the experimental set-up, lower left image shows the orifice plate and pressure measurements points, lower right image shows the transparent test section illuminated by red laser light during disinfection experiments.

Table 2: Dimensional analysis of the works presented in Table 1. ✓: parameters kept constant in all the tests. ×: parameters varied between the tests.

Authors (year)	$C_0 d^3$	$\frac{\rho v_h d}{\mu}$	$\frac{\rho v_h^2 d}{\gamma_s}$	$\frac{D}{d}$	$\frac{b}{d}$	$\frac{P_2 - P_v}{\rho v_h^2}$	n	n_p
Jyoti et al. (2001) [48]	×	×	×	×	×	×	×	×
Kalumuck et al. (2003) (a) [46]	×	×	×	✓	✓	×	×	✓
Kalumuck et al. (2003) (b) [46]	×	✓	✓	✓	✓	✓	✓	✓
Balasundaran et al. (2006) [49]	×	×	×	×	×	×	×	×
Balasundaran et al. (2011) [27]	×	×	×	×	×	×	×	×
Azuma et al. (2007) [50]	×	×	×	×	×	×	×	×
Sawant et al. (2008) [45]	×	×	×	×	×	×	×	×
Arrojo et al. (2008) (c) [12]	×	×	×	×	×	×	×	✓
Arrojo et al. (2008) (d) [12]	×	✓	✓	✓	✓	✓	✓	✓
Loraine et al. (2012) (e) [47]	×	×	×	✓	✓	×	×	✓
Loraine et al. (2012) (f) [47]	×	✓	✓	✓	✓	✓	✓	✓
Wang et al. (2015) (g) [35]	×	×	×	✓	✓	×	×	×
Wang et al. (2015) (h) [35]	×	×	×	×	×	×	×	✓
Badve et al. (2015) [51]	✓	✓	✓	✓	✓	✓	✓	✓
Filho et al (2015) [52]	×	×	×	✓	✓	×	×	×
Liu et al. (2016) [53]	✓	✓	✓	✓	✓	✓	✓	✓
Our results	✓	✓	✓	✓	✓	×	✓	✓
(numerical value)	✓	154 900	65 900	12.8	6.4	×	4	410

268 Milli-Q® water while filling the tank at the inlet of the circuit to reach the de-
269 sired concentration. The starting bacteria concentration of each experiment was
270 confirmed by Colilert Quanti-Tray 2000 assay (IDEXX). *E. Coli* concentration
271 at the different time points was determined by Colilert Quanti-Tray 2000 assay
272 (IDEXX) according to standard procedures [54].

273 Three groups of experiments were performed to analyze the effect of dif-
274 ferent cavitation numbers σ_v on the disinfection efficiency. As expressed in
275 Equation (4), assuming constant temperature conditions (and hence constant
276 values of fluid properties such as P_v , γ_s , ρ and μ), the variables involved in the
277 computation of σ_v are the recovery pressure P_2 and the orifice fluid velocity
278 v_h . The former was directly measured, whereas the latter was estimated simply

Table 3: Hydraulic and geometric characteristics of the orifice plate reactor.

σ_v	Configuration	Holes area	Q	v_h	P_1	P_2	V	t
[-]		[m^2]	[l/s]	[m/s]	[bar]	[bar]	[l]	[min]
0.20	4x2.5 mm	1.96E-05	0.6	30.5	7.5	0	21	30 - 360
0.40	4x2.5 mm	1.96E-05	0.6	30.5	7.5	1	21	30 - 120
0.65	4x2.5 mm	1.96E-05	0.6	30.5	7.5	2	21	30 - 240

279 as the ratio between the flow rate and the holes area (see also the discussion
280 section for more details on the definition of v_h and its shortcomings).

281 The downstream recovery pressure (or back-pressure) P_2 was varied by
282 means of the ball-valve (see Figure 2) in order to vary σ_v . As shown in Ta-
283 ble 3, the other parameters (orifice velocity and flow rate) were kept constant
284 and so were all the non-dimensional parameters identified in Equation 3).

285 In the first group of experiments the configuration characterized by $\sigma_v = 0.20$
286 was studied. Seven tests with initial concentration C_0 between 10^2 CFU/100 ml
287 and 10^5 CFU/100 ml were carried out. The duration of the experiments varied
288 between 120 and 360 minutes, which correspond to a number of passages $n_p \sim$
289 205 and 620, respectively. Samples were taken every 30 minutes.

290 The second group of experiments was performed at $\sigma_v = 0.40$. Six experi-
291 ments with initial concentration between 10^2 CFU/100 ml and 10^4 CFU/100 ml
292 were performed. The total duration of the tests was 120 minutes ($n_p \sim 205$)
293 and samples were taken every 30 minutes.

294 In the last group of experiments, the configuration with $\sigma_v = 0.65$ was
295 studied. Three tests of 240 minutes ($n_p \sim 410$) with initial concentrations
296 between 10^3 CFU/100 ml and 10^6 CFU/100 ml were performed. Samples were
297 taken at 60, 120, 180 and 240 minutes.

298 Two control experiments were performed by removing the orifice plate to
299 investigate the effects of the pump on disinfection efficiencies. In those scenar-
300 ios the flow rate was higher due to the absence of the orifice plate. The initial
301 concentration was 10^2 CFU/100 ml and the tests lasted for 120 minutes, cor-
302 responding to ~ 360 passes (the number of passes in this case is higher due
303 to the higher flow rate). Samples were taken every 30 minutes. The bacterial
304 concentration remained constant for the entire duration of the experiment.

305 During all the orifice-plate experiments, and the control experiments without
306 the orifice-plate reactor, the water-temperature was controlled by means of two
307 chiller units. It is finally pointed out that for all hydrodynamic configurations,
308 the ball-valve was always working in a non cavitating regime and, therefore, it
309 never played any role in the game of disinfection.

310 5. Results

311 Figure 3 shows C/C_0 vs n_p curves for each individual trial. In order to avoid
312 overcrowding of the figure, the 95% confidence intervals (as estimated from the
313 Quanti-Tray/2000 method 54) associated with each experimental data-point,
314 are reported in Table 5 in Appendix B. Figure 3 indicates that the orifice plate
315 employed in the experiments caused a reduction in bacterial concentration in
316 all the experimental configurations investigated. Confidence intervals associ-
317 ated with each measurement (see Table 5) are quite large and make it difficult
318 to identify statistically-significant trends. However, it seems that, contrary to
319 what reported in the previous literature 12, 46, the initial concentration value
320 C_0 of bacteria (or its dimensionless counterpart $C_0 d^3$) have no clear effect on
321 the non-dimensional disinfection efficiencies at all the cavitation numbers in-
322 vestigated. Moreover, contrary to what reported in the literature 12, 47, the

323 C/C_0 vs n_p curves do not show any obvious initial plateau (or quasi-stationary
 324 phase), which is commonly interpreted as a colony fragmentation, rather than
 325 an effective disinfection phase. However, it should be noted that the concen-
 326 trations of bacteria used herein (much lower than those used by [46, 47]) are
 327 unlikely to generate colonies and therefore this could be the reason underpinning
 328 the observed results.

329 Since no clear effects of the initial concentration were observed, average C/C_0
 330 vs n_p curves were computed from each group of experiments corresponding to
 331 each cavitation number (i.e., each curve is the average of the curves shown
 332 in panels [3a] - [3c]) and are reported in Figure [4a]. In this Figure the shaded
 333 error bars represent the standard deviations of concentration obtained from each
 334 experiment group. As previously predicted, Figure [4a] shows that the average
 335 C/C_0 vs n_p curves drop faster for lower values of the cavitation numbers σ_v .
 336 This is in agreement with the idea that a more intense cavitation (i.e., a lower
 337 σ_v) promotes a more efficient disinfection.

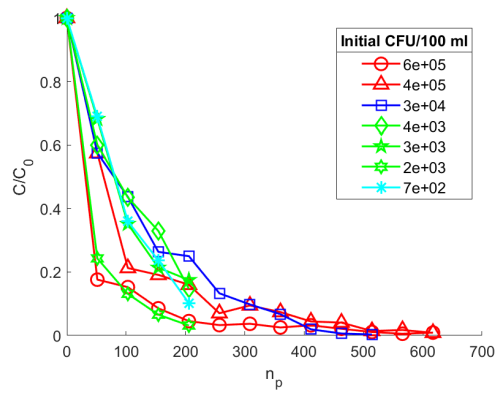
338 The series of mean disinfection values were then fitted by the exponential
 339 law $C/C_0 = \exp(-r \cdot n_p)$ as shown in Figure [4b], in order to obtain the bacterial
 340 reduction rate, r , typical of each cavitation number. Aiming to a fair com-
 341 parison, the same number of sampling values were considered for all cavitation
 342 numbers. The rates obtained are reported in Table [4] and confirm that at lower
 343 cavitation numbers correspond higher disinfection rates. The R-square values
 344 shown in Table [4] witnesses goodness of data fitting.

Table 4: Bacterial reduction rates r and coefficients of determination R^2 corresponding to the exponential fitting of the average disinfection curves shown in Figure [4b]

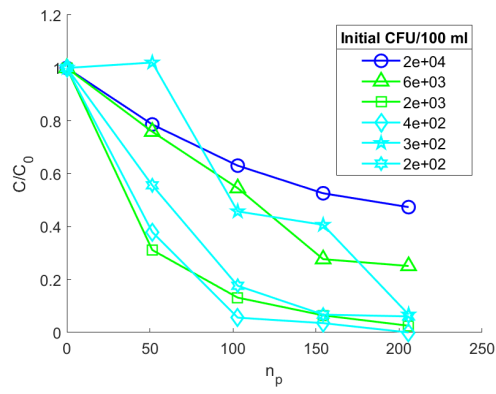
Cavitation number	$r \cdot 10^3$	R^2
$\sigma_v = 0.2$	10.5	0.980
$\sigma_v = 0.4$	9.56	0.993
$\sigma_v = 0.6$	7.10	0.997

345 6. Discussion

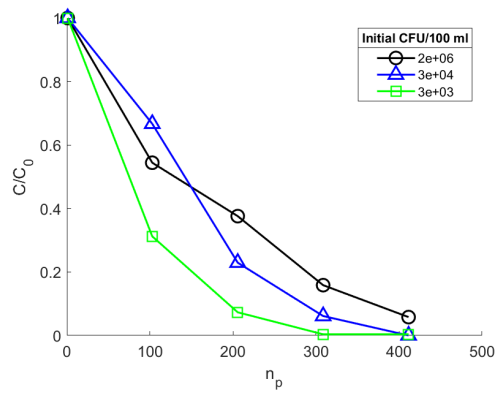
346 It is now important to point out that dimensional analysis represents a valid
 347 starting point for the design of experiments and for the development of empirical
 348 formulae, but it is certainly not free from drawbacks, which are now discussed
 349 to clarify the significance of the results presented herein and frame the scope of
 350 future research-works. A key problem of dimensional analysis is associated with
 351 the fact that it is not always straightforward to rigorously take into consideration
 352 all the factors influencing a problem, often because it is difficult to associate such
 353 factors with well-defined and measurable variables. For example, in the case of
 354 orifice-plates, the onset of cavitation (i.e., the critical number of σ_v below which
 355 cavitation occurs), can be very sensitive to fine experimental-conditions. This
 356 means that if no-control on these details is possible, the cavitation number may



(a) $\sigma = 0.20$

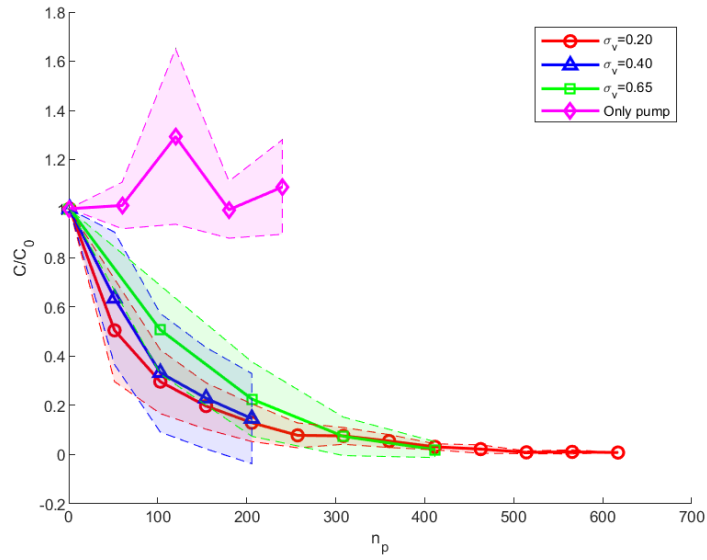


(b) $\sigma = 0.40$

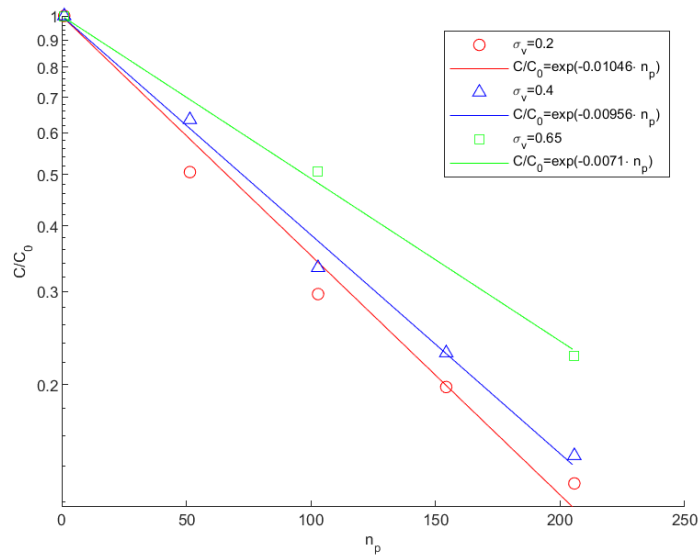


(c) $\sigma = 0.65$

Figure 3: Disinfection efficiency of the orifice-plate reactor at different cavitation numbers. Each color represents a different order of magnitude of *E. Coli* initial concentration (C_0).



(a)



(b)

Figure 4: Average behavior of the disinfection curves at different cavitation number. In the panel (a), the shaded regions correspond to the standard deviation. In the panel (b), the exponential fitting are shown.

357 not represent an objective parameter to quantify consistently the intensity of
358 cavitation among different experiments. In particular, the onset of cavitation
359 may depend on fine geometrical details of the orifice (e.g. small manufacturing
360 defects such as irregular edges of the inlet or artificial roughness due to milling),
361 upstream flow conditions (i.e. velocity statistics, turbulence length-scales and
362 the flow-structure in general) and the chemical properties of water (including the
363 concentration of nuclei) [43]. These are all factors that are difficult to identify
364 with a parameter (or a set of parameters), yet, they can have a measurable effect
365 on disinfection efficiency. In order to circumvent this issue, the experiments
366 presented herein were carried out using always the same hydraulic circuit (which
367 presumably maintained similar flow conditions upstream of the HC reactor), the
368 same orifice-plate (i.e., no changes in the slightest details of the orifice-geometry)
369 and ultra-pure water (which, from the point of view of water-chemistry, should
370 guarantee similar initial conditions). However, it is not always straightforward,
371 especially in applications, to have such controlled conditions, therefore caution
372 should be used when either comparing results from experiments carried out in
373 different facilities or when extending laboratory results to field applications.

374 Another key issue is that it is not easy to perfectly isolate the effect of indi-
375 vidual non-dimensional parameters, often because technical limitations prevent
376 to control or monitor the actual value of some dimensional parameters. For ex-
377 ample, the experiments presented herein were designed to isolate the effects of
378 the cavitation number σ_v as, for each series of trials, the other non-dimensional
379 parameters listed in Equation (3) were assumed to be constant. A key hypoth-
380 esis underpinning this argument is that v_h , could be estimated from continuity
381 principles, as the ratio between the flow rate and the holes area. This is rep-
382 resentative of the velocity at the downstream end of the holes in the case of
383 non-cavitating flows. When cavitation occurs, it is well known that, due to the
384 pressure drop caused by flow separation at the orifice inlet, a cloud of water-
385 vapor forms, meaning that the flow exiting from the orifice is multiphase with
386 an average density and velocity, which are very difficult to measure/control and
387 are clearly dependent on the cavitation number [55, 56]. Therefore, strictly
388 speaking, besides σ_v , the non-dimensional parameters containing v_h (i.e. the
389 Reynolds and the Weber number) probably varied a little among different tests
390 pertaining to the same group (i.e. the same value of σ_v). Whether such vari-
391 ations can have significant effects on the disinfection efficacy remains an open
392 question. One of the difficulties in providing an answer to this question and,
393 more generally, in the use of empirical approaches, is that dimensional analysis
394 is only a tool to find links between dimensional variables but hardly gives any
395 hint to understand the processes controlling the problem of interest, which is a
396 key prerequisite for the interpretation of experimental data. Moreover, this lack
397 of understanding makes it difficult to quantify the effects of non-dimensional pa-
398 rameters other than through blind data-fitting, whose validity is often limited
399 to the dataset it is applied to.

400 Within this context, the authors claim that, one of the tightest bottlenecks
401 for the development of efficient HC reactors is the complete lack of understand-
402 ing of what, from a purely mechanical point of view, kills bacteria. This is

403 because, in HC reactors, besides imploding bubbles, many other processes are
404 triggered, which could be harmful to microorganisms. For example, Dular and
405 co-workers [57, 29], argue (and provide good evidence) that fast and abrupt
406 pressure differences are much more effective than imploding bubbles in killing
407 pathogens in water. Moreover, there is quite a substantial literature demonstrat-
408 ing that turbulence can induce fluid stresses that can be lethal to microorganisms
409 [44]. Until it will not be possible to quantify the sensitivity of microorganisms
410 to fluid shear and normal stresses (and to the non-dimensional parameters that
411 control the magnitude of such stresses), it will be extremely difficult to design
412 and optimize HC reactors or other mechanically-based means of water disinfection.
413
414

415 7. Conclusions

416 The interest in the use of HC as a water-disinfection technique has grown
417 fast in the recent years, both from an academic and an industrial point of
418 view. The studies available from the literature have proved that HC is a very
419 promising and flexible technique which can be used alone or in series with other
420 methods (e.g., chlorination). However, robust and reliable design tools that
421 allow to go from the laboratory to full scale applications are, to the best of
422 the authors' knowledge, not available yet. This is clearly caused by the fact
423 that cavitating flows are poorly understood, and hence difficult to model, as
424 they involve turbulent multiphase flows occurring in complex geometries, which
425 leave little hope to theoretical or computational modeling approaches.

426 As a result of this complexity, the vast majority of the literature approaches
427 the problem from an empirical point of view. Empirically-derived design-relations
428 can be very effective but must be determined from a large number of experi-
429 ments, which must be designed and carried out on the basis of a rigorous dimen-
430 sional analysis. While dimensional analysis is customarily adopted to tackle an
431 enormous amount of engineering problems within the remit of Fluid Mechanics,
432 it has surprisingly never been adopted within the field of HC and this represents
433 a major shortcoming the present paper attempts to address. In particular, by
434 application of dimensional analysis and the Buckingham- π theorem, we have
435 derived Equation (3), which provides a set of non-dimensional parameters gov-
436 erning the simple problem of disinfection via HC triggered by circular orifice
437 plates.

438 On the basis of this set of parameters, a number of experiments were de-
439 signed and carried out to investigate the effects of the cavitation number and
440 the dimensionless initial concentration on disinfection efficiencies. Results from
441 these experiments indicate that C/C_0 vs n_p curves are not influenced by the
442 initial concentration whereas, although heavily masked by experimental uncer-
443 tainty, the effects of σ_v seem to be present. This points towards confirming the
444 significant role played by the formation and implosion of bubbles in the game
445 of disinfection and provides a first step towards the development of effective
446 empirical formulae for the design of HC reactors.

447 However, as discussed in the previous section, the development of effective
448 empirical formulae cannot be left to an arid coupling between experiments
449 and dimensional analysis but must be supported by a sound understanding of
450 the physical processes controlling disinfection in HC reactors. In particular,
451 the authors recommend that future research efforts should be directed towards
452 fundamental studies aiming at understanding the effects of fluid stresses on
453 microorganisms.

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459 **References**

- 460 [1] WHO-UNICEF, Progress on drinking water, sanitation and hygiene: 2017
461 update and sdg baselines, Tech. rep., World Health Organization (WHO)
462 and the United Nations Children’s Fund (UNICEF), available at [https://](https://www.who.int/water_sanitation_health/publications/jmp-2017/en/)
463 www.who.int/water_sanitation_health/publications/jmp-2017/en/
464 (2017).
- 465 [2] WBG, Reducing inequalities in water supply, sanitation, and hygiene in
466 the era of the sustainable development goals : Synthesis report of the wash
467 poverty diagnostic initiative, Tech. rep., World Bank Group, available at
468 <http://hdl.handle.net/10986/27831> (2017).
- 469 [3] S. D. Richardson, M. J. Plewa, E. D. Wagner, R. Schoeny, D. M. DeMarini,
470 Occurrence, genotoxicity, and carcinogenicity of regulated and emerging
471 disinfection by-products in drinking water: a review and roadmap for re-
472 search, *Mutation Research/Reviews in Mutation Research* 636 (1) (2007)
473 178–242 (2007).
- 474 [4] WHO, Guidelines for drinking-water quality: first addendum to the
475 fourth edition, Tech. rep., World Health Organization, available
476 at [https://apps.who.int/iris/bitstream/handle/10665/254636/](https://apps.who.int/iris/bitstream/handle/10665/254636/9789241550017-eng.pdf?sequence=1)
477 [9789241550017-eng.pdf?sequence=1](https://apps.who.int/iris/bitstream/handle/10665/254636/9789241550017-eng.pdf?sequence=1) (2017).
- 478 [5] A. Mahulkar, A. Pandit, *Analysis of Hydrodynamic and Acoustic Cavita-
479 tion reactors; numerical and experimental analysis, applications, operations
480 and scale-up*, VDM Verlag Dr. Müller, 2010 (2010).
- 481 [6] D. D. Joseph, Cavitation and the state of stress in a flowing liquid, *Journal
482 of Fluid Mechanics* 366 (1998) 367–378 (1998).
- 483 [7] Y. G. Adewuyi, *Sonochemistry: environmental science and engineering ap-
484 plications*, *Industrial & Engineering Chemistry Research* 40 (22) (2001)
485 4681–4715 (2001).

- 486 [8] S. Arrojo, Y. Benito, A theoretical study of hydrodynamic cavitation, *Ultrasonics Sonochemistry* 15 (3) (2008) 203–211 (2008).
487
- 488 [9] S. Save, A. Pandit, J. Joshi, Microbial cell disruption: role of cavitation,
489 *The Chemical Engineering Journal and the Biochemical Engineering Journal* 55 (3) (1994) B67–B72 (1994).
490
- 491 [10] J. Carpenter, M. Badve, S. Rajoriya, S. George, V. K. Saharan, A. B.
492 Pandit, Hydrodynamic cavitation: an emerging technology for the intensification of various chemical and physical processes in a chemical process industry, *Reviews in Chemical Engineering* 33 (5) (2017) 433–468 (2017).
493
494
- 495 [11] M. Zupanc, Žiga Pandur, T. S. Perdih, D. Stopar, M. Petkovšek, M. Dular,
496 Effects of cavitation on different microorganisms: the current understanding of the mechanisms taking place behind the phenomenon. a review and proposals for further research, *Ultrasonics Sonochemistry* (2019 - in press).
497
498 doi:<https://doi.org/10.1016/j.ultsonch.2019.05.009>
499 URL <http://www.sciencedirect.com/science/article/pii/S1350417719302305>
500
501
- 502 [12] S. Arrojo, Y. Benito, A. M. Tarifa, A parametrical study of disinfection with hydrodynamic cavitation, *Ultrasonics Sonochemistry* 15 (5) (2008) 903–908 (2008).
503
504
- 505 [13] M. Doulah, Mechanism of disintegration of biological cells in ultrasonic cavitation, *Biotechnology and bioengineering* 19 (5) (1977) 649–660 (1977).
506
- 507 [14] P. R. Gogate, Application of cavitation reactors for water disinfection: current status and path forward, *Journal of environmental management* 85 (4) (2007) 801–815 (2007).
508
509
- 510 [15] T. Leighton, *The acoustic bubble*, Academic press, 2012 (2012).
- 511 [16] V. Naddeo, A. Cesaro, D. Mantzavinos, D. Fatta-Kassinos, V. Belgiorno, Water and wastewater disinfection by ultrasound irradiation-a critical review, *Global NEST Journal* 16 (3) (2014) 561–577 (2014).
512
513
- 514 [17] S. Save, A. Pandit, J. Joshi, Use of hydrodynamic cavitation for large scale microbial cell disruption, *Food and Bioproducts Processing* 75 (1) (1997) 41–49 (1997).
515
516
- 517 [18] P. R. Gogate, I. Z. Shirgaonkar, M. Sivakumar, P. Senthilkumar, N. P. Vichare, A. B. Pandit, Cavitation reactors: efficiency assessment using a model reaction, *AIChE journal* 47 (11) (2001) 2526–2538 (2001).
518
519
- 520 [19] P. S. Kumar, M. S. Kumar, A. Pandit, Experimental quantification of chemical effects of hydrodynamic cavitation, *Chemical Engineering Science* 55 (9) (2000) 1633–1639 (2000).
521
522

- 523 [20] P. Milly, R. Toledo, M. Harrison, D. Armstead, Inactivation of food spoilage
524 microorganisms by hydrodynamic cavitation to achieve pasteurization and
525 sterilization of fluid foods, *Journal of food science* 72 (9) (2007) M414–M422
526 (2007).
- 527 [21] M. Ashokkumar, R. Rink, S. Shestakov, Hydrodynamic cavitation-an alter-
528 native to ultrasonic food processing., *Technical Acoustics/Tekhnicheskaya*
529 *Akustika* (9) (2011).
- 530 [22] D. Crudo, V. Bosco, G. Cavaglia, S. Mantegna, L. S. Battaglia, G. Cravotto,
531 Process intensification in food industry: Hydrodynamic and acoustic cavi-
532 tation for fresh milk treatment (2014).
- 533 [23] A. Pandit, J. Joshi, Hydrolysis of fatty oils: effect of cavitation, *Chemical*
534 *Engineering Science* 48 (19) (1993) 3440–3442 (1993).
- 535 [24] G. Ambulgekar, S. Samant, A. Pandit, Oxidation of alkylarenes using aque-
536 ous potassium permanganate under cavitation: comparison of acoustic and
537 hydrodynamic techniques, *Ultrasonics sonochemistry* 12 (1-2) (2005) 85–90
538 (2005).
- 539 [25] G. L. Maddikeri, P. R. Gogate, A. B. Pandit, Intensified synthesis of
540 biodiesel using hydrodynamic cavitation reactors based on the interesteri-
541 fication of waste cooking oil, *Fuel* 137 (2014) 285–292 (2014).
- 542 [26] A. L. Prajapat, P. R. Gogate, Intensification of depolymerization of aque-
543 ous guar gum using hydrodynamic cavitation, *Chemical Engineering and*
544 *Processing: Process Intensification* 93 (2015) 1–9 (2015).
- 545 [27] B. Balasundaram, S. Harrison, Optimising orifice geometry for selective
546 release of periplasmic products during cell disruption by hydrodynamic
547 cavitation, *Biochemical engineering journal* 54 (3) (2011) 207–209 (2011).
- 548 [28] E. F. Karamah, I. Sunarko, Disinfection of bacteria escherichia coli using
549 hydrodynamic cavitation, *International Journal of Technology* 4 (3) (2013)
550 209 (2013).
- 551 [29] A. Šarc, J. Kosel, D. Stopar, M. Oder, M. Dular, Removal of bacteria
552 legionella pneumophila, escherichia coli, and bacillus subtilis by (super)
553 cavitation, *Ultrasonics sonochemistry* 42 (2018) 228–236 (2018).
- 554 [30] B. Balasundaram, S. Harrison, Study of physical and biological factors
555 involved in the disruption of e. coli by hydrodynamic cavitation, *Biotech-*
556 *nology progress* 22 (3) (2006) 907–913 (2006).
- 557 [31] L. Mezule, S. Tsyfansky, V. Yakushevich, T. Juhna, A simple technique
558 for water disinfection with hydrodynamic cavitation: effect on survival of
559 escherichia coli, *Desalination* 248 (1-3) (2009) 152–159 (2009).

- 560 [32] K. Jyoti, A. Pandit, Hybrid cavitation methods for water disinfection: si-
561 multaneous use of chemicals with cavitation, *Ultrasonics sonochemistry*
562 10 (4-5) (2003) 255–264 (2003).
- 563 [33] K. Jyoti, A. Pandit, Ozone and cavitation for water disinfection, *Biochem-*
564 *ical Engineering Journal* 18 (1) (2004) 9–19 (2004).
- 565 [34] D. Maslak, D. Weuster-Botz, Combination of hydrodynamic cavitation and
566 chlorine dioxide for disinfection of water, *Engineering in Life Sciences* 11 (4)
567 (2011) 350–358 (2011).
- 568 [35] Y. Wang, A. Jia, Y. Wu, C. Wu, L. Chen, Disinfection of bore well water
569 with chlorine dioxide/sodium hypochlorite and hydrodynamic cavitation,
570 *Environmental technology* 36 (4) (2015) 479–486 (2015).
- 571 [36] P. R. Gogate, A. M. Kabadi, A review of applications of cavitation in
572 biochemical engineering/biotechnology, *Biochemical Engineering Journal*
573 44 (1) (2009) 60–72 (2009).
- 574 [37] A. Šarc, T. Stepišnik-Perdih, M. Petkovšek, M. Dular, The issue of cavi-
575 tation number value in studies of water treatment by hydrodynamic cavi-
576 tation, *Ultrasonics sonochemistry* 34 (2017) 51–59 (2017).
- 577 [38] V. Moholkar, A. Pandit, Modeling of hydrodynamic cavitation reactors: a
578 unified approach, *Chemical engineering science* 56 (21-22) (2001) 6295–6302
579 (2001).
- 580 [39] P. Kumar, S. Khanna, V. S. Moholkar, Flow regime maps and optimization
581 thereby of hydrodynamic cavitation reactors, *AIChE Journal* 58 (12) (2012)
582 3858–3866 (2012).
- 583 [40] B. Ebrahimi, G. He, Y. Tang, M. Franchek, D. Liu, J. Pickett, F. Springett,
584 D. Franklin, Characterization of high-pressure cavitating flow through a
585 thick orifice plate in a pipe of constant cross section, *International Journal*
586 *of Thermal Sciences* 114 (2017) 229–240 (2017).
- 587 [41] A. Simpson, V. V. Ranade, Modelling of hydrodynamic cavitation with
588 orifice: Influence of different orifice designs, *Chemical Engineering Research*
589 *and Design* (2018).
- 590 [42] G. I. Barenblatt, *Dimensional analysis*, CRC Press, 1987 (1987).
- 591 [43] C. E. Brennen, *Cavitation and bubble dynamics*, Cambridge University
592 Press, 2014 (2014).
- 593 [44] S. Goldberg, Mechanical/physical methods of cell distribution and tissue
594 homogenization, in: *Proteomic Profiling*, Springer, 2015, pp. 1–20 (2015).

- 595 [45] S. S. Sawant, A. C. Anil, V. Krishnamurthy, C. Gaonkar, J. Kolwalkar,
596 L. Khandeparker, D. Desai, A. V. Mahulkar, V. V. Ranade, A. B. Pandit,
597 Effect of hydrodynamic cavitation on zooplankton: a tool for disinfection,
598 *Biochemical Engineering Journal* 42 (3) (2008) 320–328 (2008).
- 599 [46] K. Kalumuck, G. Chahine, C. Hsiao, J. Choi, Remediation and disinfection
600 of water using jet generated cavitation, in: *Fifth International Symposium
601 on Cavitation*. November, 2003, pp. 1–4 (2003).
- 602 [47] G. Loraine, G. Chahine, C.-T. Hsiao, J.-K. Choi, P. Aley, Disinfection of
603 gram-negative and gram-positive bacteria using dynajets[®] hydrodynamic
604 cavitating jets, *Ultrasonics sonochemistry* 19 (3) (2012) 710–717 (2012).
- 605 [48] K. Jyoti, A. B. Pandit, Water disinfection by acoustic and hydrodynamic
606 cavitation, *Biochemical Engineering Journal* 7 (3) (2001) 201–212 (2001).
- 607 [49] B. Balasundaram, S. Harrison, Disruption of brewers' yeast by hydrody-
608 namic cavitation: process variables and their influence on selective release,
609 *Biotechnology and bioengineering* 94 (2) (2006) 303–311 (2006).
- 610 [50] Y. Azuma, H. Kato, R. Usami, T. Fukushima, Bacterial sterilization using
611 cavitating jet, *Journal of Fluid Science and Technology* 2 (1) (2007) 270–
612 281 (2007).
- 613 [51] M. P. Badve, M. N. Bhagat, A. B. Pandit, Microbial disinfection of seawater
614 using hydrodynamic cavitation, *Separation and Purification Technology*
615 151 (2015) 31–38 (2015).
- 616 [52] J. G. Dalfré Filho, M. P. Assis, A. I. B. Genovez, Bacterial inactivation in
617 artificially and naturally contaminated water using a cavitating jet appara-
618 tus, *Journal of Hydro-environment Research* 9 (2) (2015) 259–267 (2015).
- 619 [53] Z. Liu, M. Zhu, C. Deng, H. Su, P. Chen, Z. Wang, Pollutant and mi-
620 croorganism removal from water by hydrodynamic cavitation, *The Open
621 Biotechnology Journal* 10 (1) (2016).
- 622 [54] ISO, Iso 9308-2:2012(e) water quality – enumeration of escherichia coli and
623 coliform bacteria – part 2: Most probable number method, Standard, In-
624 ternational Organization for Standardization, Geneva, CH (July 2012).
- 625 [55] C. Stanley, T. Barber, B. Milton, G. Rosengarten, Periodic cavitation shed-
626 ding in a cylindrical orifice, *Experiments in fluids* 51 (5) (2011) 1189–1200
627 (2011).
- 628 [56] N. Mitroglou, V. Stamboliyski, I. Karathanassis, K. Nikas, M. Gavaises,
629 Cloud cavitation vortex shedding inside an injector nozzle, *Experimental
630 Thermal and Fluid Science* 84 (2017) 179–189 (2017).
- 631 [57] A. Šarc, M. Oder, M. Dular, Can rapid pressure decrease induced by su-
632 percavitation efficiently eradicate legionella pneumophila bacteria?, *Desali-
633 nation and Water Treatment* 57 (5) (2016) 2184–2194 (2016).

634 8. Appendix A

635 Jyoti and Pandit [48] explored the microbicidal effectiveness of various cav-
636 itating reactors for naturally-contaminated bore well water. They made a com-
637 parative analysis of different disinfection techniques, including ultrasonication
638 (AC), high-speed homogenisation (HC), high-pressure homogenisation (HC) and
639 a cavitating valve (HC). In ultrasonication and high-speed/pressure homogeni-
640 sation they treated a small water volume (1 l). For the case of the cavitating
641 valve, they treated 75 l of bore well water at three different pump discharge pres-
642 sures (P_1) of 1.72, 3.44 and 5.17 bar, obtaining an increase in the disinfection
643 efficiency when the pump discharge pressure increased. They observed that HC
644 was, energetically, the most efficient technique, resulting in maximum bacteria
645 concentration drops of 44% at $P_1 = 5.17$ bar. The authors provided confidence
646 intervals of the results estimated via repeated trials but failed to provide details
647 about the geometry of the valve and the cavitation numbers reached during the
648 experiments.

649 Kalumuck et al. [46] used the DynaJets[®] cavitating device to investigate the
650 effects of cavitation on a small volume of 1.5 liters of high concentrated solution
651 of *E. Coli* ($5 \times 10^8 - 2 \times 10^9$ CFU/ml). Four experiments were conducted in
652 a pressure ranges of P_1 between 4.13 and 5.17 bar and a single experiment at
653 10.3 bar, but no information on the associated cavitation number were provided.
654 In the run performed at 10.3 bar, they achieved up to $5 \log_{10}$ reduction in the
655 concentration of *E. Coli* in 30 minutes, while the experiments executed in the
656 pressure range between 4.13 and 5.17 bar shown a $3 \log_{10}$ reduction in the first
657 20 – 40 minutes. Three more experiments were performed at moderate initial
658 concentration of *E. Coli* (10^7 CFU/ml). In this case, they obtained a $3 \log_{10}$ and
659 $5 \log_{10}$ reduction in bacteria concentration at 20 and 30 minutes, respectively.
660 They also reported a bacterial reduction of $0.6 \log_{10}$ attributed exclusively to
661 the pump. No data are provided about the reactors' geometry.

662 Balasundaram and Harrison. [49] investigated the *E. Coli* cell damage due
663 to hydrodynamic cavitation, by analysing the periplasmic and cytoplasmic pro-
664 teins released from the cell wall destruction. A wide range of cavitation numbers
665 σ_v between 0.13 and 0.92 was investigated and the maximum extent of proteins
666 release was found at $\sigma_v = 0.17$. They also investigated the influence of cell
667 growth rate, finding a lower resistance to cavitation of cells grown at a higher
668 growth rate. In a later work [27] they presented the influence of the geometry
669 and the number of orifices on selective release of periplasmic proteins. Config-
670 urations with circular, squared and rectangular orifices were studied. For the
671 same holes-area, the release of total soluble proteins was similar, however the
672 plate with circular holes allowed for a greater release of acid phosphatase. They
673 also studied the influence of the flow rate on the release of acid phosphatase
674 after 1000 passes, finding higher percentage of release for higher flow rates. The
675 best configuration was the one with the higher number of circular holes, were
676 the flow rate was maximum. Unfortunately, in this study no information about
677 initial concentration and bacterial survival rate was provided.

678 Azuma et al. [50] proposed a high pressure cavitating device with two cav-

679 itating orifices in series and a plunger pump capable of discharging pressures
680 up to 1050 bar. The cavitation numbers (σ_v) used in the study varied between
681 0.037 and 0.487, while the upstream nozzle velocity varied between 176 m/s
682 and 384 m/s. No information about the downstream nozzle velocity and cav-
683 itation number were provided. In the second phase of the experiments they
684 compared sterilization rate among Gram-positive (*Bacillus Subtilis*, *Bacillus*
685 *Halodurans*) and Gram-negative (*Escherichia Coli*, *Pseudomonas Putida*) bacte-
686 ria. The disinfection mechanisms suggested in this work are the high shear
687 stresses reached in the orifice and the shock waves generated by bubbles' col-
688 lapses. They achieved a complete disinfection of a mixture of water and *E.*
689 *Coli* in three successive treatments at $\sigma_v = 0.154$. The experiments compar-
690 ing Gram-positive and Gram-negative bacteria resistance to cavitation showed
691 that Gram-positive bacteria are stronger than Gram-negative bacteria under
692 the two conditions studied, namely $\sigma_v = 0.104$ and $\sigma_v = 0.037$. This behavior
693 was ascribed to the more resistant cell-wall of Gram-positive bacteria.

694 Sawant et al. [45] studied the effect of a single orifice plate on the disinfection
695 of the zooplankton in sea water. In all the experiments just once pass through
696 the cavitation device was made. The test loop was composed of a centrifugal
697 pump, a valve and a single orifice-plate positioned in sequence. During the
698 experiments, they isolated the effects of the cavitating valve, the orifice plate
699 and the pump, individually. The maximum percentage of disinfection due to the
700 pump and the valve was 57% while almost 28% of the zooplankton was killed by
701 the pump alone. The maximum percentage of killing achieved with the orifice
702 plate (and the valve fully open) was 82%, related to a cavitation number (σ_v)
703 equal to 14.68. Similar values of disinfection efficiencies were obtained in spite
704 of wide differences in cavitation numbers tested. This behavior was explained
705 as an effect of the weak cell wall of zooplankton.

706 Arrojo et al. [12] compared the disinfection efficiency of different orifice
707 plates and Venturi tubes, varying the numbers of holes, the discharge pres-
708 sure and the initial concentration of *E. Coli*. For an initial concentration of
709 10^7 CFU/ml, they found a higher disinfection efficiency for the configuration
710 with the highest number of holes with the smallest diameter. The experiments
711 performed with orifice plates showed a first stage where the CFU number in-
712 creased. This lag-phase lasted for about 30 minutes and the authors explain this
713 behavior as an effect of bacteria-agglomerates fragmentation. from the compar-
714 ison between the orifice plate and the Venturi-tube they found that, in order
715 to develop the same number of cavitating events, orifices plates need a higher
716 discharge pressure (P_1) than Venturi tubes. They also point out that cavitation
717 achieved with orifice plates is resulting in more violent cavity collapses due to
718 the sudden pressure recovery. Acting on in initial concentration in the interval
719 $10^3 - 10^5$ CFU/ml, they found that, for orifice plates, the higher is the ini-
720 tial concentrantion the lower is the disinfection efficiency while Venturi-tubes
721 showed no correlation between disinfection efficiency (C/C_0) and initial *E. Coli*
722 concentration. In this study the cavitation number for the various trials is not
723 specified.

724 Loraine et al. [47] compared different types of cavitating devices, including

725 the so-called DynaJets[®], orifice plates, the so-called StratoJet[®] and a single
726 orifice DynaSwirl[®], all with the same total holes' area. The first group of dis-
727 infection experiments aimed at comparing the disinfection efficiency associated
728 with different types of gram-negative bacteria. The first test was performed
729 with a single orifice DynaSwirl[®] cavitating jet operating at 2.1 bar. The initial
730 concentration was 10^7 CFU/ml with a test batch volume of 2 litres. Both Kleb-
731 siella Pneumoniae and *E. Coli* underwent a $5 \log_{10}$ reduction in 60 minutes,
732 corresponding to a 99.99% removal. A similar experiment with an 8-orifice
733 StratoJet[®] operating at 16.5 bar and a batch volume of 1.8 l was used to com-
734 pare disinfection efficiency for *E. Coli*, *Pseudomonas Syringae* and *Pseudomonas*
735 *Aeruginosa*. This test showed approximately half efficiency in *E. Coli* disinfection
736 ($5 \log_{10}$ reduction in 120 minutes). Nearly $3 \log_{10}$ decrease in *P. Aeruginosa*
737 concentration was observed in 90 min, while *P. Syringae* concentrations showed
738 a $6 \log_{10}$ reduction in 20 min. These differences in disinfection efficiencies were
739 ascribed to the degree of cross-linking in the peptidoglycan layer of the cell walls.
740 However, when the results are presented as a function of the number of passes
741 through each reactor, the differences in removal efficiency of *E. Coli* between
742 the single orifice DynaSwirl[®] and the 8-orifice StratoJet[®] were relatively small.

743 These authors investigated the DynaSwirl[®] at operating pressure drops
744 ($P_1 - P_2$) of 3.45, 2.1 and 1 bar, corresponding to cavitation numbers (σ_v)
745 of 0.33, 0.5 and 1, respectively. The best disinfection efficiency was found for
746 $P_1 - P_2 = 2.1$. At this pressure drop the authors investigated disinfection
747 efficiencies for *E. Coli* (gram negative) and *B. Subtilis* (gram positive). *B.*
748 *Subtilis* concentrations were reduced by $4.5 \log_{10}$, while *E. Coli* concentrations
749 were reduced by more than $7 \log_{10}$. This experiment confirms that the thick
750 cell wall of gram-positive bacteria is more resistant to cavitation than the thin
751 cell wall of gram-negative species. A sensitivity analysis was carried out by
752 varying the initial *E. Coli* concentration between 10^3 and 10^9 CFU/ml. Gen-
753 eral trends showed a slow initial reduction in the concentration followed by a
754 higher reduction rate until the concentration fell below 100 CFU/ml. The initial
755 lag period, where the bacterial concentration remained approximately constant,
756 lasted longer for higher concentrations, while during the rapid reduction phase
757 the disinfection efficiencies were comparable for all cases. Standard deviation of
758 the bacteria concentrations were calculated from the duplicates of the CFU/ml
759 measurements, but no information about the number of trials were provided.

760 Wang et al. [35] evaluated the effectiveness of hydrodynamic cavitation on
761 bore well water disinfection. They compared the effect of HC alone with a hybrid
762 system whereby HC was combined with the use of sodium hypochlorite and
763 chlorine dioxide. All the hybrid experiments showed an increase in disinfection
764 efficiency. This study also investigates the effects of the reactor geometry (i.e.
765 by varying the number and diameter of holes) and of the inlet pressure (P_1),
766 but no information on the investigated cavitation numbers were provided. All
767 the experiments were carried out using relatively low concentration of *E. Coli*
768 (2500 – 3000 CFU/ml). It was observed that the higher the inlet pressure (i.e.
769 P_1) the higher the disinfection efficiency. Furthermore it was observed that
770 for a given constriction area, more holes of smaller diameter lead to improved

771 disinfection efficiencies. In this study, confidence intervals on the measured
772 concentration are not provided.

773 Badve et al. [51] investigated HC within the context of microbial disinfection
774 of ships ballast water. The initial concentration of microbes for all the exper-
775 iments was around 10^7 CFU/ml. They compared orifice plates and Venturi
776 tubes limiting the number of passes through the devices to 50. Results show
777 that Venturi tubes work better than single orifice plates. No precise information
778 about the cavitation numbers of the various configurations were provided.

779 Filho et al. [52] used a high pressure cavitating jet apparatus to inactivate
780 *E. Coli* in artificially - and natural - contaminated water. For the former, they
781 achieved a disinfection efficiency up to 90% in 15 minutes at 100 bar. After
782 30 minutes, the inactivation rate reached 98.30, 99.96 and 100% at pressure of,
783 80, 100 and 120 bar, respectively. No information about the cavitation number
784 characterizing the system was found. For naturally-contaminated water (i.e., for
785 concentrations of *E.Coli* around 10 – 100 CFU/ml) the disinfection efficiency
786 was independent of the jet pressure. After 30 minutes, inactivation rates of 98.89
787 and 97.31% were reached for discharge pressures of 100 and 50 bar, respectively.
788 Also in this work, confidence intervals on the measured concentration are not
789 provided.

790 Liu et al. [53] used a multi-orifice plate made of 49 holes of 1 mm diameter
791 for the disinfection of *E.Coli*. A single reactor geometry was studied with an
792 initial concentration of bacteria equal to 1.6×10^5 CFU/100 ml. This device
793 reached a disinfection efficiency of 98% in 60 minutes. The authors did not
794 provide information regarding the cavitation number characterizing the system
795 studied as well as they did not indicated the number of trials and the confidence
796 intervals on the measured concentration.

797 9. Appendix B

Table 5: Most Probable Number (MPN) of the CFU values in the single disinfection exper-
iment (run) plotted in Figure 3 with upper and lower limit of the 95% confidence interval
[54].

σ_v	run	t (min)	n_p	MPN/100 ml	Lower limit	Upper limit
0.2	1	0	0	579400	379100	847200
0.2	1	30	51	101900	72700	140400
0.2	1	60	103	88200	62900	120200
0.2	1	90	154	49500	34400	69300
0.2	1	120	206	26200	16600	39700
0.2	1	150	257	18900	11300	30400
0.2	1	180	309	21300	12700	32600
0.2	1	210	360	14600	8200	24600
0.2	1	240	411	18500	11000	29200
0.2	1	270	463	12200	6800	21400
0.2	1	300	514	6300	2900	13700

Table 5: Most Probable Number (MPN) of the CFU values in the single disinfection experiment (run) plotted in Figure 3 with upper and lower limit of the 95% confidence interval 54.

σ_v	run	t (min)	n_p	MPN/100 ml	Lower limit	Upper limit
0.2	1	330	566	3100	700	8900
0.2	1	360	617	5200	1800	10800
0.2	2	0	0	365400	231900	555500
0.2	2	30	51	209800	145500	301100
0.2	2	60	103	77600	55300	104500
0.2	2	90	154	69700	49700	95300
0.2	2	120	206	58300	40500	80600
0.2	2	150	257	25600	15700	38400
0.2	2	180	309	34500	23300	50100
0.2	2	210	360	26900	17100	39800
0.2	2	240	411	16100	12400	32300
0.2	2	270	463	14800	8500	25100
0.2	2	300	514	5100	1700	10600
0.2	2	330	566	6300	2900	13700
0.2	2	360	617	3000	700	7400
0.2	3	0	0	32550	20660	49810
0.2	3	30	51	18720	12610	28100
0.2	3	60	103	14210	10130	19680
0.2	3	90	154	8570	6110	11720
0.2	3	120	206	8130	5790	11140
0.2	3	150	257	4320	2910	6140
0.2	3	180	309	3180	2080	4640
0.2	3	210	360	2180	1340	3390
0.2	3	240	411	630	290	1370
0.2	3	270	463	200	30	710
0.2	3	300	514	100	10	550
0.2	4	0	0	4884	3100	7215
0.2	4	30	51	2481	1623	3719
0.2	4	60	103	2143	1402	3209
0.2	4	90	154	1658	1149	2380
0.2	4	120	206	767	546	1062
0.2	5	0	0	3076	1953	4712
0.2	5	30	51	2098	1455	3011
0.2	5	60	103	1081	770	1472
0.2	5	90	154	657	468	892
0.2	5	120	206	537	383	740
0.2	6	0	0	1664	1154	2340
0.2	6	30	51	404	273	574

Table 5: Most Probable Number (MPN) of the CFU values in the single disinfection experiment (run) plotted in Figure 3 with upper and lower limit of the 95% confidence interval 54.

σ_v	run	t (min)	n_p	MPN/100 ml	Lower limit	Upper limit
0.2	6	60	103	218	134	339
0.2	6	90	154	109	56	195
0.2	6	120	206	52	23	119
0.2	7	0	0	727	476	1049
0.2	7	30	51	501.2	357	688
0.2	7	60	103	261.3	171	399
0.2	7	90	154	172	116	261
0.2	7	120	206	73.8	53	100
0.4	8	0	0	17220	11940	24500
0.4	8	30	51	13540	9650	18400
0.4	8	60	103	10860	7740	15000
0.4	8	90	154	9060	6460	12410
0.4	8	120	206	8160	5820	11030
0.4	9	0	0	5810	4140	7950
0.4	9	30	51	4410	3060	6250
0.4	9	60	103	3170	2070	4660
0.4	9	90	154	1610	930	2680
0.4	9	120	206	1460	820	2460
0.4	10	0	0	2142	1527	2944
0.4	10	30	51	987	723	1337
0.4	10	60	103	441	306	625
0.4	10	90	154	189	113	304
0.4	10	120	206	75	36	149
0.4	11	0	0	410.6	260.6	618.9
0.4	11	30	51	148.3	123.1	177
0.4	11	60	103	21.8	13.4	33.1
0.4	11	90	154	6.3	2.5	12.7
0.4	11	120	206	0	0	0
0.4	12	0	0	295	188	440
0.4	12	30	51	301	197	442
0.4	12	60	103	135	78	234
0.4	12	90	154	120	60	203
0.4	12	120	206	20	3	71
0.4	13	0	0	166.4	115.4	234
0.4	13	30	51	90.8	66.5	123.1
0.4	13	60	103	28.8	18.3	42.7
0.4	13	90	154	11	5.7	20.1
0.4	13	120	206	9.8	4.7	18.4

Table 5: Most Probable Number (MPN) of the CFU values in the single disinfection experiment (run) plotted in Figure 3 with upper and lower limit of the 95% confidence interval 54.

σ_v	run	t (min)	n_p	MPN/100 ml	Lower limit	Upper limit
0.65	14	0	0	1732900	1167700	2709500
0.65	14	60	103	1046200	705000	1509000
0.65	14	120	206	727000	475700	1048900
0.65	14	180	309	290900	190400	446100
0.65	14	240	411	151500	108000	207800
0.65	15	0	0	32700	19000	44400
0.65	15	60	103	21800	13400	33900
0.65	15	120	206	7500	3600	14900
0.65	15	180	309	2000	300	7100
0.65	15	240	411	0	0	370
0.65	16	0	0	2755	1857	4168
0.65	16	60	103	860	613	1155
0.65	16	120	206	201	124	318
0.65	16	180	309	10	1	55
0.65	16	240	411	10	1	55
No Plate	17	0	0	307.6	195.3	471.2
No Plate	17	30	60	344.8	218.9	520.7
No Plate	17	60	120	461.1	292.7	687.9
No Plate	17	90	180	344.8	218.9	520.7
No Plate	17	120	240	344.8	218.9	520.7
No Plate	18	0	0	209.8	145.5	301.1
No Plate	18	30	60	204.6	137.9	306.9
No Plate	18	60	120	185	131.9	256.3
No Plate	18	90	180	204.6	137.9	306.9
No Plate	18	120	240	185	131.9	256.3
No Plate	19	0	0	3448	2189	5207
No Plate	19	10	20	3654	2319	5555
No Plate	19	20	40	4884	3100	7215
No Plate	19	30	60	3255	2066	4981
No Plate	19	60	120	5172	3384	7636
No Plate	19	90	180	3076	1953	4712
No Plate	19	120	240	4352	2762	6500