

UC Berkeley

UC Berkeley Previously Published Works

Title

Experimental Methods for the Study of Hydrodynamic Cavitation

Permalink

<https://escholarship.org/uc/item/45s3419d>

ISBN

978-3-319-49717-4

Authors

Ceccio, Steven L
Mäkiharju, Simo A

Publication Date



2017

DOI

10.1007/978-3-319-49719-8_2

Peer reviewed

Metadata of the chapter that will be visualized in SpringerLink

Book Title	Cavitation Instabilities and Rotordynamic Effects in Turbopumps and Hydroturbines	
Series Title		
Chapter Title	Experimental Methods for the Study of Hydrodynamic Cavitation	
Copyright Year	2017	
Copyright HolderName	CISM International Centre for Mechanical Sciences	
Corresponding Author	Family Name	Ceccio
	Particle	
	Given Name	Steven L.
	Prefix	
	Suffix	
	Division	Department of Naval Architecture and Marine Engineering
	Organization	University of Michigan
	Address	Ann Arbor, MI, USA
	Email	ceccio@umich.edu
Author	Family Name	Mäkiharju
	Particle	
	Given Name	Simo A.
	Prefix	
	Suffix	
	Division	Department of Mechanical Engineering
	Organization	University of California
	Address	CA, Berkeley, USA 
	Email	
Abstract	<p>A review of traditional and novel experimental methods for the investigation of hydrodynamic cavitation is presented. The importance of water quality is discussed, along with its characterization and management. Methods for the direct and indirect experimental determination of cavitation inception are presented. Along with traditional optical visualization, methods of measuring developed cavitation are described, including point and surface electrical probes, optical bubble probes, acoustic measurements, and indirect measurements of noise and vibration. Recent developments in the use of ionizing radiation as a means to visualize cavitating flows are also discussed.</p>	

Experimental Methods for the Study of Hydrodynamic Cavitation

Steven L. Ceccio and Simo A. Mäkiharju

1 **Abstract** A review of traditional and novel experimental methods for the investi-
2 gation of hydrodynamic cavitation is presented. The importance of water quality is
3 discussed, along with its characterization and management. Methods for the direct
4 and indirect experimental determination of cavitation inception are presented. Along
5 with traditional optical visualization, methods of measuring developed cavitation
6 are described, including point and surface electrical probes, optical bubble probes,
7 acoustic measurements, and indirect measurements of noise and vibration. Recent
8 developments in the use of ionizing radiation as a means to visualize cavitating flows
9 are also discussed.

10 1 Introduction

11 Hydrodynamic cavitation can occur in a variety of important liquid flows, including
12 those associated with turbines, pumps, and other turbomachinery, ship propulsors,
13 ventricular assist devices, fuel injectors, and other macro and micro fluidic systems.
14 The presence of cavitation can degrade the performance of these devices, and can
15 lead to excessive noise, vibration, and erosion. However, cavitation can be used to
16 enhance the performance of some systems, such as high-speed underwater vehicles
17 (Ceccio 2010).

18 Given the complexity of many cavitating flows, engineers have often resorted to
19 experimental testing in order to reveal the presence of cavitation and its effect on sys-
20 tem performance. And, for physically large systems such as turbines and propulsors,
21 testing of scale models is often the only practical means of developing an optimized
22 design before its manufacture at full scale. Experimental testing has also been used

S.L. Ceccio (✉)

Department of Naval Architecture and Marine Engineering, University of Michigan,
Ann Arbor MI, USA
e-mail: ceccio@umich.edu

S.A. Mäkiharju

Department of Mechanical Engineering, University of California, CA, Berkeley, USA



© CISM International Centre for Mechanical Sciences 2017

L. d'Agostino and M.V. Salvetti (eds.), *Cavitation Instabilities and Rotordynamic Effects in Turbopumps and Hydroturbines*, CISM International Centre for Mechanical Sciences 575, DOI 10.1007/978-3-319-49719-8_2

1

23 to illuminate the basic processes of cavitating flows, usually through the examination
24 of canonical flows that may be used to study specific cavitating flow processes, such
25 as flows with variable area ducts and Venturis, and over headforms and hydrofoils.

26 The goal of this chapter is to review some experimental methods that have been
27 successfully employed to study hydrodynamic cavitation (e.g., cavitation produced
28 by flowing liquids). However, many of the methods are also useful for examination of
29 cavitation produced by acoustic fields as well as other gas–liquid multiphase flows,
30 including boiling flows. And some are also applicable to gas–solid and liquid–solid
31 flows as well. The focus will be on the experimental methods that are available to
32 researchers as they examine the flow processes that lead to cavitation inception, its
33 development, and its effect on system performance, and its erosive potential rather
34 than the test facility itself. But, a brief summary is provided here.

35 Experimental examination of hydrodynamic cavitation is often performed in a
36 dedicated test facility. These can be broadly classified into flow loops and towing
37 tanks. In the former, a prime mover delivers liquid (usually through flow condition-
38 ers and a contraction) to the inlet of a test section where the cavitating flow will be
39 examined. The flow is then returned (usually after passing through a diffuser where
40 the pressure rises) to the prime mover to continue recirculation. Examples of modern
41 cavitation tunnels are the Grand Tunnel Hydrodynamique (GTH) in France (Lecof-
42 fre et al. 1987), the Large Cavitation Channel (LCC) in the U.S.A. (Etter et al. 2005),
43 and the Hydrodynamics and Cavitation Tunnel (HYKAT) in Germany (Wetzel and
44 Arndt 1994a; Wetzel and Arndt 1994b). Turbomachinery may be tested with closed
45 recirculating flow loops as well, as described by Avellan et al. (1987). Cavitation may
46 also be studied by towing a test article in a stationary liquid, and facilities have been
47 developed to allow for the ambient pressure over the free surface to be varied such
48 that cavitation can form under a variety of flow conditions, such as the Depressurized
49 Wave Basin in The Netherlands (Van der Kooij and De Bruijn 1984). The Interna-
50 tional Towing Tank Committee (ITTC) offers a catalog of many of these facilities,
51 and Brandner et al. (2007) describe the recent design of a modern cavitation tunnel.

52 The capabilities and quality of the test facility is, of course, of central impor-
53 tance to the conduct of experimental investigations of cavitating flows. Many of the
54 criteria used to assess a cavitation test facility are identical to those used for any
55 aerodynamic or hydrodynamic test apparatus, including the uniformity and quality
56 of the freestream flow, including the level of freestream turbulence, and the preci-
57 sion and range over which flow speed and pressure may be fixed. Many of the design
58 requirements and approaches of subsonic wind tunnels presented by Rae and Pope
59 (1984) apply equally to conventional water tunnels.

60 The acoustic characteristics of a cavitation flow facility may also be important
61 to manage, as the acoustic emission of cavitation may be an important aspect of the
62 testing program. The recently developed cavitation flow facility of the Japan Defense
Agency is a modern example of a channel developed with these acoustic considera-

63 tions (Sato et al. 2003). The tunnel was designed to reduce the amount of background
64 noise and reverberation to improve the signal-to-noise ratio of for both noncavitat-
65 ing and cavitating flows. Finally, an important consideration for cavitating flow is
66 management of the freestream water quality, which will be discussed below.

67 2 Characterization and Management of Water Quality

68 The inception and development of cavitation can be strongly related to the amount
69 of free and dissolved gas within the cavitating liquid. Liquid that is supersaturated
70 with dissolved gas and has many large free gas nuclei would be considered “weak”,
71 and cavitation may form where the liquid pressure falls below vapor pressure. Con-
72 versely, liquid that is undersaturated with dissolved gas and has few free gas nuclei
73 can sustain pressures below vapor pressure (e.g., can be in tension), and is considered
74 “strong”. Determination and control of the liquids cavitation “water quality” or “sus-
75 ceptibility” is an important consideration for many experimental studies of cavitating
76 flows. Discussions of the importance of water quality with regard to the conduct and
77 interpretation of cavitation experiments are found in Lecoffre and Bonnin (1979),
78 Kuiper (1985), Gindroz and Billet (1998), Arndt (2002), and Atlar (2002).

79 Cavitation inception occurs when a reduction in the liquid pressure results in a
80 local pressure below the vapor pressure, and the liquid begins to change phase into
81 vapor. Homogeneous nucleation process can occur in the bulk of the liquid as a result
82 of inclusions that naturally form due to the random motion of the liquid molecules
83 (Brennen 1995). Homogeneous nucleation typically requires a significant level of
84 liquid tension, and ultraclean water can sustain tensions of over 30 MPa at room
85 temperature (Mørch 2007). Yet, for many practical situations, cavitation incepts as
86 a result of heterogeneous nucleation whereby nucleation sites within the bulk of
87 the fluid or at solid boundaries grow when exposed to sufficiently strong tension.
88 The characterization of the fluid’s susceptibility to nucleation is an important aspect
89 of many cavitation studies, especially those concerned with inception. In turn, the
90 susceptibility of the flow is related to both the free and dissolved gas content as well
91 as the nature of potential surfaces and flow-borne nucleation sites.

92 Water quality can also affect developed cavitation. For example, the presence of
93 many freestream nuclei can lead to the suppression of sheet cavitation through the
94 formation of traveling bubbles upstream of the cavity separation location (Li and
95 Ceccio 1996; Keller 2001), and diffusion of dissolved gas into a developed tip vortex
96 can significantly alter its core size (Gowing et al. 1995). As a consequence, it is
97 incumbent upon the cavitation research engineer to adequately characterize and, if
98 possible, manage the facility’s water quality before conducting experimental studies
99 and scale testing.

100 2.1 Dissolved Gas Content

101 Henry's law states that the equilibrium amount of a dissolved gas in a liquid at a given
102 temperature is related to the partial pressure of the gas. When the gas concentration is
103 at equilibrium, this is the saturated condition. Then, a reduction in the liquid pressure
104 would result in supersaturation, and outgassing can occur. Likewise, if the pressure of
105 the liquid is increased, the undersaturated liquid can dissolve more free gas. Hence,
106 as a saturated liquid flows into regions of low pressure and cavitates, it is possible
107 that significant amounts of outgassing may accompany any vaporization. Moreover,
108 the level of gas saturation will influence the stability of free gas nuclei, which will be
109 discussed below. The total dissolved gas content can be determined using a van Slyke
110 apparatus developed for measurement of blood gas (Simoni et al. 2002). The van
111 Slyke apparatus uses a vacuum placed over the liquid sample to produce outgassing,
112 and it is quite accurate. Traditionally, the vacuum was created by the movement of a
113 mercury manometer, which has led to its replacement by other methods that do not
114 require the manual manipulation of mercury reservoirs.

115 For many practical applications, the cavitating liquid is water, and the dissolved
116 gases are the main components of air, molecular nitrogen, and oxygen. But, other
117 dissolved gases may be of interest, especially noble gases (Rooze et al. 2013). Mea-
118 surement of dissolved gas content can be achieved with a Total Dissolved Gas Pres-
119 sure (TDGP) probe. A sample of the liquid is placed in a probe beneath a headspace
120 of gas at a known pressure that is separated from the liquid by a permeable mem-
121 brane. Over a period the transfer of dissolved gas into or out of the headspace will
122 change the gas pressure, and this change can then be related to the original dissolved
123 gas concentration of the liquid sample. In order to relate the pressure change to the
124 gas concentration, the chemical composition of the dissolved gases must be known,
125 and some systems combine the probe with a separate instrument to sample and char-
126 acterize the composition of the gas released into the headspace. For air dissolved in
127 water, it is often assumed that the ratio of the dissolved gases track the ratio of nitro-
128 gen and oxygen in air at standard conditions (Yu and Ceccio 1997; Lee et al. 2016). In
129 fact, in many test facilities, only the dissolved oxygen is measured, and it is assumed
130 that the level of oxygen saturation parallels the overall dissolved air concentration.
131 Dissolved oxygen (DO) probes employ a measurement technique similar to that of
132 pH meters. Two electrodes are suspended in a liquid electrolyte, which is separated
133 from the test sample by a semipermeable membrane. A low DC voltage is applied
134 between the electrodes within the electrolyte, and when oxygen molecules from the
135 test liquid cross the membrane, the magnitude of current between the electrodes will
136 change.

137 2.2 Free Gas Content and Cavitation Nuclei

138 Measurement of the free gas content is more difficult. The intent is to characterize
 139 the nucleation sites in the freestream liquid, and a variety of methods have been
 140 proposed and evaluated (Lecoffre and Bonnin 1979; Oldenzien 1982; d'Agostino and
 141 Acosta 1991; Ceccio et al. 1995; Billet 1985; Pham et al. 1999). Freestream nuclei
 142 are any inclusion in the fluid that will cavitate when exposed to a sufficient tension
 143 (as opposed to surface nucleation sites which reside on flow boundaries). An ideal
 144 nucleus is a clean gas bubble, and the nucleation characteristics of such a bubble can
 145 be readily predicted. However, a wider variety of nucleation sites exist in the flow,
 146 including gas pockets on the surface of particles and bubbles that have significant
 147 surface contamination. Nevertheless, it is useful to review the basic nucleation process
 148 of a clean bubble in order to give us a reference to compare with practically observed
 149 nuclei.

150 Consider a nucleus that is a clean gas bubble with a radius R_N that contains vapor
 151 and noncondensable gas. The pressure inside the bubble, $P_B = P_V + P_G$ is the sum of
 152 the partial pressures of the vapor and noncondensable gas, respectively. This pressure
 153 is balanced by the liquid pressure on the bubble surface, P_∞ , such that

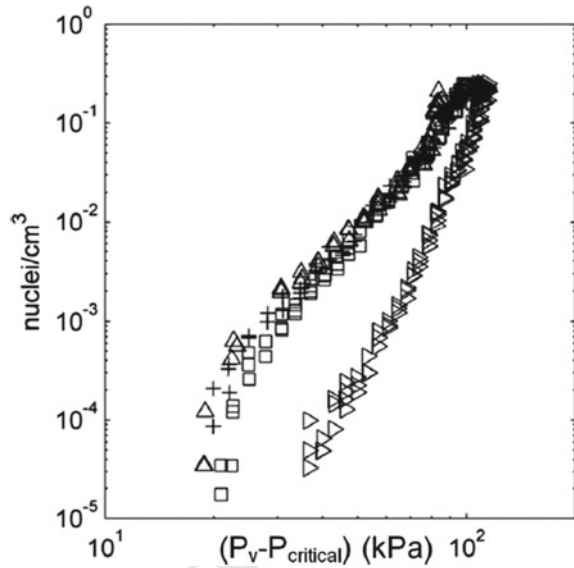
$$154 \quad P_\infty = P_V + P_G - \frac{2S}{R_N},$$

155 where S is the surface tension. When a nucleus experiences a drop in the surround-
 156 ing liquid pressure, the radius may grow quasi-statically from its initial equilibrium
 157 radius to a larger equilibrium radius. However, if a tension is applied below a criti-
 158 cal value, $P_V = P_C - P_\infty$, the radius will grow unboundedly. This critical tension is
 159 given by

$$160 \quad \frac{4S}{3R_N} < P_V - P_\infty < \frac{2S}{R_N}$$

161 (Brennen 1995). Note that since the fluid is in tension, $P_V > P_\infty$, and that the static
 162 pressure is in fact negative. While not all nuclei are clean bubbles, the fluids nuclei
 163 content is often reported as a distribution of nuclei with a given critical radius, R_C .
 164 This is the radius that corresponds to the required critical pressure, P_C , needed to
 165 produce explosive growth of the nucleus. Therefore, the nuclei content of a liquid is
 166 typically reported as a Nuclei Number Density Distribution (*NNDD*) as a function of
 167 R_C , where *NNDD*(R_C) has units of [Number]/[Length]⁻⁴. Then, the number of nuclei
 168 over a range of critical radius ΔR_C is given by *NNDD*(R_C) $\cdot R_C$. Alternatively, if the
 169 bin size of the distribution is fixed, the Nuclei Number Distribution (*NND*) with
 170 units of [Number]/[Length]⁻³ can be presented, as shown in Fig. 1 (Chang et al.
 171 2011). The typical range of nuclei critical radii in test facilities spans 1 micron <
 172 R_C < 500 micron, and the critical tensions range from $0 > P_C > -100$ kPa. Nuclei
 173 concentrations can range widely, with order 1 per cubic centimeter for the smallest
 174 nuclei and order 10 per cubic meter for the largest (Gindroz 1998).

Fig. 1 Example nuclei concentration measured with a centerbody Venturi (Chang and Ceccio 2011). The different spectra are for varying freestream dissolved oxygen levels and concentrations of long-chain polymer

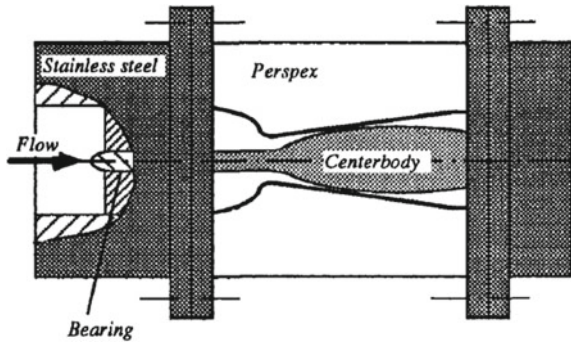


175 2.3 Direct Measurement of the Cavitation Nuclei Distribution

176 Measurement of the nuclei distribution can be accomplished with both direct and
 177 inferred means. In direct methods, a sample of the flow is exposed to a known tension,
 178 resulting in the cavitation of nuclei that incepts at (or above) that critical pressure.
 179 These devices are collectively known as Cavitation Susceptibility Meters (CSMs),
 180 as first discussed by Schiebe (1972). The most common CSM consists of a simple
 181 venture through which the liquid is passed. The pressure in the throat is measured or
 182 inferred, the occurrence of single cavitation events are detected optically, electrically,
 183 and/or acoustically. CSMs of this type have been developed by Oldenziel (1982),
 184 Chahine and Shen (1986), d'Agostino and Acosta (1991), Chambers et al. (2000), for
 185 example. During typical operation, a sample of the freestream liquid is drawn from
 186 the flow facility and delivered to the CSM inlet. Care must be taken to insure that
 187 the sampling process does not significantly alter the nuclei distribution itself. Then,
 188 the flow is passed through the CSM. Changing the flow rate then varies the throat
 189 pressure, and the number of cavitation inception events is counted at each level of
 190 throat tension. Knowledge of the flow rate and throat tension yields the concentration
 191 of nuclei that incept at or above the given tension. This data is then converted into
 192 the nuclei number distribution.

193 One limitation of Venturi-based CSMs is the limited volume of the throat. If the
 194 nuclei distribution is too dense, multiple bubbles may simultaneously form in the
 195 throat, creating a blockage. A solution is to use a centerbody Venturi (Lavigne 1991),
 196 as shown in Fig. 2. Now the high-tension region is an annulus of fluid around the center-
 197 body, increasing the volume of liquid that is in tension. Keller (1987) developed

Fig. 2 Schematic diagram of a centerbody venturi cavitation susceptibility meter (Gindroz and Billet 1998)



198 a CSM that used a swirling flow passed through a vortex to create the region of low
199 pressure.

200 While the operation of a CSM can be somewhat cumbersome, it is a device that
201 directly measures the number of cavitation nuclei and their critical tension. It is
202 important to note that not all nuclei are clean gas bubbles. In fact, particulates with
203 small gas pockets on their surface can readily act as nuclei, and free gas bubbles
204 can be coated by an organic skin, effectively modifying their interfacial properties.
205 (Mørch 2007). Hence, a measurement of the size of the nucleus in the flow may not
206 necessarily yield an accurate measure of its critical tension.

207 **2.4 Indirect Measurement of the Cavitation Nuclei** 208 **Distribution**

209 Indirect measurement of the nuclei distribution can be operationally advantageous,
210 especially if online or in situ measurement is required. Unlike CSMs, indirect mea-
211 surements ascertain some aspect of suspected nuclei, such as its light or acoustic scat-
212 tering properties. From this, the critical tension of the detected nucleus is inferred.
213 As noted above, this relationship may not be easily determined. Nevertheless, the
214 advantages of indirect methods have motivated their development and use.

215 Bubble populations in liquids can be determined via acoustic scattering.
216 Duraiswami et al. (1998) and Chahine and Kalumuck (2003) report on a method
217 that employs the dispersion of sound passing through a bubbly medium. Both the
218 attenuation and phase velocity are measured, and analytical relationships are used
219 to invert these data into the bubble population. Once the bubble population is deter-
220 mined, the cavitation susceptibility can be inferred.

221 Light scattering can be used to detect the presence of nuclei in the flow (Keller
222 1972). Mie scattering by small spherical nuclei can be detected as they pass through
223 a focused region of laser light, for example. A somewhat more sophisticated method
224 employs Phase Doppler Anemometry (PDA), where multiple detectors are used to

225 record the light scattered from a particle passing through the probe volume made
226 by two crossed laser beams (Tanger and Weitendorf 1992). PDA systems can more
227 readily determine the radius and velocity of the presumably spherical nucleus pass-
228 ing through the control volume. Care must be taken to relate the measured event
229 rate to the actual nuclei density, since the effective measurement volume may not
230 be easily determined given that nuclei may not pass directly through the measure-
231 ment volume, for example. And, it is important to discriminate between bubbles and
232 particles as they pass through the probe volume.

233 A direct optical measurement of the nuclei distribution can be made using holo-
234 graphy (Katz et al. 1984; Katz and Sheng 2010). Holographic imaging can yield the
235 absolute nuclei distribution in a volume of fluid, and with proper resolution, can be
236 used to distinguish between bubbles, particulates, and other contaminants. Hence,
237 holography is often used as the calibration standard for other nuclei measurement
238 systems. Holographic systems have been used to measure nuclei distributions both
239 in the laboratory and in the environment (Katz and Acosta 1981; O'Hern et al. 1985).
240 Kawanami et al. (2002) used laser holography to study the structure of a cloud shed
241 from a hydrofoil and estimated the bubble size distribution. Holography is not typ-
242 ically used as a routine nuclei measurement method, but recent advances in both
243 camera technology and digital processing have made its everyday use more feasible.

244 2.5 Management of Water Quality

245 Characterization of the freestream dissolved and free gas content can be an essen-
246 tial component of any experimental test and evaluation effort. Moreover, it may be
247 advantageous to actively manage these quantities through the addition or removal
248 of dissolved gas and freestream nuclei. Besides filtering, the most basic method to
249 control the water quality is through degassing the bulk of the test liquid, and deaer-
250 ation is a common practice to reduce both the free and dissolved gas during testing.
251 Typically, the dissolved gas concentration will be reduced to levels below 50.

252 Control of the water quality can be improved via the active management of the free
253 and dissolved gas content. The major flow facilities that have implemented these sys-
254 tems include the Grand Tunnel Hydrodynamique in France (Lecoffre et al. 1987) and
255 the Australian Maritime College Cavitation Tunnel (Brandner et al. 2007). Figure 3
256 shows an image of latter facility that highlights the means of gas control. The facility
257 is equipped with bulk degassing systems to control the average dissolved gas concen-
258 tration. Additionally, small gas bubbles can be controllably injected directly into the
259 flow upstream of the test section, while both small and large gas bubbles are removed
260 downstream of the test section via gravity separation, coalescence, and resorption. In
261 this way, the nuclei distribution can be prescribed and maintained during an experi-
262 ment.

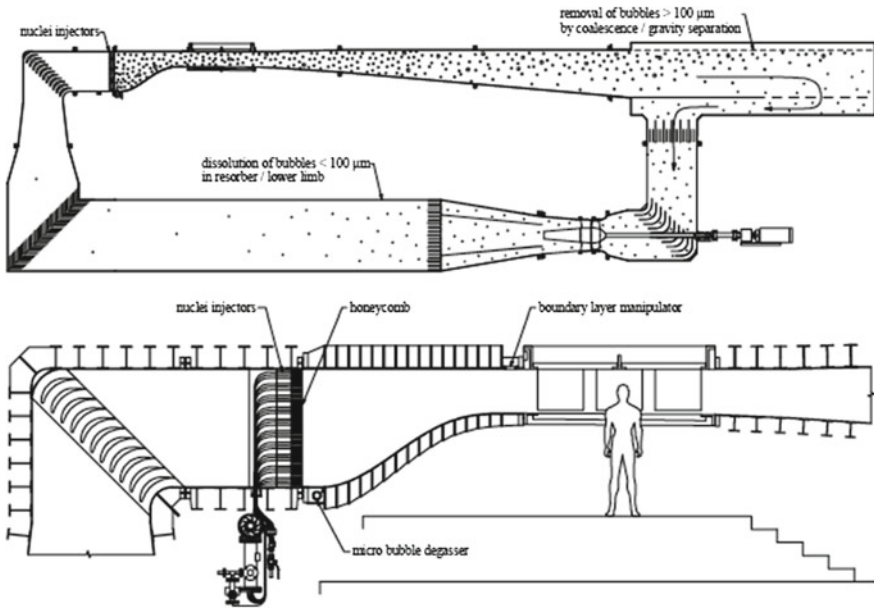


Fig. 3 A schematic diagram of the water quality management systems of the Australian Maritime College Cavitation Tunnel (Brandner et al. 2007). Nuclei can be injected upstream of the test section, and the tunnel is designed to remove gas by separation, coalescence, and resorption

263 3 Detection and Measurement of Incipient Cavitation

264 Cavitation inception occurs when cavitation is first observed in the flow, and the
 265 determination of inception conditions is important characterization of the flow itself
 266 as well as an important consideration for the scaling of the performance of model
 267 hydraulic systems. Inception usually occurs when the first freestream or surface
 268 nuclei encounter sufficient tension in the flow field to cavitate. Since a distribution
 269 of nuclei exists in the flow, and the pressure field producing the tension can often
 270 have important contributions from flow unsteadiness, inception is usually a stochastic
 271 process. Therefore, the average flow conditions under which inception is determined
 272 is, many cases, subjective. Moreover, the extent of cavitation chosen as necessary
 273 to call inception can vary widely. In some cases, such as the characterization of
 274 naval systems, only a minimal amount of cavitation is required to call inception, and
 275 the cavitation may not be easily visible to the naked eye. Conversely, limited cavitation
 276 may not be of practical interest to the operators of industrial hydraulic systems,
 277 and inception would be called only when the amount of cavitation begins to alter the
 278 performance of the device. And finally, proper use of inception observations in the
 279 scaling of model hydraulic systems to full scale is also of vital importance. Acosta
 280 and Parkin (1975) and Rood (1991) review the basic elements of cavitation inception
 281 for a variety of cavitation forms.

3.1 Detection of Inception with Acoustic, Vibration, and Force Measurements

Since the presence of incipient cavitation will many times be accompanied by emission of sound from the cavitating nuclei, the detection of inception is often accomplished through acoustic means. Hydrophones can be placed directly within the flow field (Ran and Katz 1994), within the cavitating test article itself (Ceccio and Brennen 1991; Kuhn de Chizelle et al. 1995) or in acoustically coupled chambers that are separated from the flow by an acoustic window (Choi and Ceccio 2007). Since the acoustic impedance of acrylic ($3.1 \times 10^6 \text{ Pa s / m}^3$) is only about twice that of

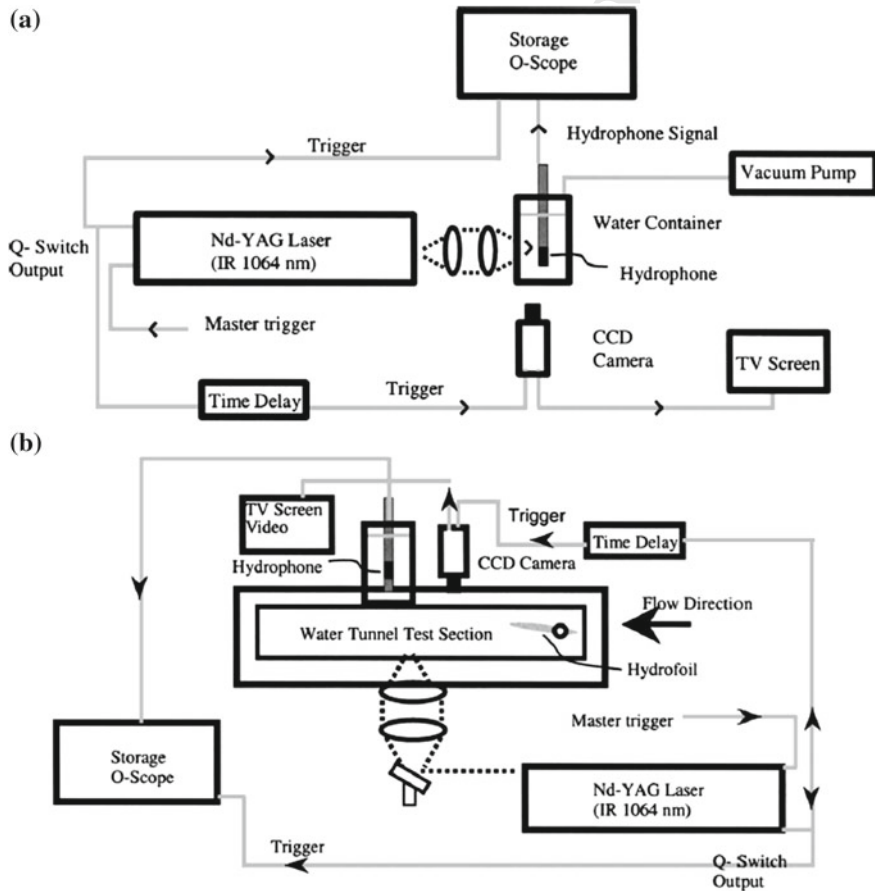


Fig. 4 Schematic diagram of the quiescent laser-induced cavitation bubble experiment (a) and a bubble-vortex interaction experiment (b). A single laser pulse is used to create a cavitation bubble in the bulk of the fluid from Oweis et al. (2004). The acoustic emission of the bubble is captured with a hydrophone within the flow (a) and in an external chamber through an acoustic window (b)

291 water ($1.5 \times 10^6 \text{ Pa s / m}^3$), it is commonly used as a rigid acoustic flow boundary.
 292 (A metal boundary would be much more reflective, with impedance mismatches in
 293 excess of ten times that of water.) Fig. 4 shows two typical setups from Oweis et al.
 294 (2004).

295 The noise produced by incipient cavitation bubbles often takes to form of discrete
 296 bursts or pulses, and example sound traces are shown in Fig. 5 from Chang and Cec-
 297 cio (2011). In this case, the bubbles were formed in the cores of stretched vortices,

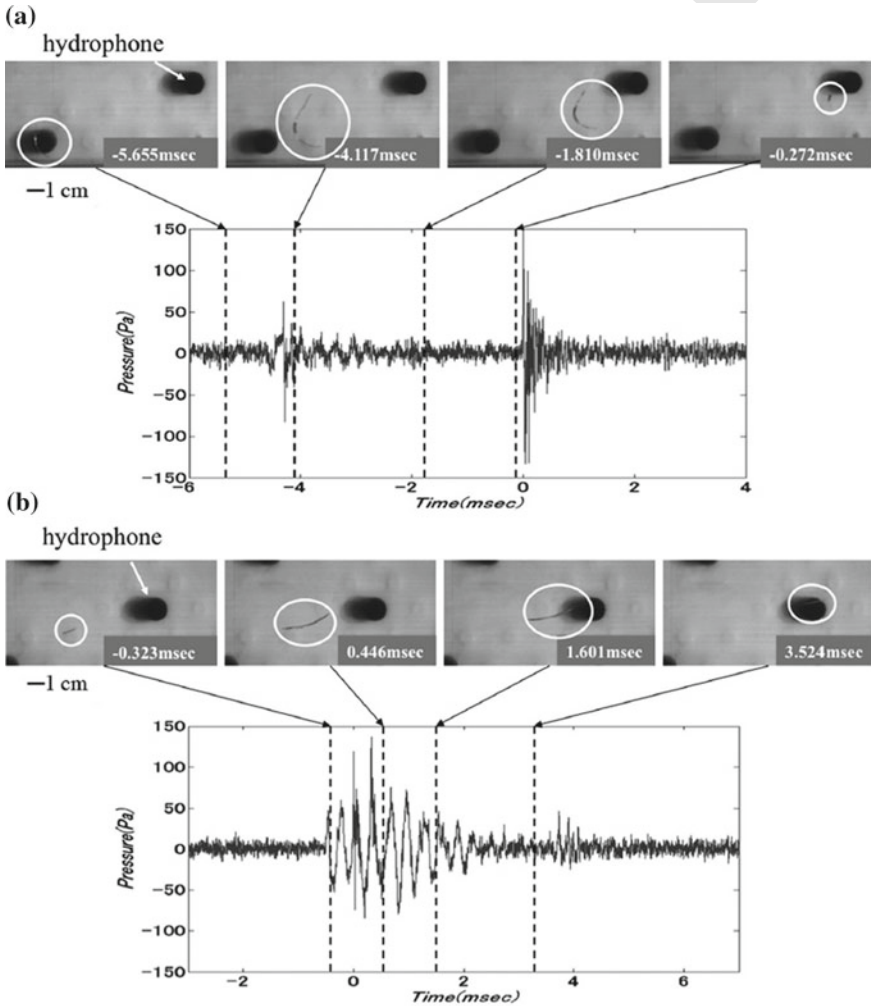


Fig. 5 Images and sound traces of a growing and collapsing vortex cavitation bubble in the secondary vortex producing an **a** acoustic “pop” and **b** a “chirp”. The broadband acoustic pulse was abrupt lasting approximately 1 ms (Chang and Ceccio 2011)

298 and the sounds recorded from individual bubbles could be a pulse (“pop”) or a
299 periodic tonal burst (“chirp”). The hydrophone array can be seen in the image, and,
300 in this case, an array of hydrophones was used to localize the sound source (Chang
301 and Dowling 2009).

302 As the cavitation develops, the amount of sound emitted and the cavitation’s
303 effect on the overall flow begins to increase. Hence, measurement of vibration and
304 changes to the system performance (e.g., lift coefficient, flow coefficient, efficiency)
305 can be used to call inception. See, for example, Arndt (1981), McNulty and Pearsall
306 (1982), Shen and Dimotakis (1989), and Koivula (2000). Indirect methods of incep-
307 tion detection are often calibrated against visual observations when optical access
308 to the incepting flow is available. Escaler et al. (2006) report on a comprehensive
309 study that illustrates how cavitation inception can be detected using measurements
310 of structural vibrations, acoustic emissions, and hydrodynamic pressures measured
311 in turbomachinery where optical access may be limited or unavailable.

312 **3.2 Optical Measurement and Light Scattering for Inception** 313 **Detection**

314 Direct visual observations of incepting nuclei are often used to call inception. Tradi-
315 tionally, the flow is illuminated with stroboscopic lighting, and a human observer is
316 tasked with determining which conditions have produced detectable and sustained
317 cavitation. The availability of high-speed video systems have enabled the digital
318 recording and analysis of the incepting flow, making inception calls with the naked
319 human eye less common. However, at the first moments of inception, the cavitation
320 bubbles may be quite small and difficult to locate; and they may occur infrequently.
321 Such limited event rate cavitation inception is difficult to discern with visual detec-
322 tion alone, and the camera systems can be synchronized with acoustic detection sys-
323 tems (see, for example, Gopalan et al. (1999) and Chang and Ceccio (2011)). If the
324 location of inception is known a priori, then focused light scattering can be used to
325 detect the onset and rate of bubble formation. Keller (1972) developed such a system
326 by directing a focused light source into the inception region of a headform and then
327 into a photodetector. The presence of the bubble in the measurement volume would
328 block the light to produce a signal.

329 **4 Optical Measurement of the Cavitating Flow Field**

330 Many optically based methods that have been developed for fluid measurements can
331 also be effectively employed to study cavitating flows. General reviews of optical
332 methods are provided by Goldstein (1996) and Tropea et al. (2007), and these meth-
333 ods and their applications are wide ranging and varied. With this in mind, this section
334 will concentrate on the use of optical methods in cavitating flows.

335 4.1 High-Speed Imaging

336 The need to study the dynamics of cavitation has stimulated the development of high-
337 speed imaging. From the early work of Benjamin and Ellis (1966), Kling and Ham-
338 mitt (1972), and Lauterborn and Bolle (1975), high-speed photography has played
339 a key role in understanding bubbly dynamics and cavitation. A recent review by
340 Thoroddsen et al. (2008) provides a good summary of the history and recent methods.
341 As the resolution and frame rate of high-speed digital imaging systems has improved,
342 the ability for detailed examination of cavitating flows has significantly improved.
343 Frame rates of order 1 KHz with spatial resolution of $10^3 \times 10^3$ pixels are now com-
344 monly available, and cameras with much higher imaging speeds are commercially
345 available. Ultrahigh-speed imaging systems have been created as well, with frame
346 rates in excess of 1 million per second. Such systems can resolve the fine details
347 of cavitation bubble dynamics, as shown by Lauterborn and Hentschel (1985), Ohl
348 et al. (1995), and Obreschkow et al. (2006).

349 The study of high-speed bubble dynamics often requires the controlled creation
350 of single or multiple bubbles. In many cases cited above, a laser pulse is focused
351 to create the bubble in the imaging region of the camera. The bubble creation can
352 then be synchronized with the imaging system. This technique can be used to con-
353 trollably place nuclei into the freestream flow as well, as shown by Choi and Ceccio
354 (2007). Figure 6 presents a time series from high-speed imaging of a laser-induced
355 bubble from Ohl et al. (1998), including a schematic of the setup and an example
356 of an aspherically collapsing bubble with detected luminescence. And, Fig. 7 shows
357 images of a vortex cavitation bubble formed after a laser-induced nucleus was cre-
358 ated within the upstream core of the vortex.

359 4.2 Laser Doppler Velocimetry and Light Scattering Methods

360 Laser Doppler Velocimetry (LDV) (also known as Laser Doppler Anemometry) is a
361 well-established technique to measure local flow velocity. In this method, two beams
362 of laser light are crossed within the flow domain to create a probe volume consisting
363 of an interference pattern of light. As flow-borne particles pass through the probe
364 volume, the scattered light from the fringe pattern is detected. The frequency of the
365 light “burst” is related to the fringe spacing (and fringe velocity if one laser beam
366 is frequency shifted) and the velocity of the particle. If it can be assumed that the
367 particle travels at the local flow speed, inference of the particle velocity yields a
368 nonintrusive measurement of the flow velocity. Laser beams with multiple colors
369 (wavelengths) can be used to measure two or three components of the flow speed
370 in the same probe volume. A comprehensive review of this method can be found in
371 Durst (1982) and Goldstein (1996).

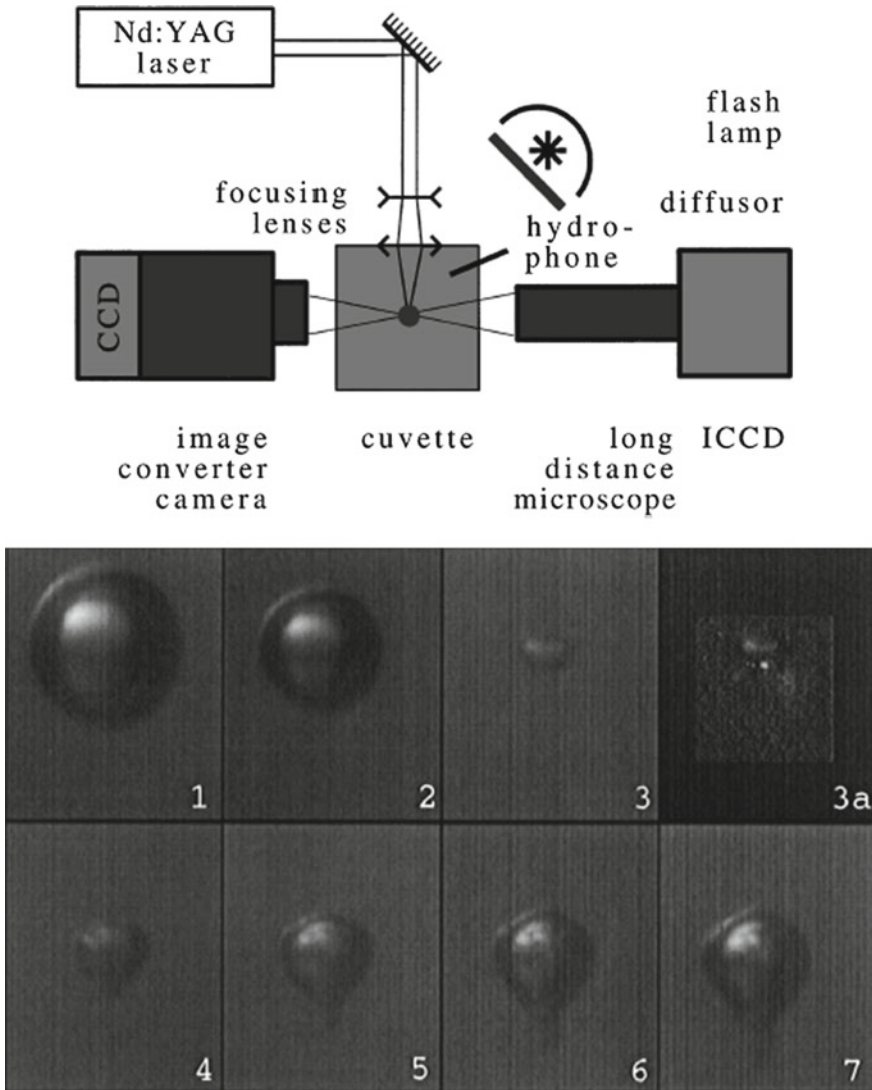


Fig. 6 High-speed imaging of a laser-induced bubble from Ohl et al. (1998). A schematic of the setup used to create the laser-induced bubbles is shown in along with images of an aspherically collapsing bubble with detected luminescence

LDV can be a useful method to examine cavitating flows. Kubota et al. (1989) used conditional sampling of the LDV for velocity measurements in a flow around a shedding partial cavity, as shown in Fig. 8. More recently, Roth et al. (2002) used similar methods to examine the cavitating flow in a fuel injector. In these cases, LDA was used to measure the velocity of the liquid flow around and outside the

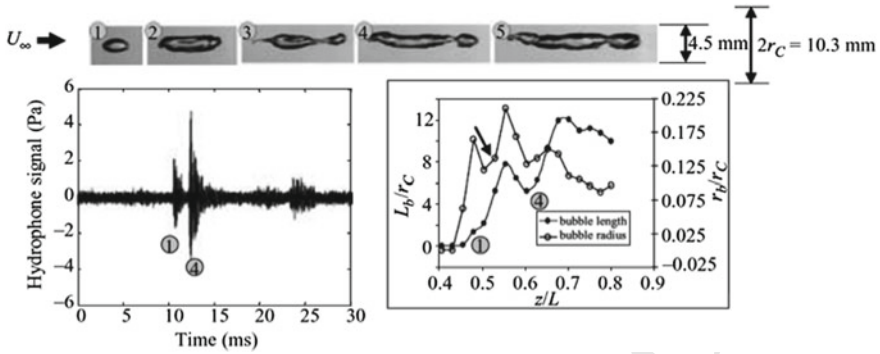


Fig. 7 Images of a vortex cavitation bubble created by a laser-induced nucleus; the images were used to compute the length and average radius of the bubble as a function of position within the Venturi. Also shown is the corresponding acoustic signal detected from a hydrophone Choi and Ceccio (2007)

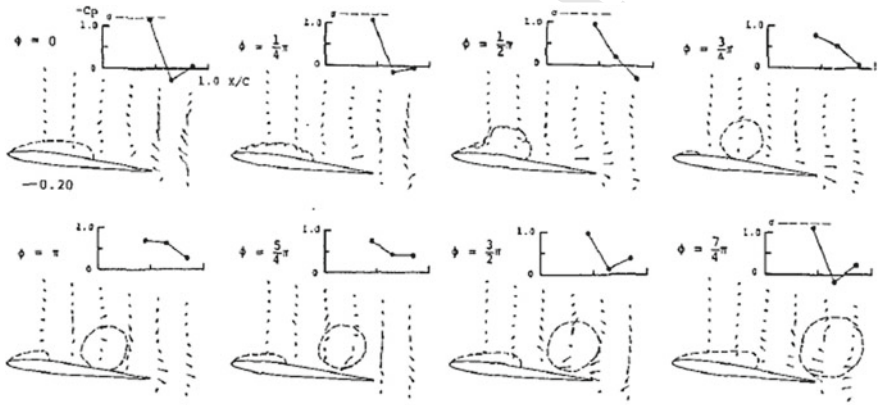


Fig. 8 Local measurements of flow velocity acquired with Laser Doppler Velocimetry were conditionally sampled and correlated to the measured surface pressure during the shedding of cloud cavitation on a hydrofoil (Kubota et al. 1989)

377 region developed cavitation. When employing LDV in this way, it is important to
 378 determine if the flow tracers are small seed particles or small bubbles generated by
 379 the cavitation itself since large bubbles may not necessarily behave as Lagrangian
 380 flow tracers, especially in regions of high turbulence and shear.

381 4.3 Particle Imaging Velocimetry

382 Particle Imaging Velocimetry (PIV) is a full-field method used to measure two or
383 three components of the flow velocity in a plane or volume. In this method, the flow
384 is densely seeded with flow tracers, and a plane or volume of the flow is illuminated
385 with pulsed laser light. Two or more images of the flow tracers are compared to
386 determine the motion of the tracers over a known time interval, and the motion of
387 many particles are analyzed to determine the spatial distribution of velocities within
388 the illuminated flow region. Since PIV's development in the 1990s there have been
389 significant advances in its development and use, and a general review is provided by
390 Adrian and Westerweel (2011). The use of PIV to study disperse multiphase flows
391 has also been progressing. In these cases, care is taken to distinguish the tracer par-
392 ticles (which are intended to be nonintrusive) from those that constitute the disperse
393 phase itself, such as larger particles or bubbles. Hassan et al. (1992), Lindken and
394 Merzkirch (2002), and Balachandar and Eaton (2010) provided examples of PIV
395 applied to such disperse multiphase flows.

396 As in the case of LDV, PIV can be used to study the low void fraction flow around
397 developed cavitation. Examples include the work of Vogel and Lauterborn (1988),
398 Leger and Ceccio (1998), Leger et al. (1998), Gopalan and Katz (2000), Laberteaux
399 and Ceccio (2001a), Laberteaux and Ceccio (2001b), Dular et al. (2005), and Foeth
400 et al. (2006). Figure 9 presents results from Foeth et al. (2006), who examined the
401 dynamic flow around shedding partial cavities. The figure shows the steps needed to
402 separate the images of the PIV tracer particles from the cavity and resulting bubbly
403 flow. Synchronization of the image acquisition with periodically shedding cavity
404 flows can yield phase-averaged flow data.

405 For limited cavitation, PIV can be used to interrogate the flow in and around the
406 cavitation bubbles. Examples include Ran and Katz (1994), Iyer and Ceccio (2002),
407 and Straka et al. (2010) who examined inception and bubble-vortex interactions in
408 shear flows, and Wosnik et al. (2003) who examined the bubbly wake of supercavi-
409 ties. Figure 10 presents an example of the use of PIV in limited cavitating flows from
410 Iyer and Ceccio (2002) who examined the influence of cavitation on the dynamics of
411 a planar shear layer. The setup and an example image of the cavitating shear layer are
412 shown in (a), and the mean flow and vorticity profiles are shown in (b) for increasing
413 levels of cavitation (void fraction) in the shear layer. Recent advances in PIV sys-
414 tems include digital holographic PIV, micro-PIV, tomographic (volume) PIV, and
415 high frame-rate cinematographic PIV. All of these methods have the potential to bring
416 new insights into our understanding of cavitating flows.

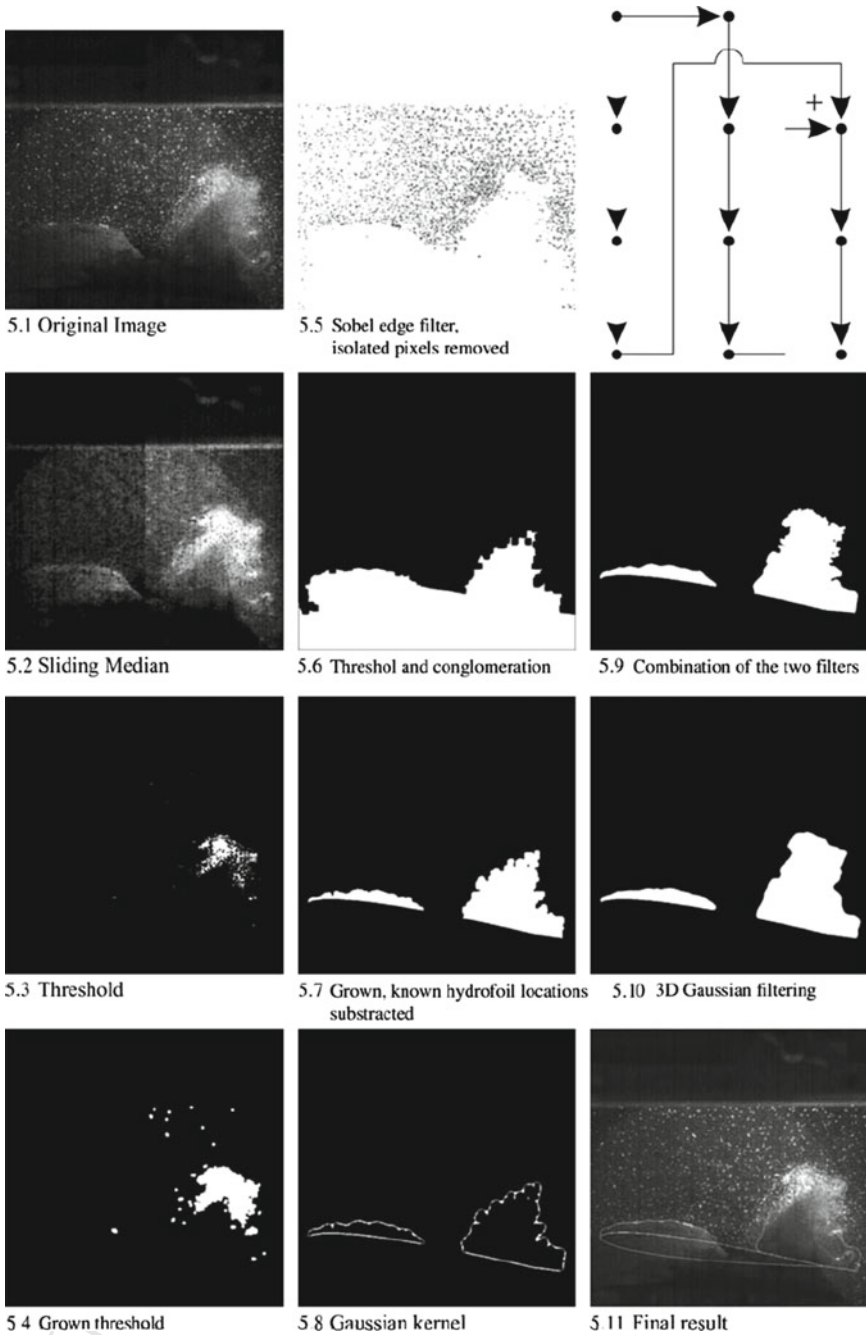


Fig. 9 The image processing steps employed by Foeth et al. (2006) to determine the flow field around a developed cavitation forming on a twisted hydrofoil

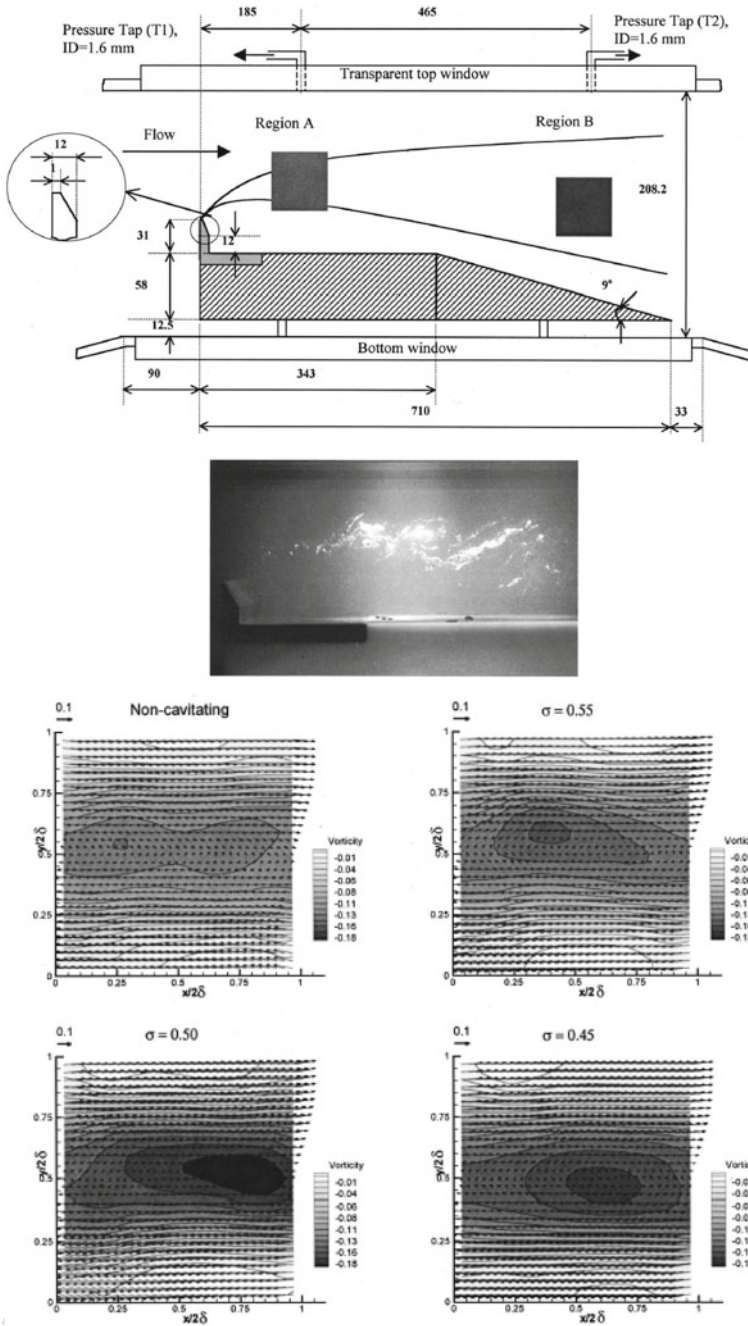


Fig. 10 Examination of the influence of cavitation on a shear layer using PIV (Iyer and Ceccio 2002). The setup and an example image of the cavitating shear layer are shown in (a) and (b), and the mean flow and vorticity profiles are shown in (c) for increasing levels of cavitation (void fraction) in the shear layer

5 Measurement of Cavity Flows with High Void Fraction

As the void fraction of the cavitating flow begins to exceed a few percent, the bubbly flow becomes opaque, and optical methods such as LDV and PIV begin to fail due to multiple scattering of the incident and reflected light. For very high void fraction flows, alternative techniques must be used, as described below.

5.1 Surface Pressure, Acceleration, and Forces

Cavitating flows with high void fraction often occur near solid boundaries, and it is therefore possible to place instruments close to or flush against the cavitating surface. The most common flush-mounted instruments measure the static and dynamic pressure. These measurements can be combined with local or average acceleration and forces on the test article to help elucidate the underlying flow. For example, Kjeldsen et al. (2000) measured the static and dynamic pressures on the surface of a cavitating hydrofoil, along with the time-varying lift force. Callenaere et al. (2001) employed dynamic and ultrasonic transducers to measure the reentrant flow beneath a partial cavity, and Le et al. (1993) employed arrays of dynamic pressure transducers to examine the unsteady pressures developed by partial cavitation. Escaler et al. (2006) illustrated how a range of nonoptical methods can be used to detect and quantify cavitation in turbomachinery, including external vibrations and noise signatures.

5.2 Electrical Impedance Probes

Since the gas and liquid phases of the cavitating flow have quite different electrical properties, measurements of the local or average mixture impedance can be used to infer the void fraction of the flow, and a review of these general methods is provided by Ceccio and George (1996). Measurement of the mixture impedance can be accomplished with flush-mounted electrodes or intrusive probes, albeit the latter may excessively perturb the cavitating flow. The electrodes can be made large enough to measure the bulk-averages void fraction, or small enough to measure the local void fraction or the passage of individual gas pockets. A high-frequency alternating current can be applied as the probing signal, making the temporal response of the transducers very rapid. However, as the path lines of the applied current are strongly affected by the presence of the gas phase, it is not always possible to fix the measurement volume of the probe. And, the relationship between the measure bulk impedance and the void fraction may not be straightforward. For bubbly flows, a mixture relationship can be developed that can relate the bulk impedance to the void fraction and electrical properties of the liquid and gas components (Hewitt 1978;

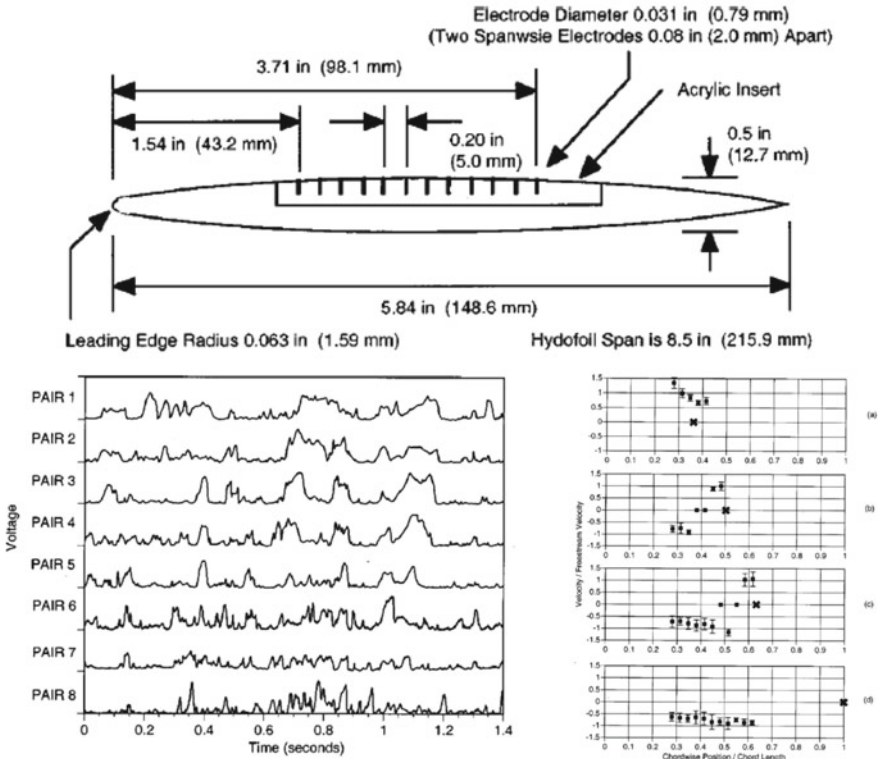


Fig. 11 The near-surface gas-phase velocity beneath a partial cavity measured with flush-mounted electrical impedance probes (George et al 2000a). The electrode locations on the hydrofoil (a), sample voltage signal transduced from the probes (b), and the gas-phase velocity determined through cross-correlation of the signals (c)

451 George et al. 2000b). But such relationships will generally fail for highly stratified
 452 flows.

453 Flush-mounted impedance probes have been used successfully to quantify cavi-
 454 tating flows. Examples include the work of Ceccio and Brennen (1991) and Kuhn de
 455 Chizelle et al. (1995) for the study of traveling bubble cavitation; and Ceccio and
 456 Brennen (1992), Pham et al. (1999), and George et al (2000a) for the study of partial
 457 cavitation. Cross-correlation of signals from multiple electrodes can be used to deter-
 458 mine the gas-phase interface velocity, as reported by George et al (2000a) (Fig. 11).
 459 Intrusive conductivity probes with one or more electrode pairs have also been devel-
 460 oped for gas-liquid flows, as discussed by Wu and Ishii (1999), Lucas and Mishra
 461 (2005), and Elbing et al. (2013).

462 5.3 Fiber Optic Probes

463 Fiber optic probes can be used to detect the presence of bubbles and gas–liquid inter-
464 faces via the difference in the index of refraction between the liquid and gas. The end
465 of the fiber is placed in the flow, and light is directed toward the sharpened tip. If
466 the tip is immersed in the pure liquid, the majority of the light will be transmitted
467 into the fluid. But, if gas is present at the tip, the light will internally reflect within
468 the fiber and return to its source to be detected. Fiber optic probes have been suc-
469 cessfully employed to measure bubble size populations, average void fraction, phase
470 speed, and interfacial area density, and a review is provided by Boyer et al. (2002)
471 and Chang et al. (2003). The performance of optical and conductivity probes for
472 measurement of bubbly flow was compared by Le Corre et al. (2003). The use of
473 intrusive optical probes in cavitating flow has been limited due to the probes, delicate
474 construction and their ability to perturb the flow, but such probes were successfully
475 used to study the dynamics of partial cavitation by Stutz and Reboud (2000) and
476 Stutz (2003). Figure 12 presents the probe employed by Stutz and Reboud (2000) to
477 measure the bubbly flow within a partial cavity, the time traces from two probes that
478 can be used to measure the local volume fraction and phase speed, and an exam-
479 ple data set showing the average volume fraction within the cavity. As in the case
480 of electrical impedance probes, care must be taken to carefully determine how the
481 signal transduced from the probe relates to the flow quantity of interest (e.g., bubble
482 size and velocity) and what the influence volume of the probe may be. Single point
483 probes have shown the best results when they are oriented in a flow with a strong
484 rectilinear velocity and when the probe tip is small compared to the bubbles to be
485 measured (Cartellier 1992; Mäkiharju et al. 2013).

486 Images of a high void fraction bubbly cavitating flow were acquired by Coutier-
487 Delgossa et al. (2006) by traversing an endoscope within a partial cavity flow. They
488 were able to demonstrate that the bubbly flow within the cavity often consists of
489 highly distorted gas bubbled, as shown in Fig. 13.

A02

490 5.4 Ionizing Radiation

491 The use of X-ray and gamma-ray densitometry and tomography for the study of
492 multiphase flows has been well established, and reviews are provided by Kumar et al.
493 (1997), George et al. (2000b), and Heindel (2011). These methods have also been
494 applied for the study of high void fraction cavitating flows.

495 The underlying principal of these systems relies the material and density depen-
496 dent attenuation coefficient of high-energy photons as they pass through the multi-
497 phase mixture. When a beam of high-energy X-ray photons, for example, encounters
498 the mixture, a fraction of the photons passes through without scattering or absorp-
499 tion, and this fraction depends on the mixture's attenuation coefficient, μ , density, ρ ,
500 and thickness, x . For a beam encountering a domain with N distinct materials, the

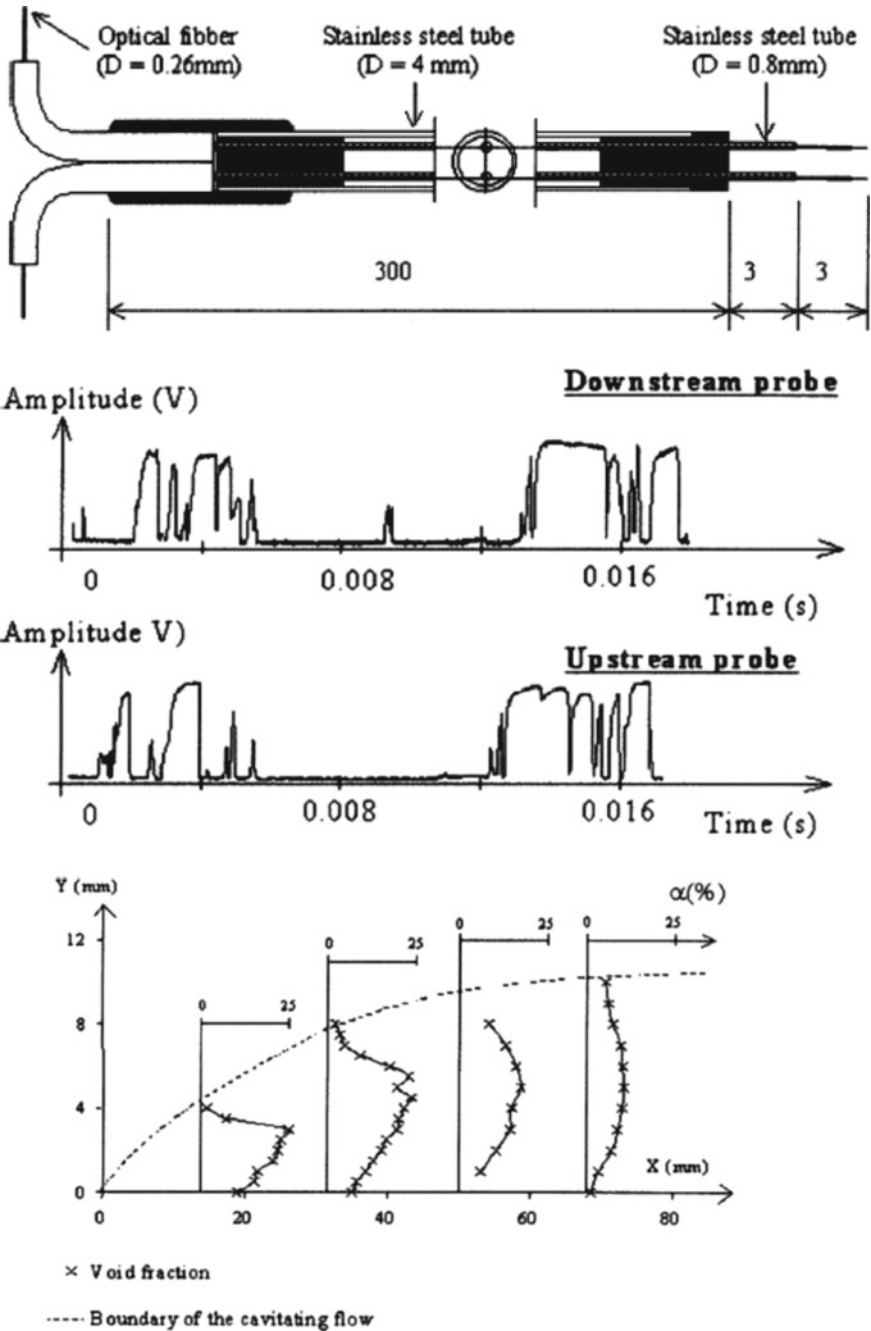


Fig. 12 The fiber optic probe used by Stutz and Reboud (2000) to measure flow within a partial cavity (a), example the time traces from two probes that can be used to measure volume fraction and phase speed (b), and a plot showing the average volume fraction within the cavity (c)

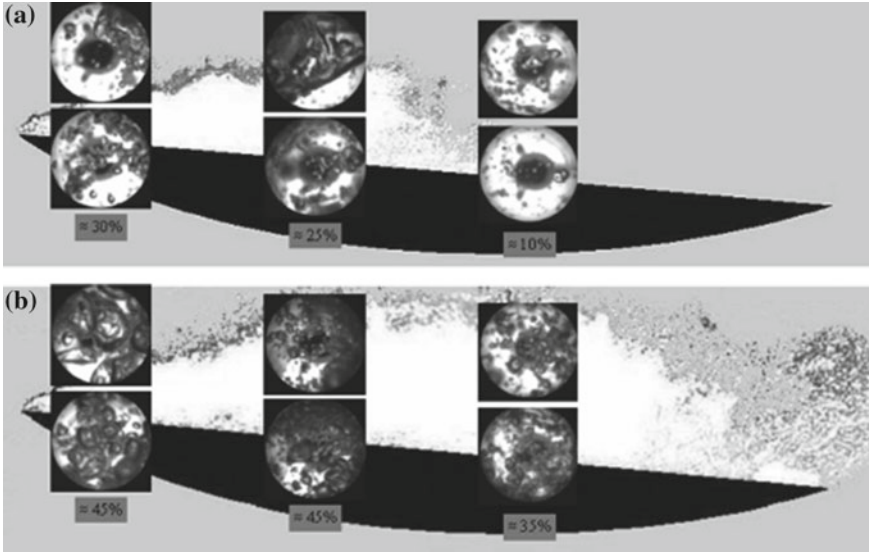


Fig. 13 Images of the bubbly flow within a partial cavity obtained by traversing an endoscope into the bubbly mixture (Coutier-Delgousha et al. 2006)

501 Beer–Lambert law provides a relationship between the transmitted, I , and incident, I_O , beam intensity:

503
$$\frac{I}{I_O} = e^{-\sum_{n=1}^N x_n \mu_n / \rho_n}$$

504 The attenuation coefficient is a function of material properties and photon energy,
 505 and is a known property for most common materials. Given this relationship, we can
 506 determine the void fraction, α , of a two-phase mixture, M , of liquid, L , and gas, G ,
 507 for a monochromatic beam of photons:

508
$$\alpha = \ln \left(\frac{I_M}{I_L} \right) / \ln \left(\frac{I_G}{I_L} \right)$$

509 The transmitted beam intensities I_L , I_G , and I_M are values obtained for the pure
 510 liquid, pure gas, and mixture, respectively. For densitometry, average mixture void
 511 fraction is determined along a known linear beam path, while tomography involves
 512 the reconstruction of the two- or three-dimensional spatial distribution of attenuation
 513 through many measurements of linear path-averaged attenuation.

514 Stutz and Legoupil (2003) used X-ray densitometry to nonintrusively measure
 515 void fraction in a partial cavity. The setup consisted of a single row of 24 detectors
 516 that could acquire void fraction profiles along a line at a rate of 1000 samples per
 517 second. The measurements were compared with optical probes, and it was found
 518 that the maximum void fraction for the case of periodic shedding was about 25%.

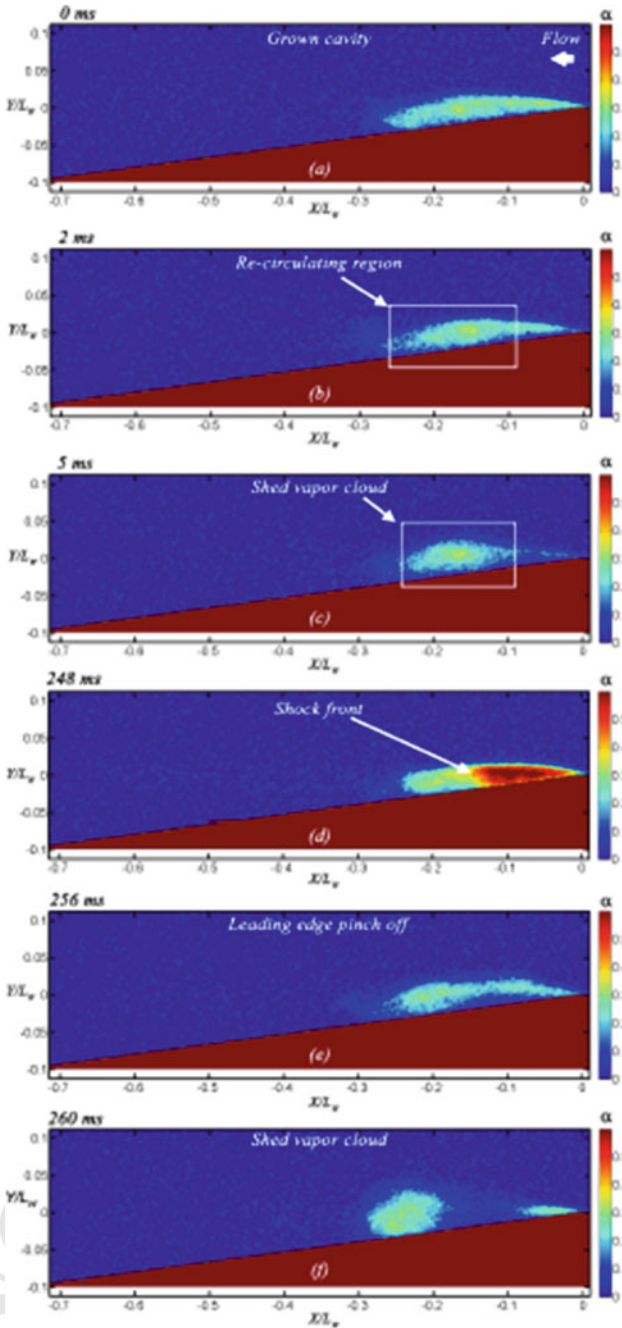


Fig. 14 A time series of X-ray densitometry-based images of a shedding partial cavity illustrating the presence of a condensation shock (Ganesh et al. 2016)

519 Coutier-Delgosha et al. (2007) used the same diagnostic setup to measure void frac-
 520 tion profiles on a plano-convex foil. They reported a maximum averaged void frac-
 521 tion values of close to 60% with instantaneous values exceeding 85%. These systems
 522 provided the time- and phase-averaged void fraction averaged across the span of the
 523 cavity. Mäkiharju et al. (2013) recently developed an cinemagraphic X-ray densito-
 524 metry system that measures two-dimensional void fraction flow fields of gas–liquid
 525 flows, and this system was used to examine the dynamic void fraction within shed-
 526 ding partial cavities with frame rates up to 1000 per second Ganesh et al. (2016).
 527 Figure 14 shows X-ray densitometry images of the partial cavity forming at the apex
 528 of a wedge revealing the presence of a condensation shock. While the spatial and tem-
 529 poral resolution of these radiation-based techniques is presently nonideal for many
 530 cavitating flows, rapid technological advances (e.g., in X-ray detectors) will make
 531 these nonintrusive techniques increasingly useful.

532 **Acknowledgements** The first author is grateful to Prof. Salvetti and Prof. d’Agostino for their
 533 invitation to the Udine summer course on cavitating flows. The authors wish to acknowledge the
 534 support of the U.S. Office of Naval Research and the U.S. Naval Sea Systems Command for their
 535 ongoing support of their research.

536 References

- 537 Acosta, A. J., & Parkin, B. R. (1975). Cavitation inception—a selective review. *Journal of Ship*
 538 *Research*, 19(4), 193–205.
- 539 Adrian, R. J., & Westerweel, J. (2011). *Particle image velocimetry*. Cambridge University Press.
- 540 Arndt, R. E. (1981). Cavitation in fluid machinery and hydraulic structures. *Annual Review of Fluid*
 541 *Mechanics*, 13(1), 273–326.
- 542 Arndt, R. E. (2002). Cavitation in vortical flows. *Annual Review of Fluid Mechanics*, 34(1), 143–
 543 175.
- 544 Atlar, M. (2002). Final report of the specialist committee on water quality and cavitation. In *Pro-*
 545 *ceedings of the 23rd ITTC*.
- 546 Avellan, F., Henry, P., & Ryhming, I. L. (1987). A new high speed cavitation tunnel for cavitation
 547 studies in hydraulic machinery. *Proceedings of international cavitation research facilities and*
 548 *techniques* (Vol. 57, pp. 49–60). Boston: ASME Winter Annual Meeting.
- 549 Balachandar, S., & Eaton, J. K. (2010). Turbulent dispersed multiphase flow. *Annual Review of*
 550 *Fluid Mechanics*, 42, 111–133.
- 551 Benjamin, T. B., & Ellis, A. T. (1966). The collapse of cavitation bubbles and the pressures thereby
 552 produced against solid boundaries. *Philosophical Transactions of the Royal Society of London*
 553 *A: Mathematical, Physical and Engineering Sciences*, 260(1110), 221–240.
- 554 Billet, M. L. (1985). *Cavitation nuclei measurements—a review*. Forum: Proceedings of ASME
 555 Cavitation and Multiphase Flow.
- 556 Boyer, C., Duquenne, A. M., & Wild, G. (2002). Measuring techniques in gas-liquid and gas-liquid-
 557 solid reactors. *Chemical Engineering Science*, 57(16), 3185–3215.
- 558 Brandner, P. A., Lecoffre, Y., & Walker, G. J. (2007). Design considerations in the development
 559 of a modern cavitation tunnel. *Proceedings of the 16th Australasian fluid mechanics conference*
 560 (pp. 630–637).
- 561 Brennen, C. E. (1995). *Cavitation and bubble dynamics*. Cambridge University Press.
- 562 Callenaere, M., Franc, J. P., Michel, J., & Riondet, M. (2001). The cavitation instability induced by
 563 the development of a re-entrant jet. *Journal of Fluid Mechanics*, 444, 223–256.

- 564 Cartellier, A. (1992). Simultaneous void fraction measurement, bubble velocity, and size estimate
 565 using a single optical probe in gas-liquid two-phase flows. *Review of Scientific Instruments*,
 566 63(11), 5442–5453.
- 567 Ceccio, S. L. (2010). Friction drag reduction of external flows with bubble and gas injection. *Annual*
 568 *Review of Fluid Mechanics*, 42, 183–203.
- 569 Ceccio, S. L., & Brennen, C. E. (1991). Observations of the dynamics and acoustics of travelling
 570 bubble cavitation. *Journal of Fluid Mechanics*, 233, 633–660.
- 571 Ceccio, S. L., & Brennen, C. E. (1992). Dynamics of attached cavities on bodies of revolution.
 572 *Journal of Fluids Engineering*, 114(1), 93–99.
- 573 Ceccio, S. L., & George, D. L. (1996). A review of electrical impedance techniques for the mea-
 574 surement of multiphase flows. *Journal of Fluids Engineering*, 118(2), 391–399.
- 575 Ceccio, S. L., Gowing, S., & Gindroz, B. (1995). A comparison of csm bubble detection methods.
 576 In Proceedings of A.S.M.E. symposium on cavitation and gas-liquid flows in fluid machinery.
 577 FED (Vol. 226, pp. 43–50).
- 578 Chahine, G. L., & Kalumuck, K. M. (2003). Development of a near real-time instrument for nuclei
 579 measurement: The abs acoustic bubble spectrometer. *Proceedings of A.S.M.E./J.S.M.E. 4th joint*
 580 *fluids summer engineering conference* (pp. 183–191).
- 581 Chahine, G. L., & Shen, Y. T. (1986). Bubble dynamics and cavitation inception in cavitation sus-
 582 ceptibility meters. *Journal of Fluids Engineering*, 108(4), 444–452.
- 583 Chambers, S. D., Bartlett, R. H., & Ceccio, S. L. (2000). Hemolytic potential of hydrodynamic
 584 cavitation. *Journal of Biomechanical Engineering*, 122(4), 321–326.
- 585 Chang, K. A., Lim, H. J., & Su, C. B. (2003). Fiber optic reflectometer for velocity and fraction
 586 ratio measurements in multiphase flows. *Review of Scientific Instruments*, 74(7), 3559–3565.
- 587 Chang, N., Ganesh, H., Yakushiji, R., & Ceccio, S. L. (2011). Tip vortex cavitation suppression by
 588 active mass injection. *Journal of Fluids Engineering*, 133(11301), 1–11.
- 589 Chang, N. A., & Ceccio, S. L. (2011). The acoustic emissions of cavitation bubbles in stretched
 590 vortices. *The Journal of the Acoustical Society of America*, 130(5), 3209–3219.
- 591 Chang, N. A., & Dowling, D. R. (2009). Ray-based acoustic localization of cavitation in a highly
 592 reverberant environment. *Journal of the Acoustical Society of America*, 125(5), 3088–3100.
- 593 Choi, J., & Ceccio, S. L. (2007). Dynamics and noise emission of vortex cavitation bubbles. *Journal*
 594 *of Fluid Mechanics*, 575, 1–26.
- 595 Coutier-Delgosha, O., Devillers, J. F., Pichon, T., Vabre, A., Woo, R., & Legoupil, S. (2007). Internal
 596 structure and dynamics of sheet cavitation. *Physics of Fluids*, 18(017103), 1–11.
- 597 Coutier-Delgosha, O., Stutz, B., Vabre, A., & Legoupil, S. (2007). Analysis of cavitating flow struc-
 598 ture by experimental and numerical investigations. *Journal of Fluid Mechanics*, 578, 171–222.
- 599 d'Agostino, L., & Acosta, A. J. (1991). A cavitation susceptibility meter with optical cavitation
 600 monitoring—part one: Design concepts. *Journal of Fluids Engineering*, 113(2), 261–269.
- 601 Dular, M., Bachert, R., Stoffel, B., & Širok, B. (2005). Experimental evaluation of numerical sim-
 602 ulation of cavitating flow around hydrofoil. *European Journal of Mechanics-B/Fluids*, 24(4),
 603 522–538.
- 604 Duraiswami, R., Prabhukumar, S., & Chahine, G. L. (1998). Bubble counting using an inverse
 605 acoustic scattering method. *Journal of the Acoustical Society of America*, 104(5), 2699–2717.
- 606 Durst, F. (1982). Review—combined measurements of particle velocities, size distributions, and
 607 concentrations. *Journal of Fluids Engineering*, 104(3), 284–296.
- 608 Elbing, B. R., Mäkiharju, S. A., Wiggins, A., Perlin, M., Dowling, D. R., & Ceccio, S. L. (2013).
 609 On the scaling of air layer drag reduction. *Journal of Fluid Mechanics*, 717, 484–513.
- 610 Escaler, X., Eguisquiza, E., Farhat, M., Avellan, F., & Coussirat, M. (2006). Detection of cavitation
 611 in hydraulic turbines. *Mechanical Systems and Signal Processing*, 20(4), 983–1007.
- 612 Etter, R. J., Cutbirth, J. M., Ceccio, S. L., Dowling, D. R., & Perlin, M. (2005). High reynolds
 613 number experimentation in the U.S. Navy's William B. Morgan large cavitation channel. *Mea-
 614 surement Science and Technology*, 16(9), 1701–1709.
- 615 Foeth, E. J., Van Doorne, C. W. H., Van Terwisga, T., & Wieneke, B. (2006). Time resolved PIV
 616 and flow visualization of 3D sheet cavitation. *Experiments in Fluids*, 40(4), 503–513.

- 617 Ganesh, H., Mäkiharju, S. A., & Ceccio, S. L. (2016). Bubbly shock propagation as a mechanism
618 for sheet-to-cloud transition of partial cavities. *Journal of Fluid Mechanics*.
- 619 George, D. L., Iyer, C. O., & Ceccio, S. L. (2000a). Measurement of the bubbly flow beneath partial
620 attached cavities using electrical impedance probes. *Journal of Fluids Engineering*, 122(1), 151–
621 155.
- 622 George, D. L., Torczynski, J. R., Shollenberger, K. A., O'Hern, T. J., & Ceccio, S. L. (2000b). Val-
623 idation of electrical-impedance tomography for measurements of material distribution in two-
624 phase flows. *International Journal of Multiphase Flow*, 26(4), 549–581.
- 625 Gindroz, B. (1998). Cavitation nuclei and cavitation inception of marine propellers: State of the art
626 at the dawn of the 21st century. *J.S.M.E. International Journal Series B*, 41(2), 464–471.
- 627 Gindroz, B., & Billet, M. L. (1998). Influence of the nuclei on the cavitation inception for different
628 types of cavitation on ship propellers. *Journal of Fluids Engineering*, 120(1), 171–178.
- 629 Goldstein, R. (1996). *Fluid mechanics measurements*. CRC Press.
- 630 Gopalan, S., & Katz, J. (2000). Flow structure and modeling issues in the closure region of attached
631 cavitation. *Physics of Fluids*, 12(4), 895–911.
- 632 Gopalan, S., Katz, J., & Knio, O. (1999). The flow structure in the near field of jets and its effect
633 on cavitation inception. *Journal of Fluid Mechanics*, 398, 1–43.
- 634 Gowing, S., Briançon-Marjollet, L., Frechou, D., & Godeffroy, V. (1995). Dissolved gas and nuclei
635 effects on tip vortex cavitation inception and cavitating core size. In *Proceedings of 5th interna-
636 tional symposium on cavitation* (pp. 173–180).
- 637 Hassan, Y. A., Blanchat, T. K., Seeley, C. H., & Canaan, R. E. (1992). Simultaneous velocity mea-
638 surements of both components of a two-phase flow using particle image velocimetry. *Internat-
639 ional Journal of Multiphase Flow*, 18(3), 371–395.
- 640 Heindel, T. J. (2011). A review of X-ray flow visualization with applications to multiphase flows.
641 *Journal of Fluids Engineering*, 133(074001), 1–16.
- 642 Hewitt, G. F. (1978). *Measurement of two phase flow parameters*. Academic Press.
- 643 Iyer, C. O., & Ceccio, S. L. (2002). The influence of developed cavitation on the flow of a turbulent
644 shear layer. *Physics of Fluids*, 14(10), 3414–3431.
- 645 Katz, J., & Acosta, A. (1981). Observations of nuclei in cavitating flows. *Proceedings of I.U.T.A.M.
646 symposium on mechanics and physics of bubbles in liquids* (pp. 123–132).
- 647 Katz, J., & Sheng, J. (2010). Applications of holography in fluid mechanics and particle dynamics.
648 *Annual Review of Fluid Mechanics*, 42, 531–555.
- 649 Katz, J., Gowing, S., O'Hern, T., & Acosta, A. (1984). A comparative study between holographic
650 and light-scattering techniques of microbubble detection. *Proceedings of I.U.T.A.M. symposium
651 on measuring techniques in gas-liquid two-phase flows* (pp. 41–66).
- 652 Kawanami, Y., Kato, H., Yamaguchi, H., Maeda, M., & Nakasumi, S. (2002). Inner structure of
653 cloud cavity on a foil section. *J.S.M.E. International Journal Series B Fluids and Thermal Engi-
654 neering*, 45(3), 655–661.
- 655 Keller, A. P. (1972). The influence of the cavitation nucleus spectrum on cavitation inception, inves-
656 tigated with a scattered light counting method. *Journal of Fluids Engineering*, 94(4), 917–925.
- 657 Keller, A. P. (1987). A vortex-nozzle cavitation susceptibility meter in routine application in cavitat-
658 ion inception measurements. In *Proceedings of euromech colloquium 222-unsteady cavitation
659 and its effects*.
- 660 Keller, A. P. (2001). Cavitation scale effects—empirically found relations and the correlation of
661 cavitation number and hydrodynamic coefficients. In *Proceedings of fourth international sym-
662 posium on cavitation-CAV2001*.
- 663 Kjeldsen, M., Arndt, R. E. A., & Effertz, M. (2000). Spectral characteristics of sheet/cloud cavitat-
664 ion. *Journal of Fluids Engineering*, 122(3), 481–487.
- 665 Kling, C. L., & Hammitt, F. G. (1972). A photographic study of spark-induced cavitation bubble
666 collapse. *Journal of Fluids Engineering*, 94(4), 825–832.
- 667 Koivula, T. (2000). On cavitation in fluid power. In *Proceedings of 1st FPNI-PhD symposium,
668 Hamburg* (pp. 371–382).

- 669 Kubota, A., Kato, H., Yamaguchi, H., & Maeda, M. (1989). Unsteady structure measurement of
 670 cloud cavitation on a foil section using conditional sampling technique. *Journal of Fluids Engi-*
 671 *neering*, 111(2), 204–210.
- 672 Kuhn de Chizelle, Y., Ceccio, S. L., & Brennen, C. E. (1995). Observations and scaling of travelling
 673 bubble cavitation. *Journal of Fluid Mechanics*, 293, 99–126.
- 674 Kuiper, G. (1985). Reflections on cavitation inception. In *Proceedings of A.S.M.E. cavitation and*
 675 *multiphase flow forum*, FED-23.
- 676 Kumar, S. B., Dudukovic, M. P., Chaouki, J., Larachi, F., & Dudukovic, M. P. (1997). Computer
 677 assisted gamma and x-ray tomography: Applications to multiphase flow systems. *Non-invasive*
 678 *monitoring of multiphase flows* (pp. 47–103).
- 679 Laberteaux, K. R., & Ceccio, S. L. (2001a). Partial cavity flows. part 1. cavities forming on models
 680 without spanwise variation. *Journal of Fluid Mechanics*, 431, 1–41.
- 681 Laberteaux, K. R., & Ceccio, S. L. (2001b). Partial cavity flows. part 2. cavities forming on test
 682 objects with spanwise variation. *Journal of Fluid Mechanics*, 431, 43–63.
- 683 Lauterborn, W., & Bolle, H. (1975). Experimental investigations of cavitation-bubble collapse in
 684 the neighbourhood of a solid boundary. *Journal of Fluid Mechanics*, 72(2), 391–399.
- 685 Lauterborn, W., & Hentschel, W. (1985). Cavitation bubble dynamics studied by high speed pho-
 686 tography and holography: Part one. *Ultrasonics*, 23(6), 260–268.
- 687 Lavigne, S. (1991). Le venturi analyseur de germes. *Journées DRET Cavitation*.
- 688 Le, Q., Franc, J. P., & Michel, J. M. (1993). Partial cavities: Pressure pulse distribution around
 689 cavity closure. *Journal of Fluids Engineering*, 115(2), 249–254.
- 690 Le Corre, J.-M., Hervieu, E., Ishii, M., & Delhay, J.-M. (2003). Benchmarking and improvements
 691 of measurement techniques for local-time-averaged two-phase flow parameters. *Experiments in*
 692 *fluids*, 35(5), 448–458.
- 693 Lecoffre, Y., & Bonnin, J. (1979). Cavitation tests and nucleation control. In *Proceedings of*
 694 *A.S.M.E. international symposium on cavitation inception* (pp. 141–145).
- 695 Lecoffre, Y., Chantrel, P., & Teiller, J. (1987). Le grand tunnel hydrodynamique (GTH): France's
 696 new large cavitation tunnel for naval hydrodynamics research. In *Proceedings of A.S.M.E. inter-*
 697 *national symposium on cavitation research facilities and techniques* (pp. 13–18).
- 698 Lee, I.-H., Mäkiharju, S., Ganesh, H., & Ceccio, S. L. (2016). Scaling of gas diffusion into limited
 699 partial cavities. *Journal of Fluids Engineering*.
- 700 Leger, A. T., & Ceccio, S. L. (1998). Examination of the flow near the leading edge of attached
 701 cavitation. part 1. detachment of two-dimensional and axisymmetric cavities. *Journal of Fluid*
 702 *Mechanics*, 376, 61–90.
- 703 Leger, A. T., Bernal, L. P., & Ceccio, S. L. (1998). Examination of the flow near the leading edge of
 704 attached cavitation. part 2. incipient breakdown of two-dimensional and axisymmetric cavities.
 705 *Journal of Fluid Mechanics*, 376, 91–113.
- 706 Li, C. Y., & Ceccio, S. L. (1996). Interaction of single travelling bubbles with the boundary layer
 707 and attached cavitation. *Journal of Fluid Mechanics*, 322, 329–353.
- 708 Lindken, R., & Merzkirch, W. (2002). A novel piv technique for measurements in multiphase flows
 709 and its application to two-phase bubbly flows. *Experiments in Fluids*, 33(6), 814–825.
- 710 Lucas, G. P., & Mishra, R. (2005). Measurement of bubble velocity components in a swirling gas-
 711 liquid pipe flow using a local four-sensor conductance probe. *Measurement Science and Tech-*
 712 *nology*, 16(3), 749–758.
- 713 Mäkiharju, S. A., Gabillet, C., Paik, B.-G., Chang, N. A., Perlin, M., & Ceccio, S. L. (2013). Time-
 714 resolved two-dimensional x-ray densitometry of a two-phase flow downstream of a ventilated
 715 cavity. *Experiments in Fluids*, 54(7), 1–21.
- 716 McNulty, P. J., & Pearsall, I. S. (1982). Cavitation inception in pumps. *Journal of Fluids Engineer-*
 717 *ing*, 104(1), 99–104.
- 718 Mørch, K. A. (2007). Reflections on cavitation nuclei in water. *Physics of Fluids*, 19(072104), 1–7.
- 719 Obreschkow, D., Kobel, P., Dorsaz, N., De Bosset, A., Nicollier, C., & Farhat, M. (2006). Cavitation
 720 bubble dynamics inside liquid drops in microgravity. *Physical Review Letters*, 97(094502), 1–4.




- 721 O'Hern, T. J., Katz, J., & Acosta, A. J. (1985). *Holographic measurements of cavitation nuclei in*
722 *the sea*. In Proceedings of A: S.M.E. cavitation and multiphase flow forum.
- 723 Ohl, C. D., Philipp, A., & Lauterborn, W. (1995). Cavitation bubble collapse studied at 20 million
724 frames per second. *Annalen der Physik*, 507(1), 26–34.
- 725 Ohl, C. D., Lindau, O., & Lauterborn, W. (1998). Luminescence from spherically and aspherically
726 collapsing laser induced bubbles. *Physical Review Letters*, 80(2), 393–396.
- 727 Oldenzien, D. M. (1982). A new instrument in cavitation research: the cavitation susceptibility
728 meter. *Journal of Fluids Engineering*, 104(2), 136–141.
- 729 Oweis, G. F., Choi, J., & Ceccio, S. L. (2004). Dynamics and noise emission of laser induced
730 cavitation bubbles in a vortical flow field. *Journal of the Acoustical Society of America*, 115(3),
731 1049–1058.
- 732 Pham, T. M., Larrarte, F., & Fruman, D. H. (1999). Investigation of unsteady sheet cavitation and
733 cloud cavitation mechanisms. *Journal of Fluids Engineering*, 121(2), 289–296.
- 734 Rae, W. H., & Pope, A. (1984). *Low-speed wind tunnel testing*, 2nd edition. Wiley.
- 735 Ran, B., & Katz, J. (1994). Pressure fluctuations and their effect on cavitation inception within
736 water jets. *Journal of Fluid Mechanics*, 262, 223–263.
- 737 Rood, E. P. (1991). Review—mechanisms of cavitation inception. *Journal of Fluids Engineering*,
738 113(2), 163–175.
- 739 Rooze, J., Rebrov, E. V., Schouten, J. C., & Keurentjes, J. T. (2013). Dissolved gas and ultrasonic
740 cavitation—a review. *Ultrasonics Sonochemistry*, 20(1), 1–11.
- 741 Roth, H., Gavaises, M., & Arcoumanis, C. (2002). *Cavitation initiation, its development and link*
742 *with flow turbulence in diesel injector nozzles*. S.A.E. Technical Paper, (2002-01-0214).
- 743 Sato, R., Mori, T., Yakushiji, R., Naganuma, K., Nishimura, M., Nakagawa, K., & Sasajima, T.
744 (2003). Conceptual design of the flow noise simulator. In *Proceedings of joint A.S.M.E./J.S.M.E.*
745 *4th joint fluids summer engineering conference* (pp. 129–133).
- 746 Schiebe, F. R. (1972). Measurement of the cavitation susceptibility of water using standard bodies.
747 *St. Anthony Falls Laboratory Project Report 118*, University of Minnesota.
- 748 Shen, Y. T., & Dimotakis, P. E. (1989). Viscous and nuclei effects on hydrodynamic loadings and
749 cavitation of a naca 66 (mod) foil section. *Journal of Fluids Engineering*, 111(3), 306–316.
- 750 Simoni, R. D., Hill, R. L., & Vaughan, M. (2002). The measurement of blood gases and the
751 manometric techniques developed by donald dexter van slyke. *Journal of Biological Chemistry*,
752 277(27), e16.
- 753 Straka, W. A., Meyer, R. S., Fontaine, A. A., & Welz, J. P. (2010). Cavitation inception in quiescent
754 and co-flow nozzle jets. *Journal of Hydrodynamics, Series B*, 22(5), 813–819.
- 755 Stutz, B. (2003). Influence of roughness on the two-phase flow structure of sheet cavitation. *Journal*
756 *of Fluids Engineering*, 125(4), 652–659.
- 757 Stutz, B., & Legoupil, S. (2003). X-ray measurements within unsteady cavitation. *Experiments in*
758 *Fluids*, 35(2), 130–138.
- 759 Stutz, B., & Reboud, J. L. (2000). Measurements within unsteady cavitation. *Experiments in Fluids*,
760 29(6), 522–545.
- 761 Tanger, H., & Weitendorf, E. A. (1992). Applicability tests for the phase doppler anemometer for
762 cavitation nuclei measurements. *Journal of Fluids Engineering*, 114(3), 443–449.
- 763 Thoroddsen, S. T., Etoh, T. G., & Takehara, K. (2008). High-speed imaging of drops and bubbles.
764 *Annual Review of Fluid Mechanics*, 40, 257–285.
- 765 Tropea, C., Yarin, A. L., & Foss, J. F. (Eds.). (2007). *Springer handbook of experimental fluid*
766 *mechanics*. Springer Science and Business Media.
- 767 Van der Kooij, J., & De Bruijn, A. (1984). Acoustic measurements in the NSMB depressurized
768 towing tank. *International Shipbuilding Progress*, 31(353), 13–25.
- 769 Vogel, A., & Lauterborn, W. (1988). Time-resolved particle image velocimetry used in the investi-
770 gation of cavitation bubble dynamics. *Applied Optics*, 27(9), 1869–1876.
- 771 Wetzel, J. M., & Arndt, R. E. A. (1994a). Hydrodynamic design considerations for hydroacoustic
772 facilities: Part I- flow quality. *Journal of Fluids Engineering*, 116(2), 324–331.

- 773 Wetzel, J. M., & Arndt, R. E. A. (1994b). Hydrodynamic design considerations for hydroacoustic
774 facilities: Part II- pump design factors. *Journal of Fluids Engineering*, 116(2), 332–337.
- 775 Wosnik, M., Schauer, T. J., & Arndt, R. E. (2003). Experimental study of a ventilated supercavitat-
776 ing vehicle. In *Proceedings of fifth international symposium on cavitation* (pp. 1–4).
- 777 Wu, Q., & Ishii, M. (1999). Sensitivity study on double-sensor conductivity probe for the measure-
778 ment of interfacial area concentration in bubbly flow. *International Journal of Multiphase Flow*,
779 25(1), 155–173.
- 780 Yu, P. W., & Ceccio, S. L. (1997). Diffusion induced bubble populations downstream of a partial
781 cavity. *Journal of Fluids Engineering*, 119(4), 782–787.

Author Queries

Chapter 2

Query Refs.	Details Required	Author's response
AQ1	Please provide high-resolution source file for Fig. 14.	
AQ2	Please check and confirm if the inserted citation of Fig. 13 is correct. If not, please suggest an alternate citation. Please note that figures should be cited sequentially in the text.	

UNCORRECTED PROOF

MARKED PROOF

Please correct and return this set

Please use the proof correction marks shown below for all alterations and corrections. If you wish to return your proof by fax you should ensure that all amendments are written clearly in dark ink and are made well within the page margins.

<i>Instruction to printer</i>	<i>Textual mark</i>	<i>Marginal mark</i>
Leave unchanged	... under matter to remain	Ⓟ
Insert in text the matter indicated in the margin	∧	New matter followed by ∧ or ∧ [Ⓢ]
Delete	/ through single character, rule or underline or ┌───┐ through all characters to be deleted	Ⓞ or Ⓞ [Ⓢ]
Substitute character or substitute part of one or more word(s)	/ through letter or ┌───┐ through characters	new character / or new characters /
Change to italics	— under matter to be changed	↵
Change to capitals	≡ under matter to be changed	≡
Change to small capitals	≡ under matter to be changed	≡
Change to bold type	~ under matter to be changed	~
Change to bold italic	≈ under matter to be changed	≈
Change to lower case	Encircle matter to be changed	≡
Change italic to upright type	(As above)	⊕
Change bold to non-bold type	(As above)	⊖
Insert 'superior' character	/ through character or ∧ where required	Υ or Υ under character e.g. Υ or Υ
Insert 'inferior' character	(As above)	∧ over character e.g. ∧
Insert full stop	(As above)	⊙
Insert comma	(As above)	,
Insert single quotation marks	(As above)	ʹ or ʸ and/or ʹ or ʸ
Insert double quotation marks	(As above)	“ or ” and/or ” or ”
Insert hyphen	(As above)	⊞
Start new paragraph	┌	┌
No new paragraph	┐	┐
Transpose	└┐	└┐
Close up	linking ○ characters	Ⓞ
Insert or substitute space between characters or words	/ through character or ∧ where required	Υ
Reduce space between characters or words		↑