Appendix

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Acoustic Properties

Here we summarize the acoustic properties of liquids (Table A.1) and solids (Table A.2).

The speed of sound in water, c_w, depends on both temperature and pressure. The dependence is described as

$$\begin{aligned} c_w(T, p_0) = {} & 1402.39 + 5.03711T - 0.0580852T^2 + 3.33420 \times 10^{-4} T^3 \\ & - 1.47800 \times 10^{-6} T^4 + 3.14643 \times 10^{-9} T^5 + 1.6 \times 10^{-6} (p_0 - 10^5) \end{aligned} \tag{A.1}$$

where T is temperature in °C and p_0 is absolute pressure in Pascals. This equation was obtained as a fitting curve on experimental data taken between 0 and 99.9°C.

If you need further information about acoustic properties, please visit the appropriate websites [1, 2]. Povey [3] also provides the speed of sound in some solutions with different concentrations and the speed in bulk of some mixtures.

Ultrasonic Transducers

Figures A.1 and A.2 show ultrasonic transducers for ultrasonic Doppler velocity profiler (UVP) measurement that can be purchased commercially. Specifications of the transducer are summarized in Tables A.3 and A.4, respectively. Please read Sect. 2 to understand the details of the transducers and the content of the tables.

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Table A.1 Acoustic properties of liquids

Material	Speed of sound (m/s)	Density (10^3 kg/m^3)	Acoustic impedance [10^6 kg/(m^2 s)]	Temperature (°C)
Water	1,480	1.00	1.483	20
Seawater	1,531	1.025	1.569	25
Ethanol	1,207	0.79	0.95	25
Methanol	1,103	0.791	0.872	25
Silicone oil (1 cSt)[a]	960	0.818	0.74	
Silicone oil (10 cSt)[a]	968	0.94	0.91	
Silicone oil (1,000 cSt)[a]	990	0.972	0.96	
Gasoline	1,250	0.803	1.00	
Glycerin	1,904	1.26	2.34	25
Fluorinert FC-40	640	1.19	1.86	
Fluorinert FC-75	585	1.76	1.02	
Liquid gallium	2,870	6.09	17.5	30
Lead bismuth eutectic	1,750	10.2	N/A	125
Mercury	1,450	13.5	19.58	25
Sodium	2,420	8.81	21.31	300

[a]*cSt* centi-Stokes

Table A.2 Acoustic properties of solids

Material	Speed of sound (m/s)	Density (10^3 kg/m^3)	Acoustic impedance [10^6 kg/(m^2 s)]
Acrylic resin	2,730	1.18	3.2
Mild steel	5,900	7.8	46
Stainless steel (347)	5,790	7.89	45.7
Aluminum	6,320	2.7	17
Copper	4,700	8.9	42
Tin	3,320	7.3	24
Pyrex glass	5,640	2.24	13.1

All properties in the table are for longitudinal wave

Fig. A.1 Photograph of ultrasonic transducers provided by Met-flow S.A. [8]

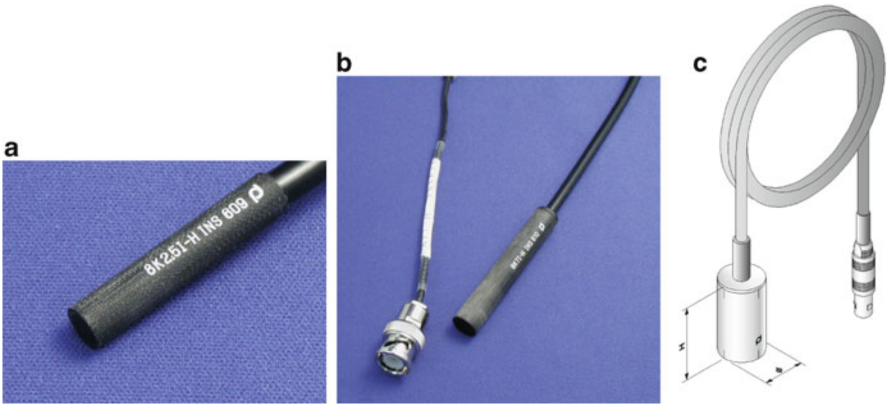

Fig. A.2 (**a**) Head. and (**b**) overview of a probe (8 K2.5-H (**c**) Central frequency 8 MHz, active diameter 2.5 mm). Schematic of standard transducers provided by Japan Probe Co. [9]

Table A.3 Lineup of ultrasonic transducers provided by Met-flow S.A. [8]

Central frequency (MHz)	Active diameter (mm)	Overall diameter (mm)	Focal distance (mm)	Divergence half-angle (degrees, °)
0.5	19	23	30.5	4.6
1	13	16	28.5	3.4
2	10	13	33.8	2.2
4	5	8	16.9	2.2
8	2.5	8	8.5	2.2

Table A.4 Conditions for producing ultrasonic transducers by Japan Probe Co. [9]

Central frequency	Active diameter	Operating temperature limit
0.1–10 MHz	2–50 mm	120°C

Couplants

One of the advantages of the UVP method is that a sensor (transducer) can be set outside the containing wall, which enables avoiding any disturbance to the flow, i.e., noninvasiveness. In such configurations, a gap between the transducer front surface and the wall surface has to be filled with any substance that eliminates the air layer to prepare a smooth transition of acoustic impedance from the transducer to the wall. This requirement is also true even when two surfaces make direct contact without inclination of the transducer, because the surface roughness of the materials inevitably holds an air layer between the two surfaces.

In a simple configuration water is used as it is for nondestructive testing. Or, an ultrasonic gel is widely used in medical applications. Both couplants are effective for our applications also. The latter is composed mainly of water, but the composition varies from product to product.

Table A.5 Specifications of seeding particles commercially available

Product name	Type	Material	Mean diameter (μm)	Density (g/cm^3)	Supplier
Griltex 5P1	Sphere	Nylon	75	1.06	EMS Co. Ltd.
DIAION HP20SS	Porous sphere	Divinylbenzen	~100	1.02	Mitsubishi Chemical Co.
SEPABEADS SP20SS	Porous sphere	Divinylbenzen	~50	1.02	Mitsubishi Chemical Co.
Flobeas CL-2507	Sphere	Polyethylene	180	0.919	Sumitomo Seika Chemicals Co., Ltd.
HGS	Hollow sphere	Glass	10	1.1	Dantec Co.
Q-Cel	Hollow sphere	Glass	50–90	0.14–0.48	Potters Industries LLC
Spherical	Hollow sphere	Glass	12–47	0.25–1.10	Potters Industries LLC

It is important to know that gel dries, so that it should be refreshed from time to time, especially when the surface or surrounding temperature is high. Special products of high-temperature couplant are available; for example, Sono 600 is applicable for ultrasonic flaw inspections in high-temperature environments up to 260°C [acoustic impedance is $1.35–1.40 \times 10^6$ kg/(m^2 s)] [4].

Seeding Particles

Examples of tracer particles for UVP measurements that can be purchased on the market are specified in Table A.5. Please refer to Sect. 3.2.6 to know the requirements for tracer particles.

Particle motions in unsteady flows are described by equations of motion of a particle (Maxey–Riley equations [5, 6]), for example:

$$\frac{\pi d^3}{6}\rho_p\frac{\mathrm{d}\boldsymbol{u}_p}{\mathrm{d}t} = 3\pi\upsilon\rho_f d\left(\boldsymbol{u}_f-\boldsymbol{u}_p\right)+\frac{\pi d^3}{6}\rho_f\frac{\mathrm{d}\boldsymbol{u}_f}{\mathrm{d}t}+\frac{1}{2}\frac{\pi d^3}{6}\rho_f\left(\frac{\mathrm{d}\boldsymbol{u}_f}{\mathrm{d}t}-\frac{\mathrm{d}\boldsymbol{u}_p}{\mathrm{d}t}\right) + \frac{3}{2}d^2\rho_f\sqrt{\pi\upsilon}\int\frac{\mathrm{d}\xi\left(\mathrm{d}\boldsymbol{u}_f/\mathrm{d}t-\mathrm{d}\boldsymbol{u}_p/\mathrm{d}t\right)}{\sqrt{t-\xi}} \tag{A.2}$$

where $\boldsymbol{u}_p$ and $\boldsymbol{u}_f$ are the velocity vector of the particle and the flow at a point, d, and ρ_p, ρ_f, and ν are the diameter and density of the particle and the density and kinetic viscosity of the fluid, respectively. The foregoing equation, Eq. (A.2), takes into account four forces, namely, viscous drag, pressure gradient force, added mass, and Basset history force (development of boundary layer). Further, lift force, buoyancy, or centrifugal force would not become negligible in some cases.

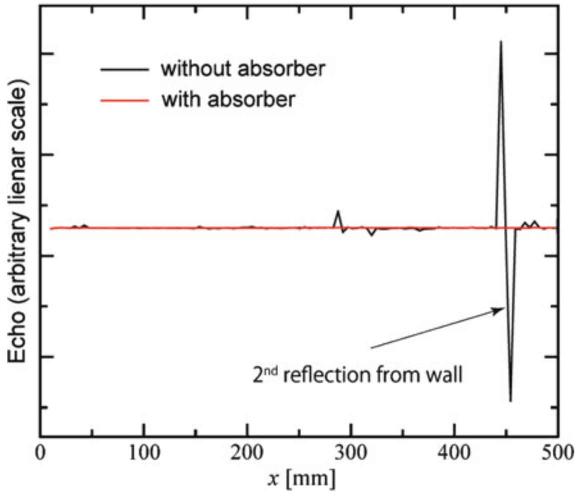

Fig. A.3 Averaged echo profile recorded in a 2,000-mm-long rectangular tank with or without an ultrasonic absorbing plate placed on the wall

Ultrasonic Absorbers

Detection of a spurious echo signal often cannot be avoided, depending on the geometric configurations and seeding conditions. Especially in the small contained configuration where there are many solid materials around the measurement volume, multiple scattering of the ultrasonic pulse bouncing from these solid walls causes time-frame aliasing, which deteriorates the velocity profile to an annoying extent. It is therefore important to design measurement configuration such that a pulse reflected on the wall shall not reach back to the transducer by arranging the beam line in an appropriate manner. A key practice for this is to use the oscilloscope to monitor the echo signal. This step is especially important where a reflection on the free surface is foreseen, because a reflection from the moving free surface will destroy the velocity profile from measurement frame to frame.

It is still often unavoidable to have echo reflected from the wall. In such cases a special ultrasonic absorbing material can be used to replace the wall material or to cover the wall surface by the absorber. Figure A.3 shows an example of eliminating echo reflected from the wall. The front face of a 2-MHz ultrasonic transducer is located at 1,500 mm from the wall of a rectangular tank 2,000 mm long. The tank is filled with water and the transducer is fully submerged in the water. The figure indicates the average echo profile with or without attaching an ultrasonic absorbing plate (EUA201A is shown in Fig. A.5a) on the wall of the tank. The wall position from the transducer is outside the range in this graph, and the large peak on the profile indicated by the arrow is the second reflection from the wall: the emitted ultrasonic pulse propagated between the walls in the tank twice before the transducer detected it. The profile utilizing the absorber seems smooth, and the echo of the second reflection is eliminated.

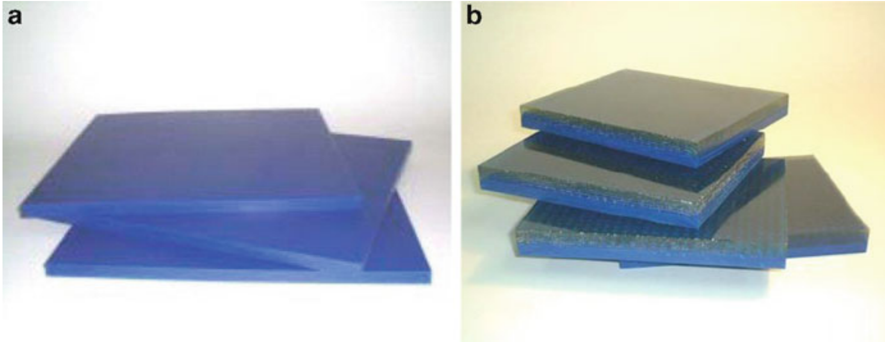

Fig. A.4 (**a**) Photographs of ultrasonic absorber EUA201A. and (**b**) EUA101A provided by EASTEC Co. (specifications of the materials are summarized in Table A.6)

Table A.6 Specifications of ultrasonic absorbers provided by EASTEC Co. [7]

	EUA201A	EUA101A	AptFlex
Material	Polyurethane	Polyurethane	Polyurethane
Range of frequency for US	> 0.5 MHz	> 0.7 MHz	> 0.4 MHz
Echo reduction at 1 MHz	25 dB	40 dB	2.29 dB/mm
Size (mm)	300×300×10	120×95×14 250×200×14	

Fig. A.5 Cylindrical test section made of ultrasonic absorbing material (AptFlex; see Table A.6)

Figure A.4 shows photographs of ultrasonic absorbing plates that can be purchased on the market [7]. Table A.6 specifies the characteristics of the plates. Using AptFlex makes possible to design a universal shape of test sections with the absorbing material. Figure A.5 shows a cylindrical test section made of AptFlex for flowrate measurement of bubbly flows (see Sects. 5.5 and 7.3).

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