Cold Regions Science and Technology 112 (2015) 66–86

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Laboratory measurements of acoustic backscattering from polystyrene pseudo-ice particles as a basis for quantitative characterization of frazil ice

J.R. Marko *, D.R. Topham

ASL Environmental Sciences Inc., Saanichton, B.C., Canada

ARTICLE INFO

Article history:
Received 8 November 2013
Received in revised form 11 December 2014
Accepted 10 January 2015
Available online 17 January 2015

Keywords:
Acoustic backscattering
Frazil characterization
Measurement framework

ABSTRACT

Measurements of volume backscattering coefficients in brine suspensions of neutrally buoyant, uniformly-sized, polystyrene spheres and disks were used to quantify size, shape and concentration dependences expected in equivalent measurements on freshwater suspensions of frazil ice. The results confirmed expectations of qualified compatibility with existing scattering theory. Specifically, the measured logarithmic backscattering coefficients were expressible, to within 1–2 dB, as products of particle concentration and individual cross sections as calculated from the modal expansion of Faran (1951) applied to spheres with radii equal to either their actual values or (for hexagonal disks) to "effective" spherical radii. The limitations on the applicability of the theory were closely linked to: acoustic frequency, target-volume-determined effective radii; the linear dimensions of the faces of the individual target disks; and to particle concentrations. For combinations of particle dimensions, acoustic frequencies and concentrations outside of a well-defined Rayleigh Linear (RL) concentration dependence range, the relationships between measured volume backscattering coefficients and particle properties were complex and not amenable to a simple interpretation: reflecting, it is believed, polystyrene-specific scattering features. The features of the observed extensive Anomalous Linear (AL) and Non-Linear (NL) concentration dependence regimes were documented in terms of both their parameter dependences and the forms and parameters associated with their deviations from RL regime dependences. Analyses focused on identifying the boundaries of the latter regimes which currently provide the only measurement environments compatible with accurate extraction of particle concentration and size parameters. These identifications, made on the basis of polystyrene in brine data, were used, after insertion of frazil and freshwater material parameters, to identify equivalent RL boundaries for ABS (Acoustic Backscattering Sonar) frazil measurements. In practical terms, this framework led to estimates of upper and lower limits for usable ABS acoustic frequencies and established upper limits on the concentrations of larger frazil particles contributing significantly to backscattering signal returns. These results formed the basis for a measurement framework for obtaining validated frazil characterizations. This framework was tested on mixtures of differently-sized pseudo-frazil species to show compatibility between mixture data and equivalent backscattering coefficients calculated for each mixture on the basis of its composition and measured single species coefficients. Applications of this framework to actual frazil field data are essential for both further testing of effectiveness and to allow refinements of imposed, intentionally conservative, restrictions. Results of such applications are described and interpreted in a second publication.

1. Introduction

Recent river ice research efforts have included several studies (Jasek et al., 2005; Morse and Richard, 2009; Marko and Jasek, 2010a,b,c; Richard et al., 2011 and Ghobrial et al., 2012, 2013) directed at quantifying frazil suspensions from acoustic backscattering (ABS) data. Although the reported results offered previously unavailable insights into frazil dynamics and properties, underlying simplifications and approximations left considerable interpretative uncertainties. The present work identifies these deficiencies prior to presenting results from a laboratory study directed at achieving improvements. A major objective is to develop a definitive and data-validated framework for multifrequency ABS frazil measurements and data interpretation. This framework provides a basis for actual frazil field data characterizations reported in a separate publication (Marko et al., 2014), hereafter referenced as Paper II.

We begin in Section 2 with an outline of the basic steps involved in connecting ABS data to frazil target properties prior to discussions of complicating physical factors. These discussions make references to past efforts in suspended sediment characterization and in laboratory

* Corresponding author at: ASL Environmental Sciences Inc., 6703 Rajpur Place, Victoria, BC V8M 1Z5, Canada. Tel.: +1 250 656 0177.
E-mail address: jmarko@aslenv.com (J.R. Marko).

http://dx.doi.org/10.1016/j.coldregions.2015.01.003

and field frazil studies: ultimately offering a rationale for making fundamental measurements on suspensions of controllable, well characterized, pseudo-frazil targets. A methodology for such measurements, described in Section 3, is followed, in Section 4, by presentation and interpretation of results obtained in studies of populations of two different types of uniformly-sized frazil surrogate species carried out at four different acoustic frequencies. Section 5 presents additional data acquired on mixtures of differently-sized surrogate species prior to comparisons with expectations based upon single species results. All results are briefly summarized (Section 6) to provide guidelines for acoustic measurements on actual frazil populations directed at further validation and expansion of a multifrequency ABS frazil characterization methodology.

2. Uncertainties in ABS frazil measurements: evolving a validation approach

ABS data are typically acquired in the form of volume backscattering coefficients, S_v (defined as the fraction of acoustic power flux incident upon a unit volume of suspended targets which is scattered directly back towards the acoustic source). In frazil applications, S_v data, in the form of values corresponding to well-defined individual range cells, must be interpreted in terms of the backscattering properties of ice particle targets. With one exception, such interpretations have relied on the basic assumption that $S_v(\nu)$, the volume backscattering coefficient measured at frequency ν, can be written as:

$$S_v(\nu) = \sum_{1}^{n} N_i \sigma_i(\nu). \tag{1}$$

In this equation, the index i denotes any distinct target species (typically a specific combination of shape, dimensions, material properties and orientation) characterized by a common backscattering cross section $\sigma_i(\nu)$ (the two-dimensional equivalent of $S_v(\nu)$) which is present in numbers N_i per unit volume. [See Marko and Jasek (2010b) for a description of the development of Eq. (1) and its connection with the Sonar Equation.} The noted exception to this approach (Ghobrial et al., 2012) involved the development of empirical relationships between water column-averaged $S_v(\nu)$ and fractional volume (the ratio of ice- to total fluid + ice volume) as discussed below.

The most frequently noted (Marko and Jasek, 2010a,b,c) deficiencies of ABS data interpretations based upon Eq. (1) arise from remaining uncertainties in the relationships between $\sigma_i(\nu)$ and particle size, shape and material properties. Additionally, other difficulties potentially undermine a basic assumption of this approach, which is that the detected acoustic returns can be expressed as sums of powers scattered by individual targets. This requires the validity of the independent scattering assumption which neglects possible cross-correlations between acoustic waves scattered by two or more particle targets. Other deviations from Eq. (1) can be expected when target concentrations become sufficiently high to measurably attenuate the acoustic power incident upon a given target and when significant portions of the detected backscattered returns have undergone more than one distinct scattering event. All of these effects have been observed (Hay and Schaafsma, 1989; Thorne et al., 1995; Varadan et al., 1985) in ABS sediment suspension studies.

To date, all applications of Eq. (1) to interpretations of ABS frazil data have employed a simplified form of the equation limiting considerations to a single target species characterized by a common backscattering cross section, $\sigma_{bs}(\nu)$. Various approaches have been taken for estimating the latter quantity. Marko and Jasek (2010b,c) utilized a truncated form of the modern extension (Anderson, 1950) of Rayleigh's early theory (Rayleigh, 1945) of scattering to fluid spheres of radius a. This extension allowed σ_{bs} to be expressed in terms of spherical Bessel (j_m) and Neumann (n_m) functions as:

$$\sigma_{bs} = 4\pi a^2 \frac{\left| \sum_{m=0}^{\infty} \frac{(-1)^m (2m+1)}{1 + iC_m} \right|^2}{(k_1 a)^2}, \tag{2}$$

where:

$$C_m = \frac{[j'(k_2a)n_m(k_1a)\text{-}gh\,j_m(k_2a)n'_m(k_1a)]}{[j'_m(k_2a)j_m(k_1a)\text{-}gh\,j_m(k_2a)j'_m(k_1a)]} \tag{3}$$

and the parameters g and h, respectively, denote the ratios of the target (ρ_2) to host (ρ_1) fluid densities and corresponding sound speeds (c_2/c_1). The primes (') in this equation denote first derivatives with respect to the arguments of the indicated spherical Bessel and Neumann functions and $k_1 = 2\pi\nu/c_1$ and $k_2 = k_1/h = 2\pi\nu/c_2$ represent the acoustic wave numbers in, respectively, the host and target fluids.

The truncation utilized values of σ_{bs} calculated from Eq. (2) for perfectly rigid, immobile, spheres (corresponding to values of $g = h = \infty$) converted to values crudely appropriate to the elastic ice target material through the use of a scaling factor which incorporates the finite compressibility and density values of freshwater ice (Clay and Medwin, 1998; Urick, 1984) with compressibility, expressed (Bower, 2010) in terms of the longitudinal and shear wave velocities c_{2l} and c_{2s}. This scaling factor is expressed as:

$$\kappa = \left\{ \rho\left[c_{2l}^2 - (4/3)c_{2s}^2\right] \right\}^{-1}. \tag{4}$$

In each case, the usually disk-shaped frazil ice particles were represented by spheres with"effective radii" defined (Ashton, 1983) to have volumes equal to those of the disk targets. Concerns regarding the validity of this procedure included the unknown effects of differences between frazil ice disks and their spherical stand-ins, as well as the imposition of $k_1a < 1$ limits on particle size to avoid more complicated dependences of σ_{bs} on k_1a. The procedure also introduced additional problems through the correction factor (Urick, 1984) which was representative of only the first two, monopolar and dipolar, terms of the multipolar series (Eq. 2). The neglect of the third (quadrupolar) and other higher order terms begins to be detectable at values of k_1a on the order of, or slightly less, than 0.5. The neglect of such terms was likely to preclude representation of more complex dependences on the mechanical properties of the target material.

Nevertheless, this approach enabled extraction of self-consistent, physically reasonable, estimates of frazil concentration, particle size and fractional suspended ice volume from ABS measurements made, near-simultaneously, at two different acoustic frequencies on the Peace River (Marko and Jasek, 2010c). The radii of the "effective" spherical particles, were derived by maximizing agreement between the ratios of the S_v values measured at the two frequencies and corresponding ratios calculated from the theoretical $\sigma_{bs}(\nu,a)$ relationship. These radii were then used with one of the measured S_v values and $\sigma_{bs}(\nu,a)$ to deduce values for particle concentrations, N.

Other theoretical and empirical equivalents of $\sigma_{bs}(\nu,a)$ have been used to try to avoid the obvious uncertainties involved in applying a theory derived for spherical fluid targets to predominantly disk-shaped elastic frazil particles. One formulation (Johnson, 1977) sometimes, for convenience, applied to sediment targets (Sheng and Hay, 1988), was designed to both average out deviations from sphericity and to reproduce expected results at very high and very low values of k_1a. It has been applied to St. Lawrence River frazil data (Richard et al., 2011) gathered at a single acoustic frequency (1.229 MHz) to identify possible compatible combinations of particle size and concentration. North Saskatchewan River frazil data (Ghobrial et al., 2013) were also