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# Three dimensional passive acoustic spatial identification of nucleations in superheated droplet detectors

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ABSTRACT

A new method for spatial localization of bubble nucleations in superheated droplet detectors is presented which has two steps: validation and localization. Validation is accomplished through signal processing techniques serving the purpose of filtering out electromagnetic noise and gaseous micro-leaks. The 3D spatial localization uses a passive acoustic sound source localization technique using a microphone array (5 elements) and a simple generalised cross-correlation (GCC) time delay of arrival (TDOA) algorithm. The approach for the nucleation validation is new and regarding the localization, as of this writing, we are the first to endeavour its feasibility assessment. Experimental results are shown.



## 1. Introduction

A superheated droplet detector (SDD) [1] is a generic denomination for a class of commonly employed systems for neutron detection [2]. SDDs have been used in neutron dosimetry for over a decade [3,4]; more recent applications include neutron spectrometry [5,6], and dark matter detection [7,8].

An SDD consists of a uniform dispersion of over-expanded, micrometric-sized halocarbon droplets suspended in a hydrogenated gel, each droplet of which functions as a mini-bubble chamber. Energy deposition by irradiation nucleates the phase transition of the superheated droplets, generating millimetric-sized bubbles [3] which can be recorded by either visual or chemical means. Because a bubble nucleation is accompanied by an acoustic shock wave, acoustic detection is also possible.

For several applications, the devices are operated under pressure, and submerged within a water bath which acts as both neutron moderator and temperature control. In tests with refrigerant-free modules, signals similar to bubble nucleation events were found to arise from pressure microleaks through the plastic SDD caps [9]. In rare event searches, these events may dominate the detector response, reducing the SDD application sensitivity by orders of magnitude. Improved construction has so far only succeeded in reducing the rate of these events.

Spatial localization of a nucleation through an array of microphones brings meaningful information which serves several important purposes. One that might come up immediately to mind is further validation of a nucleation by automatically rejecting those that appear out of the vial volume. The detection of phantoms, i.e., replicas of a nucleation due to neighboring droplets also nucleating becomes easier since we now can correlate both time and space to identify them. Another, perhaps even more important, is that it allows for a nucleation spatial density mapping. From this spatial mapping of the nucleation important information related to the underlying physics might be inferred.

Acoustic source localization is of interest in many important research activities and has become a field of active study. The approach taken in this paper has been the generalized cross-correlation (GCC) method for assessing time delays of arrival (TDOA) [10] between pairs of microphones within the microphone array. From the combinatorial TDOAs of the microphone array a maximum likelihood estimator [11] is used to determine the most probable voxel for bubble nucleation.

## 2. Superheated droplet detectors (SDDs)

### 2.1. Detector physics

The physics underlying the SDD operation is described in detail in [3]; here we provide only a short description. The superheated emulsions share the same working principle as bubble chambers, with the significant difference being that SDDs are continuously sensitive since the liquid is kept in steady-state superheated conditions (i.e., above its boiling point), whereas in the bubble chamber the liquid is only sensitized for brief periods of time. Two conditions are required [2] for the nucleation of the gas phase by energy deposition in the superheated liquid: (i) the energy deposited must be greater than a thermodynamic minimum, and (ii) this energy must be deposited

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within a minimum thermodynamic distance inside the droplet. The amount of energy and the critical size required for bubble nucleation depend on the composition and on the degree of superheat of the emulsion. Typically the higher the superheat of the droplets, the lower the nucleation energy required for their evaporation, i.e., the lower is the threshold energy of the detector. The threshold energy of each detector depends on the composition of the droplets, and their operating temperature and pressure.

### 2.2. Detector specification

SDDs are commonly fabricated with light halocarbons (freon) since, with a moderate superheat, they can be used in neutron detection inasmuch as they are only nucleated by energetic heavy ions such as those produced by fast neutrons [6]. If a high degree of superheat is applied, the nucleation can occur with sparsely ionising radiations such as photons and electrons [3].

Three types of SDDs are employed in our experimental trials: (i) "CCLF", implying a uniform dispersion of ~6 g of superheated droplets of $CCl_2F_2$ (R-12), and (ii) "CFI", implying a uniform dispersion of ~6 g of superheated droplets of $CF_3I$. Both of the detectors had their superheated droplets suspended in ~150 ml of hydrogenated gel. (iii) A third "CCLF-m" and fourth "CCLF-M" detectors, using the same uniform dispersion of ~6 g of superheated droplets of $CCl_2F_2$ (R-12), but modified with a different concentration in ~80 ml of hydrogenated gel, "m" less ~60% and more "M" 60%.

The experimental results shown in this paper relate only to type (i) detectors at 0 atm.

## 3. Instrumentation for the SDD

### 3.1. Experimental setup and spatial identification

The acoustic shock wave associated with the rapid bubble expansion is accompanied by oscillating pressure pulses of <10 ms duration, which can be acoustically recorded. The experimental setup consists of five high quality electret microphone cartridges (MCE-200) with a frequency range of 20 Hz–16 kHz (3 dB), SNR of 58 dB and a sensitivity of 7.9 mV/Pa at 1 kHz, associated with an audio preamp with high gain, low noise and high flexibility achieved through programmable gain, at the core of which stands a digitally controlled microphone preamplifier (PGA2500) which then couples to the input of an acquisition channel controlled by the DAQ toolbox in Matlab. This setup allows high resolution acquisition vectors for all of the five microphones which are then digitally processed. Mechanically one of the microphones is inside the detector within a protective glycerine layer and the rest is around and beneath the detector, as shown in Fig. 1. The microphones outside the vial are glued to the vial using an epoxy and a very thin outer perimeter rubber layer is used between the microphone and the glass to avoid mechanical acoustic coupling. The electronic setup is connected to the microphones using a long shielded cable (~5 m). The electronic setup is itself also shielded to minimize the very high electromagnetic noise usually found near the nuclear reactor.

For the acquisition a National Instruments PXI-5105 high-speed digitizer was used, which is capable of acquiring up to 8 channels simultaneously at 60 MSps. This gives a theoretical resolution of about 30 μm considering an average sound speed, in the hydrogenated gel, near 1600 $ms^{-1}$. The speed of sound within the media needs to be accurately known as it directly relates to the spatial resolution of the system. To this end, and since the speed of sound varies considerably with the gel consistency, we made a measurement of the speed of sound within the gel that was to be used for the SDD.

The measurement was carried out on a 2 m tube with 10 cm radius filled with the hydrogenated gel at 18 °C. The speed was measured for lengths varying from 2 m down to 20 cm at 20 cm intervals, as shown in Fig. 2. In this figure is shown the distance in the ordinate and the emitter–receiver delay in the abscissa which makes it easy to find the sound speed in the gel through the slope.

The sound speed measurement procedure consisted in the emission of a Gaussian pulse, with central frequency at 1 kHz and with 100 Hz bandwidth. The time delay was assessed through correlation between emission and reception. The delay measurement at each of those distances was carried out by making small cuts on the outer wall of the tube through which the receiver hydrophone was inserted. This means the emitter position was kept fixed at one end of

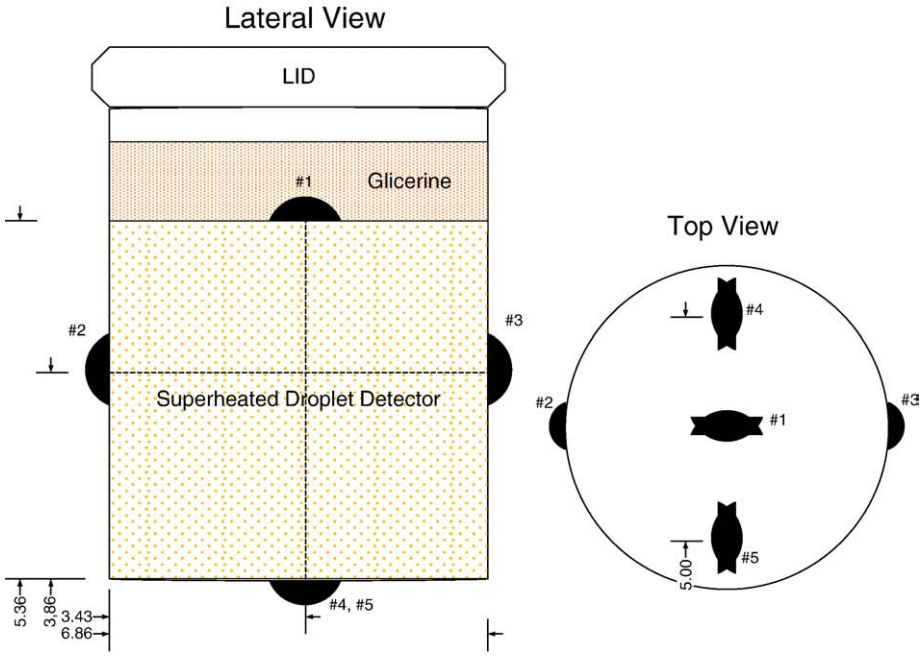


**Fig. 1.** Position of the microphones around the detector vial. Dimensions are in cm and # denotes the microphone number.

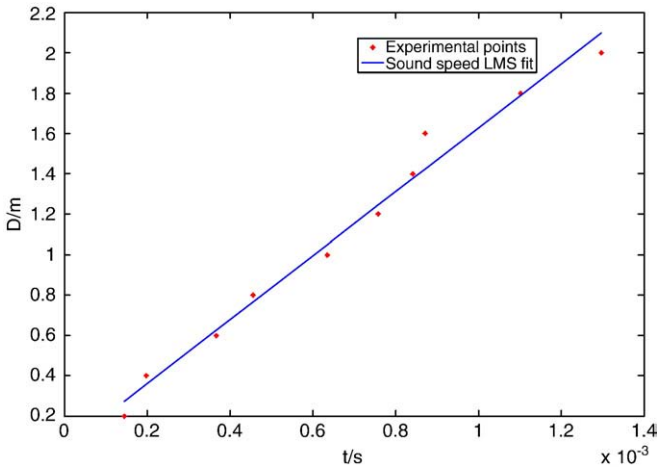


**Fig. 2.** Experimental results for the sound speed measurements within the hydrogenated gel using a 2 m cylinder with 10 cm radius at 18 °C.

the cylinder while the receiver kept getting closer to the emitter. Each of the experimental points shown in Fig. 2 (red crosses) corresponds actually to an average of 10 readings, being each reading a full acquisition with delay assessment by correlation between emitter and receiver signals.

The experimental setup for the sound speed measurement is the same as previously described for the nucleation localization with some minor changes: (i) only one microphone is used, (ii) a second data acquisition board (NI PCI-6013) was used for the impulse generation which was then (iii) amplified by a high power audio amplifier (20 W) and, (iv) the PXI 5105 acquired both the generated impulse and the signal at the terminals of the receiver hydrophone. The experimental setup was calibrated for compensation of the phase errors in each of the blocks in the acquisition path, mainly the hydrophones, by measuring the speed of sound in distilled water at 20 °C.

We still have to determine the dependence of the speed of sound with the freon and with temperature.

For the experimental assessment of the validation and localization procedures the SDD was heated both laterally using a hair dryer and locally using very small platinum heating probes (2 mm diameter head). The later setup was used to validate the localization algorithm by inducing nucleations through localized heating.

The bubble nucleation spatial localization consists of a 2 step procedure: time validation and spatial localization. In the first step, for each of the five data vectors, corresponding to each of the five microphones, a relatively thorough approach is taken to identify each nucleation consisting of three steps. This starts with the use of a continuous wavelet Morlet based transform [12]. The choice of the base was the result of a maximum likelihood study between the typical nucleation and the most common wavelet bases using the crest factor as the cost function. The scales at which the transform is analysed depends on the gel, the pressure, temperature and whether the microphone is inside or outside the vial. For the results found in this paper the scales 17 (outside) and 33 (inside) were used.

From the output of the wavelet transform the selection of the possible candidates for nucleation is carried out by threshold analysis, being the threshold set at 5% of the measured crest factor. Each of the possible candidates for a nucleation will be analysed separately by centring a window on the location of the candidate, therefore segmenting the data. Each will endure a time and frequency analyses.

The time analysis consists of a simple pulse shape validation routine [13] in which each pulse is first amplitude demodulated and the time decay constant then determined through an exponential fit.

The amplitude demodulation is achieved simply by taking the modulus of the Hilbert transform of the pulse waveform,

$$y(t) = |\mathrm{H}\{x(t)\}|, \tag{1}$$

as depicted in Fig. 3, where the amplitude envelope, $y(t)$, is drawn in red.

After the envelope has been obtained, the maximum and the minimum of the pulse shape are found to set the time window that will be used for evaluating the decaying time constant. The decaying part of the amplitude envelope is fit to an exponential,

$$h(t) = Ae^{\alpha t}, \tag{2}$$

by means of a linear regression after linearization of the envelope,

$$\ln(y(t)) = \ln(A) + \alpha t + er(t) \tag{3}$$

where $er(t)$ corresponds to the residual of the fit. In Fig. 4 is shown both the decaying interval of the envelope and the exponential fit.

Following, frequency analysis is carried out for each candidate window using the chirp-z transform [14] to determine the spectrum between 200 Hz and 700 Hz, frequency window within which the oscillations of the nucleation are expected to be found.

Once all of the previously described three steps are taken all candidates that survived endure one final challenge: true nucleations must be present, nearly simultaneously, on all five channels. Only those candidates that exist nearly simultaneously in all five channels will be spatially located.

The determination of each nucleation's position is an ill-posed inverse problem, being the direct problem the determination of the sound waves at each of the microphones knowing when, where and with what intensity did a nucleation occur.

The approach we have taken to solve this ill-posed inverse problem, since the geometry of the problem is well known, consists in mapping the vial volume with a regular, albeit dense, hexahedron mesh each with a volume of 5 $mm^3$, the voxel. For each of these voxels, the TDOAs at all the combinatorial pairs of the microphone array for nucleations taking place at each voxel are theoretically assessed and stored in a multidimensional matrix. The matching of the voxel with each nucleation is carried out by an LMS algorithm, which compares the experimental TDOAs at pairs of the microphones with the ones previously theoretically determined and stored for each of the voxels.

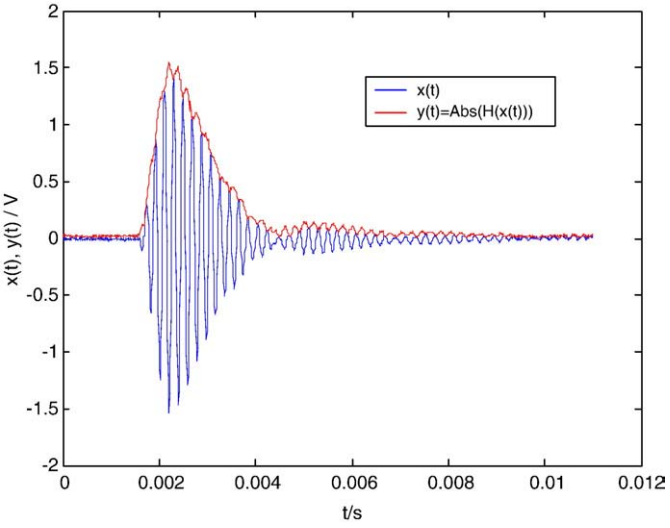


**Fig. 3.** Pulse shape of a bubble nucleation (blue line) and its amplitude envelope (red line) as assessed by means of Eq. (1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

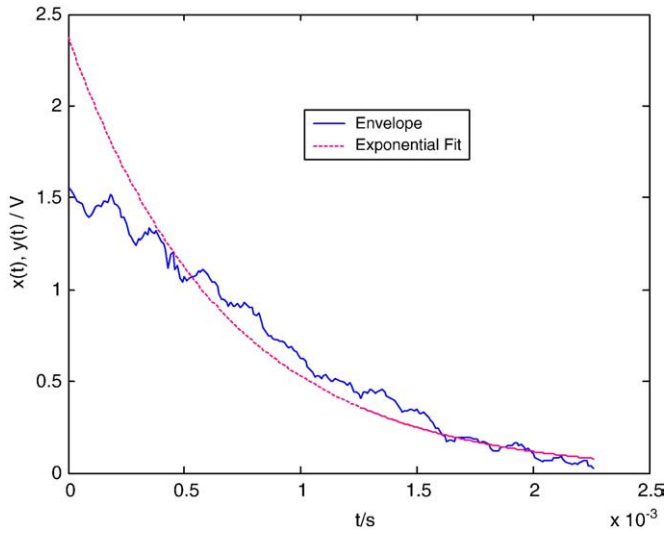


**Fig. 4.** Best fit of the exponential in Eq. (2) to the amplitude envelope of the pulse shown in Fig. 3 For this particular pulse the time constant was found to be 0.7 ms.

It is obvious that this approach, as is now, cannot give any information on the intensity of the nucleation and is crude both in spatial resolution and in accuracy since in the forward problem we do not take into account the sound dispersion in the gel with a given bubble concentration, neither the reflections of the sound wave on the walls of the vial. Nevertheless, the experimental results, as we shall see in the next section are promising and the approach is versatile, albeit computationally intensive.

This approach requires a time correlation between all channels to ascertain all relative delays. This correlation is digitally computed through the Wiener–Khinchin theorem by inverse Fourier transforming the products of the Fourier transforms of each pair of signals. The delay measured must be compensated for the phase delays of the system which are determined in a calibration stage. During this calibration stage the phase errors associated with the time delays in each of the microphones and analog input circuits are determined for compensation during the actual measurements. This is done by measuring the time delays associated with the fixed and known distances between the emitter and the receiver in open air at controlled temperature and humidity, measured by a thermometer and a hygrometer.

As mentioned before, to locate and correctly identify nucleations, discriminating spurious events, we used four microphones outside the vial and one inside. The spurious event suppression will hopefully be achieved by spatially-locating the bubble nucleation and correlating this information with the time interval of events, their relative phase information and time constant of each microphone.

### 3.2. Experimental results

To validate the system we used a small heating probe (2 mm diameter platinum heater), which was placed, at known positions within the vial. Each time the probe was heated 20 s of nucleations were recorded and the location estimated. Fig. 5 shows a nucleation map resulting from the insertion of the heating probe at five angular positions at the top to depths of up to 2 cm. From these measurements, at 0 bar, 1 bar and 2 bar, and room temperatures from 15 °C to 20 °C we found the maximum error to be 1.2 cm (accuracy) and the precision to be 1.8 cm with 99.2% confidence, which defines the uncertainty interval. The errors were highest along the centre of the vial, especially in the middle, which proved to be good since no nucleations showed up “outside” the vial. The accuracy was better, <9 mm, at room temperatures of 18 °C and 0 bar, temperature and pressure at which the sound speed within the hydrogenated gel was measured, which might indicate high temperature and pressure dependence of the speed of sound in the medium.

We also heated the SDD in a bath and using a hand heating gun (Fig. 6) and once again no “outside” nucleations were found which was in accordance with the knowledge that no leakage took place.

## 4. Conclusions

The determination of the time constants of each nucleation is good to provide an in-depth knowledge of the gel media and is usually enough to discriminate real from fake nucleations. However, the spatial location of each nucleation serves three purposes:

1. to corroborate the data of the nucleation detection — fake events appear “outside” the vial.
2. to make easier the identification of a phantom — very close in time and space to previous nucleation.
3. to determine the spatial density of the nucleations and through it the incidence of the energy source.

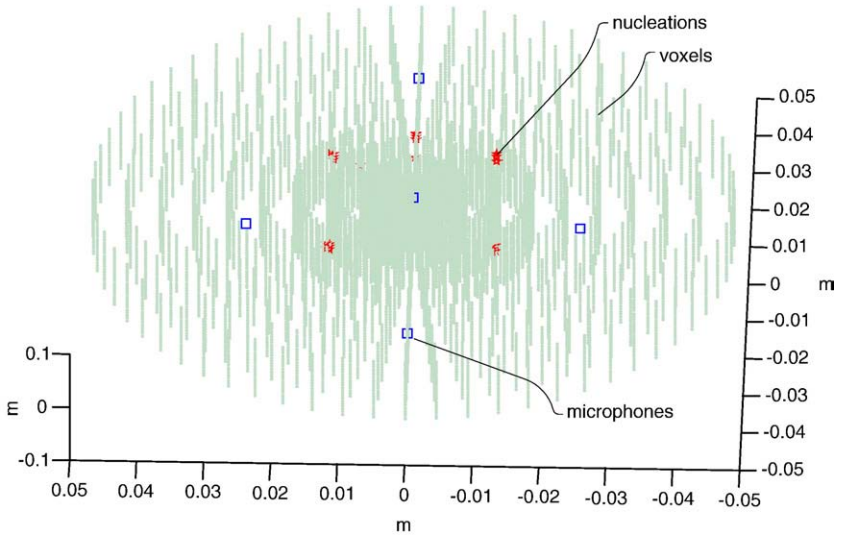


**Fig. 5.** Bubble nucleation map when inserting heating probes at five angular positions (π/4, 3π/4, 5π/4, 7π/4, 0) and radius 1.71 cm at depths, from top, of 0 cm to 2 cm. The spatial map shown is larger than the vial. The microphones identify the limits.

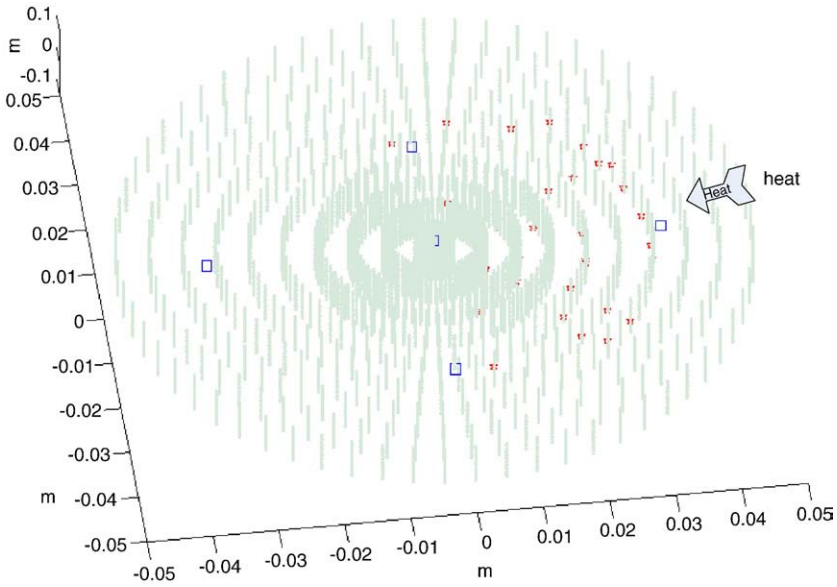


**Fig. 6.** Bubble nucleation map when using an outside heating gun. Once again the spatial map shown is larger than the vial, being the limits identified by the microphones.

In this paper we have shown a thorough approach to discriminate valid nucleations and to locate them within the vial. The spatial identification has clearly a space for improvement, especially regarding a better model for sound propagation within the hydrogenated gel and glass reflections, pressure and temperature dependence of the sound speed and finer mesh resolution. It is also needed further validation of the phantom suppression and a better understanding of spatial distribution of the nucleations.

Nevertheless, our experimental setup showed some encouraging results giving errors close to the mesh resolution and, in our understanding, shows that spatial localization within the vial can be carried out.

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