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OBSERVATIONS OF AN ACOUSTIC AEROSOL PARTICLE TRANSDUCER

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1. INTRODUCTION

The capability of aerosol particle detection in various environments has been becoming increasingly desirable in recent years. Interests of its application include clean-room mointoring of microelectronics fabricating facilities and air quality control. Detecting military aerosols used as obscurants is also important. The technologtical challenge lies in detecting micron and submicron particles with a concentration ranging from a few particles per liter (ppl) to a few parts per cubic meter [1]. It would serve great economic interests to develop a relatively portable device for such aerosol particle detection.

Much of the early work in acoustic detectors was performed in the 1950s to 1960s by Langer [2–5]. He noticed a change in flow noise through a vacuum cleaner while collecting dust from an aerosol generator. It was determied that the noise was created by a clamp on the vacuum hose. Langer reported the ability to detect particles down to 5 μm in diameter by the noise generated when they were drawn with air through a flow contraction. He aslo reported that all particles above 30 μm could be counted. Below 30 μm, not all particles were counted and below 10 μm the apparatus hardly performed counting [3]. He also reported that he was not able to detect particles smaller than 5 μm. Karuhn [6] used a capillary to draw particle-laden air and claimed to detect the oscillating shock wave at the exit of the capillary. He attributed the oscillating shock wave to the disturbance caused by the exiting particles; the shock wave was stationary without particles. Langer [3–5] suggested a transient shock wave initiated at the exit of the capillary by a temporary flow bolckage created by a particle exiting the capillary. However, it is noted that for a shock wave to occur the flow exiting the capillary must be supersonic. Supersonic flows will occur in the diverging section of a capillary for pressure ratios (inlet pressure to outlet pressure) less than 0·528 for air [7]. In reference [2] a pressure drop of 18 cmHg was reported across the capillary. Since

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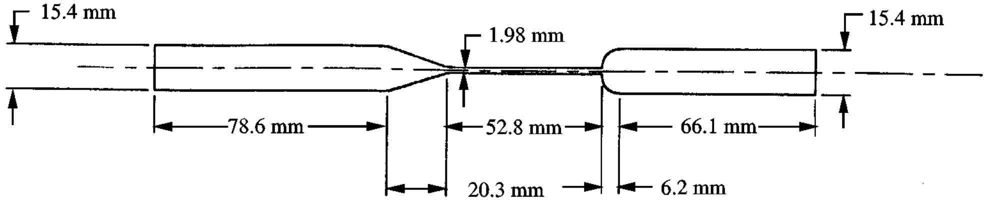

Figure 1. Sketch of the acoustic transducer.

the inlet was expose to the room air (at $\approx$760 mmHg), such a pressure drop was not sufficient to cause the capillary to produce a supersonic flow. Therefore, there should be no supersoic expansion and, consequently, there would be no shock wave at the capillary exit. As described below, acoustic signatures have been obtained in this study with pressure ratios up to 0·9, which is not sufficiently low to produce shock-related phenomena.

There are other types of particle detecting devices including the commonly used aerodynamic phase Doppler particle dynamic sizer. It involves a laser-based scattering technique and is much more expensive and requires a more skilled operator than the capillary/nozzle device of interest in this study.

After trying a wide range of variations of acoustic particle transducers resembling Figure 1, efforts were concentrated on the one that has the basic structure of a converging–diverging nozzle with the throat area replaced by a constant-area capillary (i.e., the one sketced in Figure 1). The following is hereof reported: (1) the capability of detecting aerosol particles having a diameter of 15 μm when drawn through acoustic particle counters that resemble the one sketched in Figure 1, (2) insight of the mechanism causing the the distinct particle related noise, and (3) effects of operational parameters on the signal characteristics of the aerosol particles.

2. EXPERIMENT

The experimental procedure is briefly described as follows; detail information is contained in reference [1]. The acoustic transducer is effectively a converging–diverging nozzle, as shown in Figure 1. The inlet tube had an inside diameter of 15·4 mm and a length of 78·6 mm, and was connected to the capillary tube, 1·98 mm in diameter, through a smooth contraction overa distance of 20·3 mm. The outlet tube was connected to the capillary with a more abrupt transition, as shown in Figure 1, and also had the same inside diameter as that of the inlet tube. Figure 2 shows the sketch of the complete experimental set-up. The acoustic transducer was placed in two separate (inlet and outlet), sealed but adjoining chambers made of Plexiglas and acrylic, respectively. The inlet chamber was open to the room air through a filter capable of filtering out naturally occurring particles larger than 0·5 μm. Verification of the filter effectiveness was confirmed using a TSI aerodynamic particle sizer (Model APS 3310). When the filter was removed, naturally occuring particles were observed to generate signals similar to those by aerosol particles used in the experiment. The aerosol particles having known nominal sizes, carried by particle-free pure bottled air, were injected into the inlet

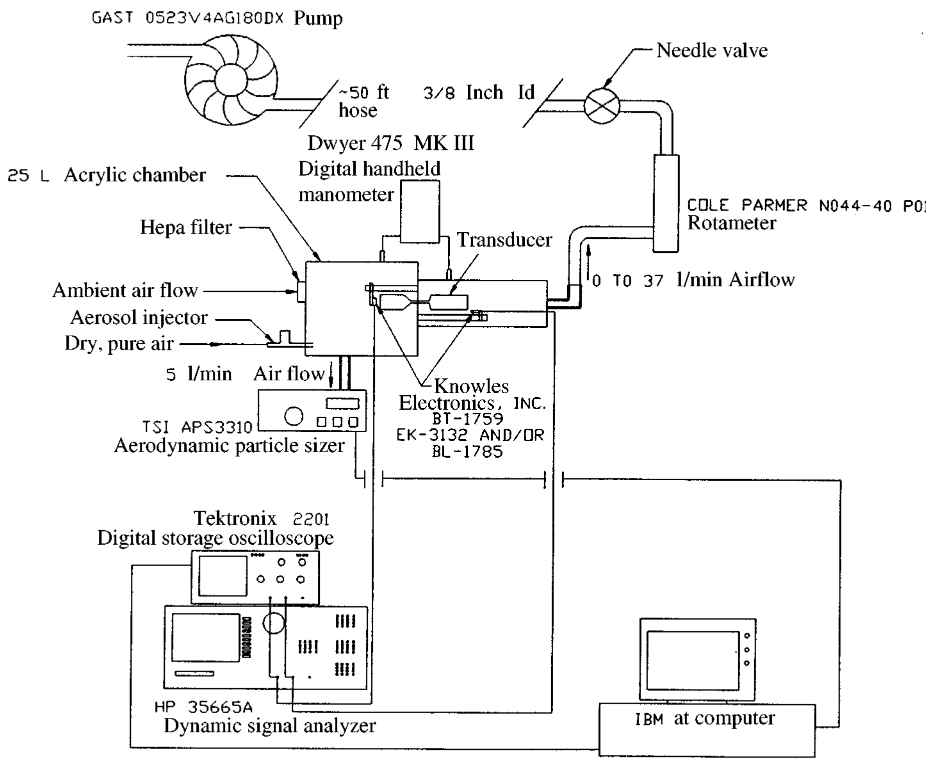

Figure 2. Diagram of experimental set-up.

chamber, as shown in Figure 2. During the experiment, some of these particles were also withdrawn into the APS 3310 for size verification. An air pump was used to draw room air through the acoustic transducer. When exploring acoustic characteristics, the microphone (manufactured by Knowles Electronics, Inc.) might be placed inside the transducer, all the way to the contration and the expansion part of it, and outside of the outlet tube. The microphone output was transferred to an HP 35665A Dynamic Signal Analyzer (DSA), coupled with a digital storeage oscilloscope (Tektronix 2201) for on-line observation. The DSA has FFT capabilities, yielding power spectra of the particle generated noise. An oscilloscope was used for real-time display of the signal.

A digital manometer as well as a vacuumeter were used to measure the prewssure drop across the capillary. The air mass flow rate was mointored by a rotameter.

The acoustic transducer must be carefully constructed so that the internal surfacs are smooth with no protrusions into the flow stream. Prostrusions into the flow generated noise similar to those generated by particles, as discussed in the Reults section.

3. RESULTS AND DISCUSSION

The following discussion concerns results obtained with the microphone placed upstream of the capillary. It was placed either outside or within the inlet tube. There was *audible* popping noise associated with particles entering the acoustic transdcer as verified by the real-time oscilloscope record. It is therefore possible to determine the particle density in ppl knowing the air flow rate. Concentrations lower than 10 ppl were measured. However, this report will concentrate on the acoustic characteristics of the acoutic signal as affected by the operation parameters.

A typical oscilloscope trace with the microphone placed 5 mm outside the inlet tube on the axis of symmetry of the transducer is shown in Figure 3. The particles used were 50 μm polystyree latex (PSL) microspheres. The signal began with a high-frequency output with a negative voltage, suggesting the signal began as a drop in pressure rather than as an increase. This occurred over a 0·5 ms period, followed by low-frequency signals for about the next 10 ms. It is noted that prior to when the drop was observed the acoustic signal has a much smaller amplitude than what follows the pressure drop. This is typically observed when care was taken so that there were no particles passed through the transducer. The spectral contents of the signal of Figure 3 are shown in Figure 4. Four distinct peaks can be seen at approximately 900, 2700, 4500, and 6300 Hz. It is noted that the higher frequencies are multiples of the lowest one. The fundamental frequency of the acoustic response is therefore approximately 900 Hz. These peaks remained to have nearly the same frequencies when particles of various sizes or different flow rates were used. This remained so when PSLwas replaced by 1/4-in fibers. Cutting off and removing the outlet tube and the capillary did not affect these frequencies as long as an about 10 mm long capillary was left for good signal-to-noise ratios. It was further observed that the degree of polishing of the tube inside walls did not have significant effects on the signal-to-noise ratio as long as they were polished with 600 grit polishing compounds and above.

It was found that over the flow rate range up to 30 l/min, the pressure drop across the capillary was measured to be les than 10 kPa. Since the inlet chamber had a pressure equal to the atmosphere ($\approx$ 101 kPa), the pressure ratio is about 0·9, not enough for the capillary to be choked and display shock wave formation.

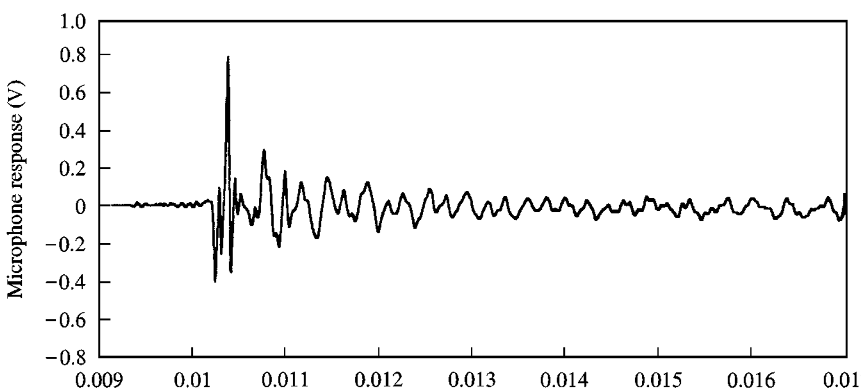

Figure 3. Typical oscilloscope trace of the acoustic signature produced by 50 μm polystyrene spheres; microphone placed outside of the inlet tube.

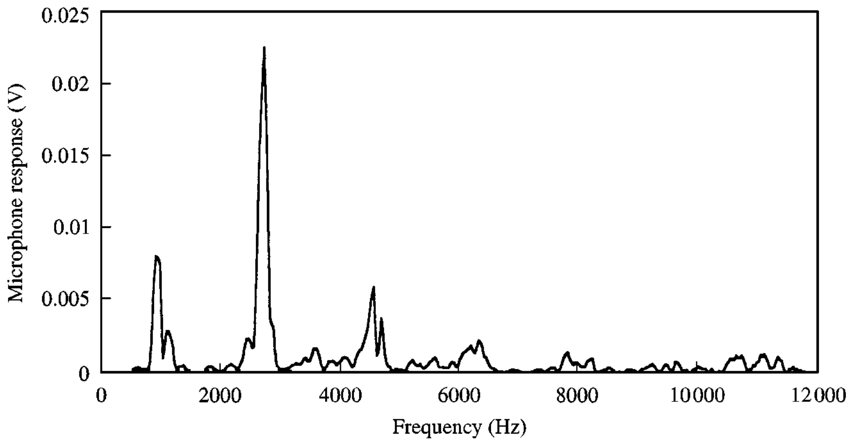

Figure 4. Spectral distribution of the acoustic signal of Figure 3.

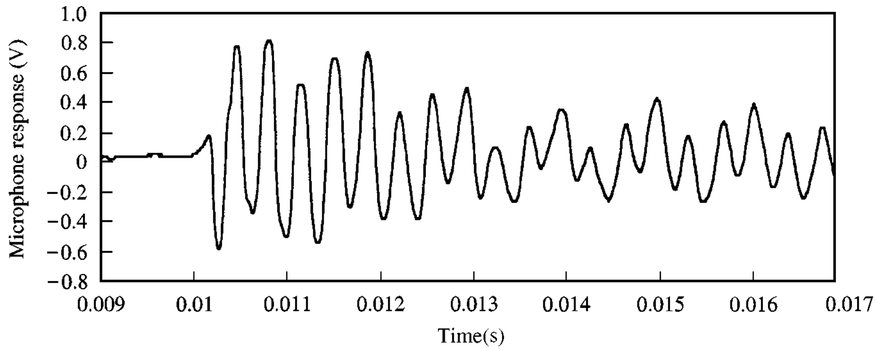

Figure 5. Typical oscilloscope trace of the acoustic signature produced by 50 μm polystyrene spheres; microphone placed 25 mm within the inlet tube.

It is believed that the acoustic signal had its origin in the contraction area. Supportive evidence may be based on the fact that when the microphone was placed downstream of the capillary, the downstream signals began with a increase in pressure. This suggests qualitatively different phenomena when the signal was detected upstream and downstream of the capillary. The positive leading peak detected downstream may be expected because the flow decelerates and its pressure rises exiting an expansion. The lead peak detected with the upstream microphone can likewise be expected to begin with a decrease in pressure. Where could the signal be generated between the inlet and the contraction? To resolve this, the microphone was placed at various locations within and outside the inlet tube. The oscilloscope and spectral results are similar to those shown in Figures 3 and 4, respectively. The results of Figures 5 and 6 were obtained with the microphone placed 25 mm within the inlet tube. The following can be noted from these figures. First, the signal began with a drop in pressure. Secondly, spectral peaks were observed at approximately the same frequencies as those in Figure 4. That is, the signals are at least qualitatively similar to those obtained with the microphone placed upstream of the inlet tube. Measurements were also done without the

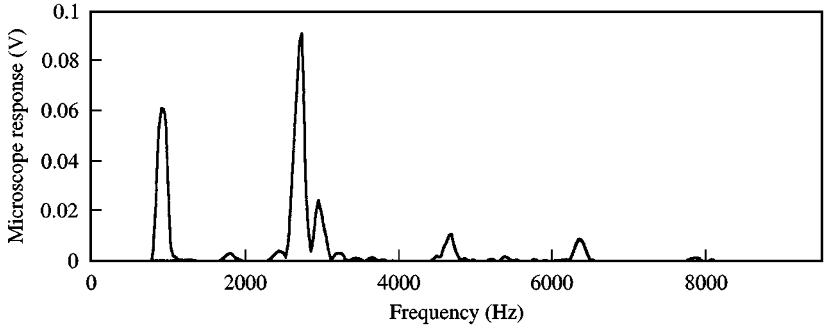

Figure 6. Spectral distribution of the acoustic signal of Figure 5.

capillary and the downstream diverging section, when acoustic signals were also observed with the microphone placed upstream of the inlet. These results appear to suggest that the signal source resides in the contraction area or immediately downstream of it within the capillary.

Questions arise regarding what physical process causes the noise as particles travel through the contraction. It was initially conjectured that particles going through the contraction may not follow the acceleration faithfully and will cause flow and pressure disturbances due to the separation bubble or wake behind them. To test this hypothesis, a wire was placed at the inlet of the transducer to “trip” the flow, without PSL particles, and produce separation bubbles. Signals could be aqudibly observed and were detected by the DSA. A 30 l/min flow of air was estimated to give a velocity of 0·67 m/s in the constant tube and a Reynolds number, based on the inlet tube diameter, equal to about 680. This Reynolds number is much lower than that required for turbulent flows in pipes, which is at least 2300 for a smooth pipe. It is then believed that no flow disturbances other than those caused by particles occurred. The larger particles are expected to lag more in the flow than the smaller ones. A simple one-dimensional finite-difference technique was used to solve for the particle motion going through the contraction. A Stokes drag was assumed in the calculation. Typical results for 2 and 50 μm particles with similar air flow rates are shown in Figures 7 and 8 respectively. The air velocity increased from about 1 m/s to more than 160 m/s through the contraction. The 2 μm particle faithfully followed the accelerating air motion, i.e., without velocity difference, throughout the contraction, as can be seen in Figure 7. On the otherhand, the 50 μm particle velocity never reaches the air velocity through the entire contraction area. As shown in Figure 8, the maximum velocity difference reached about 160 m/s before entering the capillary. In fact, the 50 μm particle still did not pick up the air speed at the end of the capillary. In terms of the particle-induced flow disturbance, the larger particles are expected to give higher signal amplitude than the smaller ones. Indeed, when the microphone was placed 5 mm outside the inlet tube, the peak-to-peak magnitudes for the same flow rate (20 l/min) were measured to be 0·7 and 0·4 V (not reported here), respectively, for 50 and 15 μm PSL particles. With the help of the APS, it was found that about 15% of the 9·6 μm and only 8% of the 5·9 μm PSL particles were detected by the acoustic

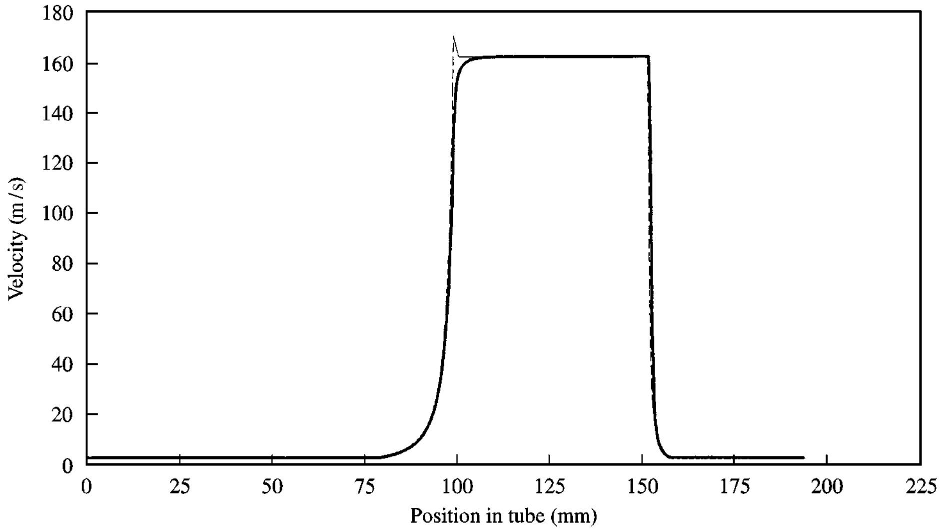

Figure 7. Calculated flow and particle velocity as a function of location in the acoustic transducer. The particle is a polystyrene sphere, 2 μm in diameter. ——: Particle velocity; ---- air velocity.

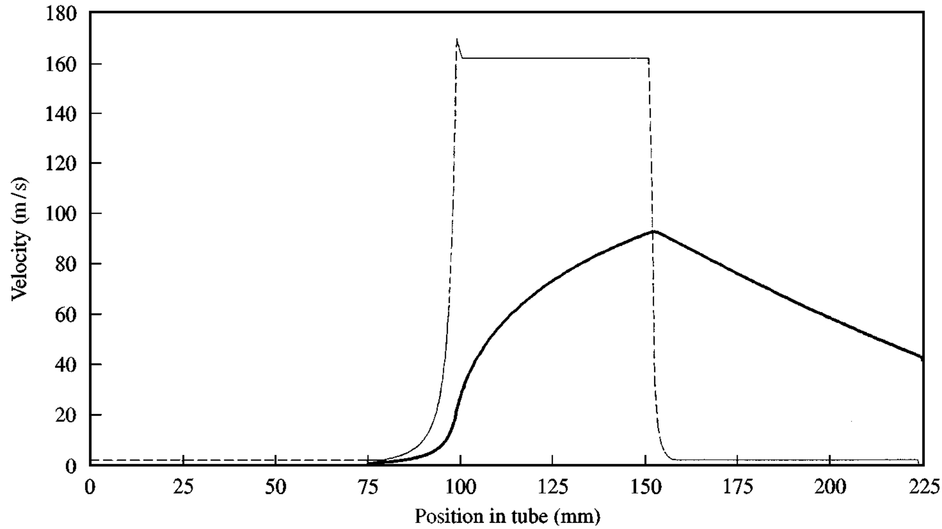

Figure 8. Calculated flow and paerticle velocity as a function of location in the acoustic transducer. The particle is a polystyrene sphere, 50 μm in diameter. ——: Particle velocity; ---- air velocity.

transducer [1]. This observation consistently indicates that larger particles produce larger acoustic amplitudes and are, therefore, more dectable. Similarly, as the flow rate increases the velocity difference between the air flow and the particle will increase. This is expected to increase the degree of flow disturbance and, therefore, the signal magnitude. The results of Figure 9 confirm this. However, the benefits of increasing the flow rate beyond 30 l/min is only marginal.

Another possibility for an acoustic source to reside in the contraction area is as follows. As the particle passes through the contraction, its motion may become

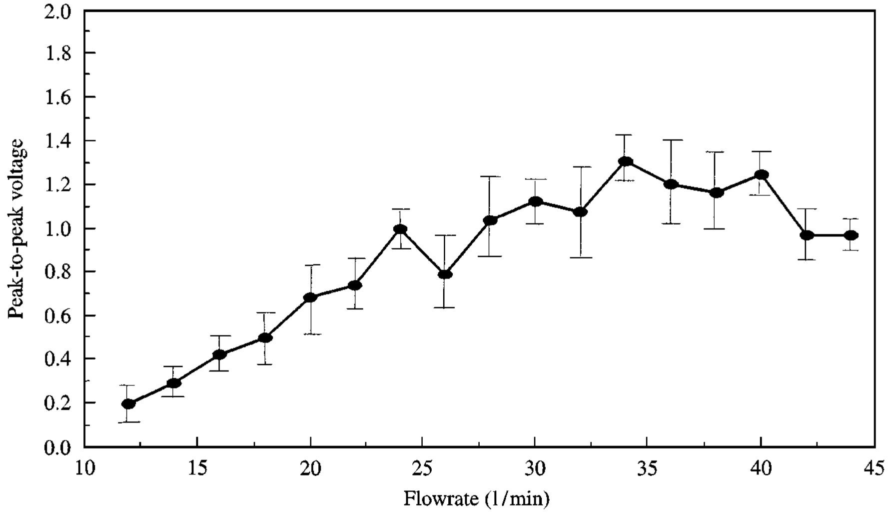

Figure 9. Peak-to-pea acoustic signal amplitude as a function of flow rate; the particle is the 50 μm polystyrene sphere.

TABLE 1

Theoretical and measured fundamental and overtone frequencies of several transducers

Transducer	Pipe length, L (mm)	f_o^* (Hz)	$3f_o$ (Hz)	$5f_o$ (Hz)	$7f_o$ (Hz)
Figure 1[†]	78·6 (inlet tube only)				
	Theoretical	1101	3302	5503	7704
	99·0 (inlet tube and contracrtion)				
	Theoretical	874	2621	4369	6116
	Measured[‡]	≈ 920	≈ 2710	≈ 4560	≈ 6320
A1[†]	86·0 (inlet tube and contraction)				
	Theoretical	1006	3017	5029	7041
	Measured[‡]	≈ 1000	≈ 3000	≈ 5060	≈ 7000
B2[†]	59·4 (inlet tube and contraction)				
	Theoretical	1456	4368	7280	10 192
	Measured[†]	≈ 1530	≈ 4380	≈ 7060	≈ 10 050
B3[†]	61·8 (inlet tube and contraction)				
	Theoretical	1400	4199	6998	9798
	Measured[‡]	≈ 1560	≈ 4519	≈ 7200	—[§]

*$f_o = c/4L$, where sonic speed, c, is based on 25°C.
[‡]Measured frequencies were estimated because spectral peaks could contain two or more narrowly spaced peaks.
[§]Cannot be easily determined because of very broad peaks.
[†]All transducers have an outlet tube and the capillary length ranges from 43·4 to 52·0 mm.

unsteady or vibrating as a result of the difference in velocities and flow disturbances. Small PSL spheres used in this study can be considered moving "compact" spheres and radiate a sound power proportional to U^2d^6, where d is the diameter and U is the r.m.s. particle velocity [8]. The radiated sound is then amplified at the fundamental frequency of the inlet tube, to be discussed in the text below. This theory also appears useful in explaining the above-mentioned signal strength increase with the flow rate since the r.m.s. velocity should also increase with the flow rate. However, this theory deserves further investigation for the acoustic transducer application. For example, wider ranges of flow rates and particle sizes need to be examined. It can be summarized that, whether the acoustic source is generated by the particle-induced flow disturbance or by particle velocity instability, it can be measured with a microphone placed upstream of the inlet and within the inlet tube.

The similar spectral contents of the acoustic signals shown in Figures 4 and 6 suggestes that some fundamental values exist within the transducer. Tests indicated that changing the length of the inlet tube and the contraction alter the spectral contents accordingly. The inlet tube or the inlet tube/cotraction appear to constitute an organ pipe with one open end. The fundamental frequency of an organ pipe is $f_o = c/4L$, where c is the sonic speed and L is the length of the organ pipe. The measured frequencies of the present transducer of Figure 1 and others (conveniently labeled as A1, B1 and B3, which have inlet tube diameters equal to 10·0, 10·0, and 6·7 mm respectively) are listed in Table 1. All the four transducers have an outlet tube and a capillary length range from 43·4 to 52·0 mm. The measured values agree better with the calculated ones with L including the lengths of the tube and the contraction. The theoretical values of f_o of A1, B2, and B3 transducers were similarly calculatedin Table 1. For organ pipes with one open end, the overtones (or harmonics) are the odd multiples of f_o, and both their theoretical and measured values are also given in Table 1 for all four transducers. Overall, the agreement between the theoretical and experimental values is very encouraging. This further suggests that the acoustic transducer acts like an organ pipe with the pressure disturbance/fluctuation produced by the aerosol particle near the close end of it (i.e., in the contraction area or the capillary immediately downstream of it). The inlet tube diameters ranged from 6·7 to 15·4 mm (as noted above) and did not seem to affect the spectral contents. These findings regarding the acoustic transducer have not been previously reported to the authors' best knowledge.

4. SUMMARY

(1) Unlike previous claims, the results of the present study reveal that acoustic signals are generated by particles going through a flow contraction and are not caused by the shock waves at the exit of the transducer. They are possibly caused by either or both of two mechanisms: (1) the flow disturbance arising by the particle unable to follow the flow acceleration in the flow contractrion, and (2) the unsteady particle motion in an accelerating flow field. For either mechanism, the acoustic source appears to be in the contraction area or immediately downstream of it within the capillary.

(2) Since the accelerating flow field occurs in the contraction or expansion areas of the transducer, the acoustical signal can be located in those areas. Key results of this study were obtained with the microphone placed upstream of the contraction of the flow. The leading peak of the signal began with a decrease in pressure, consistent with the accelerating flow in that region.

(3) The acoustic disturbance due to particle motion is amplified by the inlet tube acting like an organ pipe. The measured frequencies using inlet tubes of different lengths were found to be nearly the same as the fundametal organ pipe frequencies with one end closed and their overtones/harmonics calculated based on the inlet tube length.

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