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Noise Generated by Multiple-Jet Nozzles With Conical Profiles

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Conical multiple-jet nozzles, which reduce the risk of nozzle openings being blocked, are tested for their effectiveness in noise reduction. Nozzles with different exit spacings are tested. It is found that the multiple-jet design significantly decreases noise levels in the audible range by shifting emitted sound power to higher and ultrasonic frequencies. No significant difference in noise characteristics between exits distributed on a flat plane and beveled exits on a conical surface is observed. When the exits are more densely distributed, there is a trend of spectra shifting back toward the low frequency. This phenomenon is found to increase sound levels in a certain range of frequencies much lower than the peak one. Although this increase contributes little to the total emitted sound power, it is an important factor in determining the sound levels of audible noise.

jet noise   multiple-jet nozzle   ultrasound

1. INTRODUCTION

High-speed air jets are a major industrial noise source. For applications that require high thrust or high air volume, noise control methods that rely on the dissipation of the jet kinetic energy are not practical. To obtain the required thrust, one may use a large-diameter jet at low velocity to reduce the total kinetic energy of the exhausted air, thus reducing the emitted sound power. However, this approach will increase the consumption of compressed air.

One noise control method that maintains the required thrust without increasing the air consumption is the multiple-jet nozzle, which uses multiple and smaller jets to replace a single jet. Because the reduced length scales of smaller jets increase noise frequencies, this approach has been shown to shift a portion of emitted sound power into the ultrasound range, thus reducing the sound levels of audible noise [1].

Although ultrasound is a potential hazard itself, the recommended limiting levels for airborne ultrasound in general are much higher than those for noise in the audible range. Current suggested limiting levels for airborne ultrasound are typically at 110 or 115 dB for the one-third-octave bands above 20 kHz [2].

In addition, ultrasound is attenuated much more rapidly in air than sound in the audible range. At 20 °C and 50% relative humidity, 20-kHz sound is attenuated by 0.5 dB/m in air, while 40-kHz sound will be attenuated by 1.3 dB [3]. Thus, air absorption will effectively attenuate ultrasound radiation after a few reflections even without sound absorption by solid surfaces, which tends to be high for ultrasound, too. Therefore, the shifting of emitted sound power to higher frequencies will significantly reduce the overall levels of the reflected sound, which often dominates the sound field in the generally reverberant industrial environments. This analysis indicates that increased ultrasound levels generated by a multiple-jet nozzle should be a relatively less severe hazard.

Huang and Rivin reported the noise-abating effect of multiple jets discharged from a flat surface [4]. Sheen and Hsiao demonstrated the spectrum-shifting effect of multiple-jet nozzles [1].

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In addition to noise, another risk associated with the use of hand-held blow-off guns with exits distributed on a flat surface, either single-jet or multiple-jet, is that the exits are likely to be accidentally blocked, inducing high air pressure at the nozzle exits.

The Occupational Safety and Health Administration (OSHA) of the USA created regulation 29 CFR 1910.242(b), requiring that the static pressure should be reduced to less than 30 psi (206.8 kPa) when the exits are dead-ended for nozzles used for cleaning purposes [5]. To satisfy this requirement by simply lowering the supply pressure would not be practical because it would reduce the exit velocity and increase the air consumption. Using pressure-releasing valves is a feasible option with the disadvantages of bulky and complicated components. Other possible approaches include the use of guards to prevent the blocking of nozzle exits.

This risk of high air pressure can be reduced, if not eliminated, by using a multiple-jet nozzle with exits distributed on a conical surface. It is unlikely to accidentally block all the exits at the same time if the exits are distributed on a conical surface. Any unblocked exit will act as a pressure-releasing vent, thus reducing the pressure at the blocked exits. Coupled with air-releasing valves, this design will offer an increased level of safety. Many commercial nozzles also add ribs between adjacent exits, further reducing the possibility of nozzle exits being blocked.

Although an approximate sound spectrum is available for noise generated by a single jet [6], the prediction of noise characteristics for a multiple-jet nozzle is not necessarily a straightforward task, especially for sound levels at frequencies much lower than the peak frequency in the sound spectrum.

For a single jet, noise sources are distributed along the mixing layer formed between the jet core and the ambient air. In general, sources generating sound near the peak frequency are located near the nozzle exits, while those of lower-frequency noise are distributed more downstream [7].

For jet flows discharged from a multiple-jet nozzle, in regions immediately downstream of the nozzle exits, individual jets basically develop independently. Therefore, noise generated in this region can be predicted by the known jet noise spectrum for a single jet. High-level noise consisting of high frequencies is generated in this region.

For noise generated by a single jet, the peak frequency in general exceeds one-fifth of a reference frequency that is defined as the exit velocity divided by the exit diameter [6, 8]. For example, for a nozzle discharging air at sound speed from an exit of 1-mm in diameter, this peak frequency will exceed 70 kHz. For isentropic flows, the exit velocity will reach the sound speed with an upstream pressure of only 90.2 kPa gauge pressure [9]. Because this peak frequency is inversely proportional to the exit diameter, for small-diameter jets common in most hand-held applications, dominant noise, which is emitted from the region close to the nozzle exits, is expected to consist of frequencies mostly in the ultrasound range. In contrast, noise sources responsible for the generation of audible noise, which is relatively low frequency in the sound spectrum, should be located further downstream.

As air exhausted from the multiple exits of a multiple-jet nozzle flows downstream, it will entrain ambient air and create attracting forces between jet streams, eventually leading to the formation of a single jet, which generates lower frequency noise than the smaller jets because of its larger length scales. Therefore, the standard noise spectrum has to be modified for noise generated in the region where individual jet streams start to merge.

Because the merging of jet streams will not start immediately after the air is exhausted from the nozzle openings, this process should affect mostly sound sources that are downstream of those responsible for the generation of peak frequency noise. The associated noise radiation is expected to be relatively weaker and contain lower frequencies than that emitted from regions near the nozzle exits. Because the position where the effect of merging starts to emerge should be related to the spacing between nozzles exits, nozzle exit spacing is expected to affect noise at frequencies much lower than the peak one even if it has little effect on the total emitted sound power, which is mostly determined by the high-frequency noise generated near the exits.

Although noise in this relatively lower frequency range constitutes only a small part of total emitted sound power, the possibility that its frequency content overlaps the frequencies that are most damaging to human hearing can not be excluded. Therefore, even though exit spacing in a multiple jet nozzle is not expected to significantly change the total emitted sound power, it might be an important factor in the evaluation of lower-frequency noise, which is more closely related to the risk of noise-induced hearing loss.

Therefore, in this work, we plan to study the characteristics of noise generated by flows discharged from multiple-jet nozzles with conical profiles, which is an effective approach for preventing pressure build-up at the nozzle exits. Special attention will be paid to the effect of exit spacing on the frequencies which human hearing is most sensitive to.

Noise generated by small-diameter jets common in many industrial applications covers a wide range of frequencies. Except for frequencies below 8–10 kHz, which are commonly used to evaluate occupational noise exposures, small-diameter jets also generate high levels of high-frequency audible noise of 8–20 kHz and even higher levels of noise in the ultrasound range. A significant portion of the radiated sound power exists at frequencies beyond the frequency range of today's free-field ultrasound measurement microphones. In this work, we will limit our scope to frequencies below 20 kHz.

2. METHODS

2.1. Experiment Setup

The compressed air that drives the jet flows in this work is supplied by a common industrial air compressor. Two air tanks in series supplies a total storage volume of ~210 L. Maximum pressure regulated with a pressure switch is ~760 kPa. Flow rate is controlled with a pressure regulator, which keeps the supply pressure at the set value to produce a steady flow rate. Mass flow rate is measured with a Dwyer GFC-1144 mass flow controller (Dwyer Instruments, USA), which contains a mass flow rate display as well as a control valve. The measuring range is 0–10 g/s. Since the pressure regulator alone is capable of maintaining a steady flow rate, we de-activate the control valve and use the mass flow controller simply as a mass flow meter.

Instrument for noise measurements is a Svan945a Class 1 sound level meter with real-time one-third-octave-band analyzing capability (Svantek, Poland). The sound level meter is fitted with a GRAS 40AN free-field microphone (GRAS Sound and Vibration, Denmark). This whole instrument's frequency response has deviations no more than 2 dB from 20 to 16 kHz when the internal compensation filter is not used. The sound level meter is calibrated onsite using a Quest QC-20 calibrator (Quest Technologies, USA). Time constant is set at the fast response and the period of measurement is 5 s. It is found that the measured sound pressure levels are very steady over this measuring period. The recorded time history of sound pressure levels shows that the differences between the maximum and the minimum *A*-weighted overall sound pressure levels are generally below 0.5 dB over the 5-s measuring period. This also indicates that the pressure regulator is capable of maintaining a steady flow rate.

2.2. Acoustical Test Environments

Sound measurements are made in a room 11 m long, 4.5 m wide, and 4 m high. One of the 11-m walls is made of double plywood panels with insulation materials in between. Other surfaces, excluding furnishings, are either painted concrete or ceramic tiles. To improve the sound absorbing property, we use 4-cm-thick acoustical foam wedges and fabrics that are suspended overhead and along the walls. Foam wedges are also placed on the floor right below the nozzle tip.

Because noise generated by small-diameter jets contains little power at low frequencies, sound reflection in the test environment after treatment should have little influence on the overall sound pressure level measurements. A measuring distance of 30 cm, which is equal to the wavelength of sound of ~1.1 kHz, from the microphone diaphragm to the nozzle's axis is used. At this distance, it can be verified the ratio of the strength of the direct field to that of the reverberant field will exceed 10 if the room constant is larger than 45 m^2 for a point source that radiates sound uniformly in all directions. A room constant of 45 m^2 corresponds to an average absorption coefficient of ~0.2 in a diffuse field for a room of this size, which should be easily attained for frequencies above 1 kHz, where most sound power exists.

Background noise levels are below 30 dB in all the one-third-octave bands above 400 Hz during all measurements.

Noise measurements are made in three different directions, with the microphone positioned at three different angles of 30°, 90°, and 135° relative to the nozzle's axis. The angle is defined such that, at 0°, the microphone axis is aligned with the nozzle's center line and the microphone's diaphragm faces the nozzle's exit. Figure 1 shows the position and orientations of the sound level meter to the nozzle at the three angles. Nozzles are attached to the end of a 60-cm steel pipe extended from a table. Both nozzles and microphone are placed at the same height of ~90 cm.

2.3. Nozzles Tested

All nozzles tested in this work are chosen to have approximately equal total exit area so that they will produce equal thrust at the same flow rate. Nozzles with larger exit area can generate the desired thrust with lower exit velocities, which is achieved by decreasing the supply pressure. This in general increases air consumption, because the process of regulating the supply pressure wastes the energy used to compress air. Since the sound power grows as the eighth power of velocity [7], larger nozzles generally generate less noise at the same thrust. However, the increased air consumption makes this approach not economically practical.

Theoretically, if the flow is one-dimensional and the air properties at the nozzle exits are fixed,

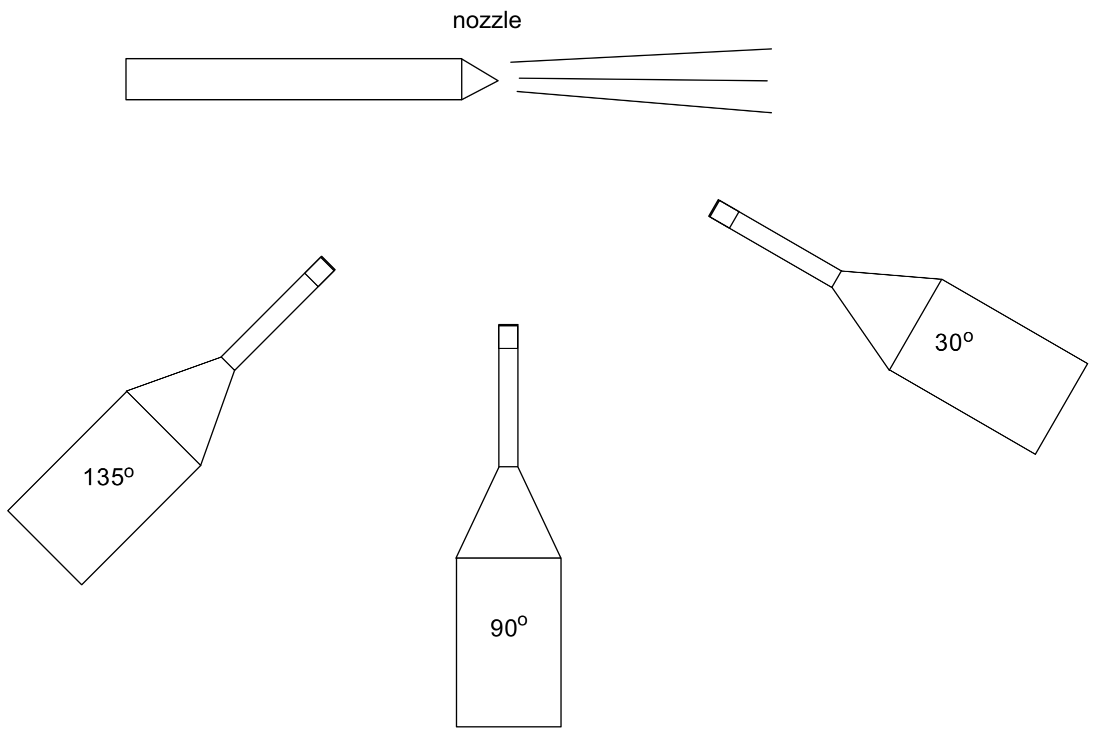

Figure 1. Setup of the sound level meter for sound measurements. Distance of the microphone diaphragm to the tip of the nozzle is 30 cm.

nozzles with equal exit areas should generate the same thrust. Since the nozzle exits have very small dimensions, especially for a multiple-jet nozzle, it is difficult to machine the nozzles to exactly satisfy the equal-exit-area requirement. In addition, the assumption of one-dimensional flows has its intrinsic deficiency. Therefore, the relationship between thrust and flow rate will be verified by measurements of thrust on a flat plate positioned 20 cm from the nozzle tips.

A single-jet open-pipe nozzle with an inner diameter of 3.2 mm is used as the reference. This nozzle is denoted as 1 × 3.2 mm. The first number is used to indicate the number of exits, while the second one specifies the diameter of the exits. Similar notations are used for other nozzles. The total length of this pipe is ~20 cm.

Three multiple-jet nozzles with conical profiles are tested. Those nozzles are machined from hexagon rods with a diagonal of 24 mm. The cone apex angle is 80° (Figure 2). Two nozzles have exits distributed on an 8-mm circle. They have 8 and 10 exits. The exit diameters are 1.1 and 1.0 mm respectively. The third nozzle also

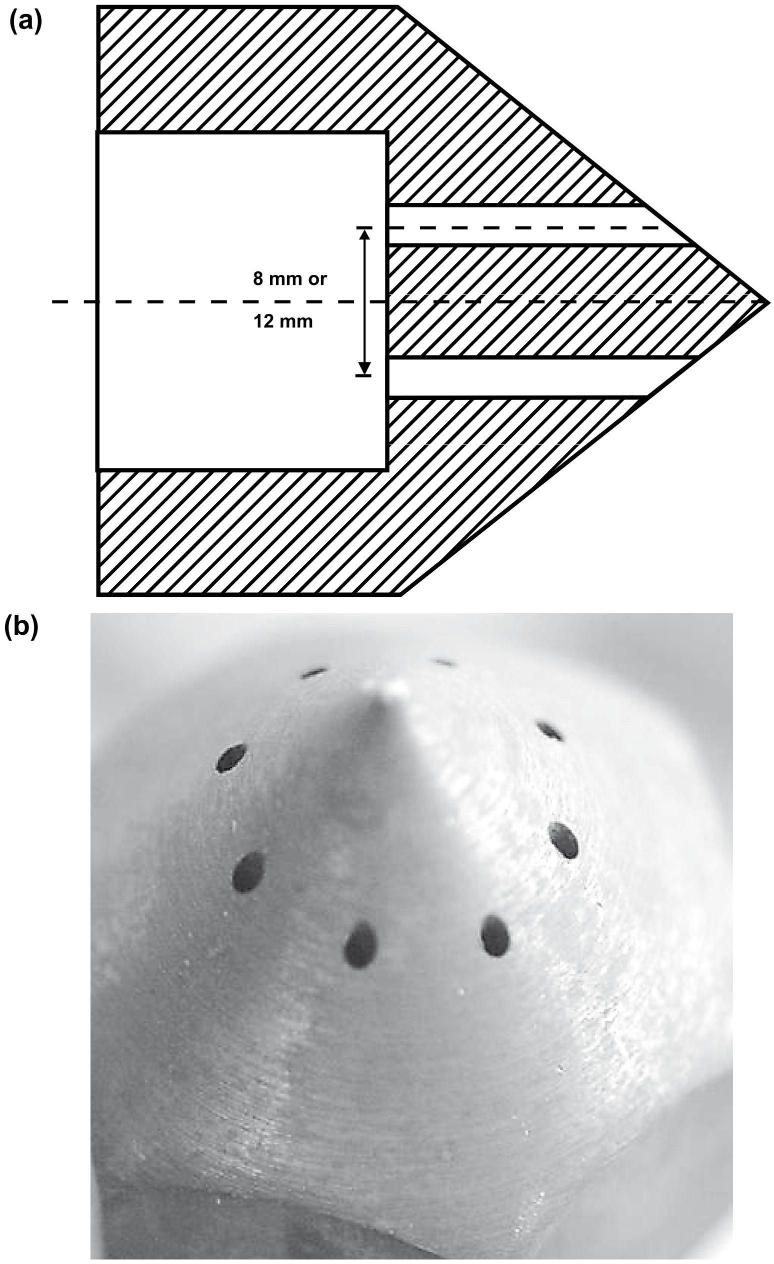

Figure 2. (a) Cross-sectional view of a conical multiple-jet nozzle, (b) photo of the conical nozzle with eight 1.1-mm exits distributed on a 12-mm circle.

has eight 1.1-mm exits. But they are distributed on a 12-mm circle. Therefore, the exit spacings for the three nozzles are 2.5, 3.1, and 4.7 mm respectively, measured along the circle where the exits are distributed.

3. RESULTS AND DISCUSSIONS

3.1. The Variations of Thrust Versus Flow Rate

Nozzles used in this work all have similar total exit area so that they will generate equal thrust at the same flow rate. However, many factors may lead to unpredictable deviations. Those factors include, among others, the precision of machining, the variations of flow properties such as density and temperature at the exit, and the validity of the assumption of one-dimensional flows, which ignores the existence of boundary layers and the non-uniform velocity profile on the cross-section at the exit plane.

To evaluate the uncertainties in thrust, we measure thrust on a plane 20 cm from the nozzle for varying flow rates. Note that the thrust force is not sensitive to the distance from the nozzle. Figure 3 shows the results. The exit velocity will reach sound speed at the flow rate of ~3.2 g/s if the temperature at the exit, which determines the sound speed, is equal to the ambient one.

There are noticeable differences among tested nozzles. However, the deviations in thrust are found to be equivalent to the variations of no more than 1 dB in sound pressure levels for flow rates of interest. For example, the 3.2-mm single-jet nozzle consistently generates the largest thrust among all tested nozzles. To generate the same thrust at the exit velocity near the sound speed, it requires ~8% less flow rate than the nozzle with eight 1.1-mm exits distributed on an 8-mm circle. An 8% flow rate change is equivalent to ~1 dB in overall sound pressure level at the choked flow rates (when the exit velocity reaches the sound speed at ~3.2 g/s).

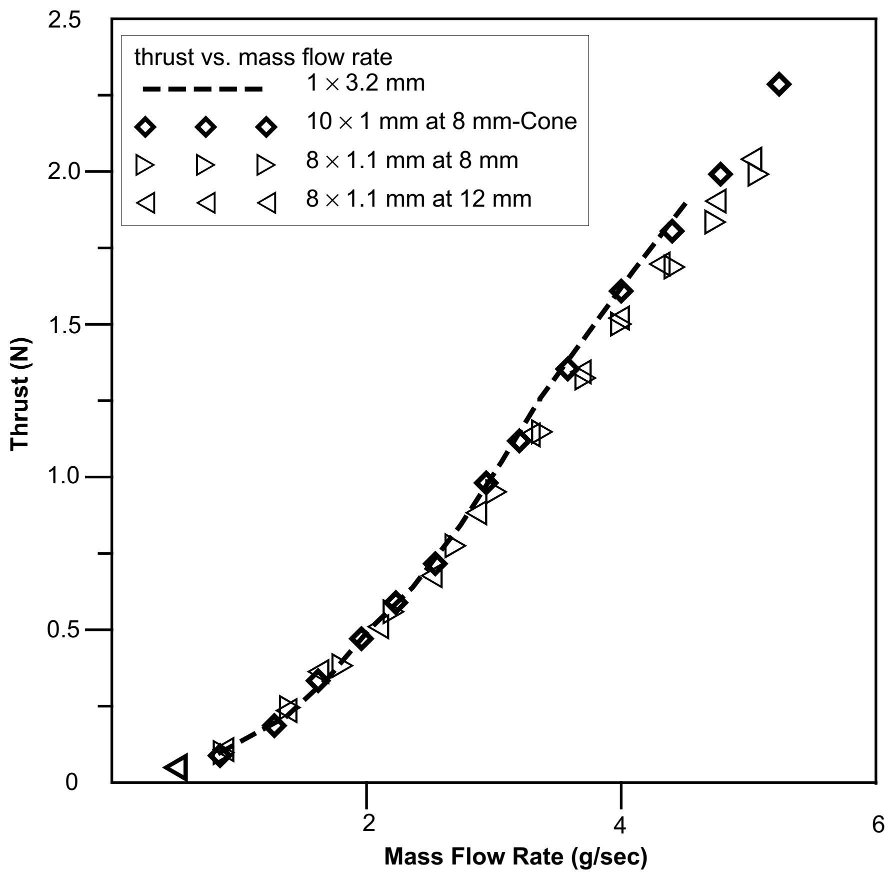

Figure 3. Thrust at 20 cm from the nozzle exit for the tested nozzles.

3.2. Variations of Sound Pressure Levels with Measuring Distances

For work with hand-held air guns, the distance from the nozzle tip to the operator's ears can vary from as little as ~30 cm for some precision work, such as that performed in a dental lab, to more than 1 m for many cleaning jobs. In addition to the distance to the nozzle, the actual sound pressure levels in workplaces are also influenced by sound absorption in the working environment. Therefore, it is difficult to predict the noise exposure in an actual working environment simply on the basis of measurements performed in a laboratory.

In this work, we will focus on the variations in noise characteristics caused by different nozzle designs instead of on the actual sound levels in a workplace. Measuring distance in this work is chosen to be 30 cm to minimize the influence of the testing environment without significant near field effect for frequencies above 1 kHz, below which there is little sound power. To demonstrate the environmental effect in sound measurements, we made a few test measurements at different distances from the nozzle tip at the angle of 90°. The nozzle with ten 1-mm exits is used for these tests.

Figure 4 presents sound spectra obtained from these measurements. The flow rate is fixed at 4 g/s, which is typical of industrial applications using nozzles with similar exit area. Visual observation using schlieren optics also verifies the existence of strong shock-cells, which are generated by a sudden pressure drop at the nozzle exits.

Three measuring distances, 20, 30, and 45 cm, are tested. For a point source in a free field, the inverse square law predicts a decrease of 3.52 dB for a 50% increase in measuring distance. Even though the noise sources associated with jet flows are not exactly point ones, a scale of 3.5 dB is shown as a reference. In general, we observe

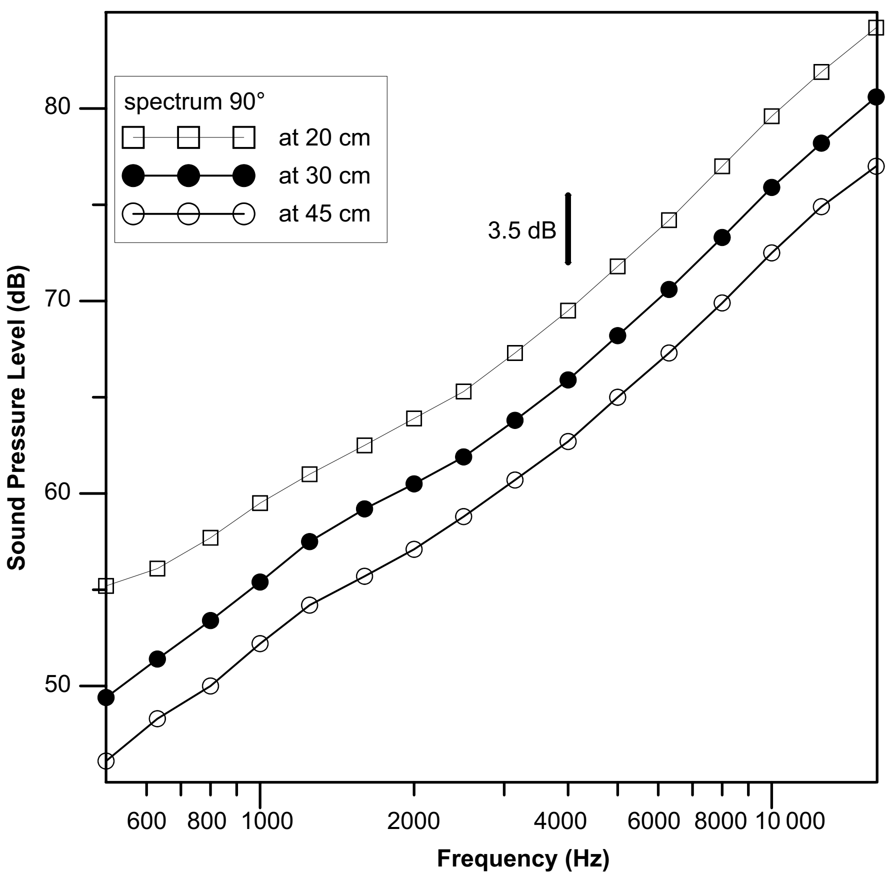

Figure 4. Sound spectra at 90° with different measuring distances for the 10-exit nozzle at the flow rate of 4 g/s.

similar spectra above the frequency of 1 kHz for the three distances. One kilohertz is equivalent to the wavelength of ~34 cm, close to the 30 cm we use in the following measurements. For noise generated by small-diameter choked jets, little contribution to the overall sound pressure levels, *A*-weighted or un-weighted, comes from frequencies below 1 kHz.

The sound pressure level differences between 20 and 30 cm range from 3.4 to 3.6 dB in the one-third-octave bands from 2 to 16 kHz. The differences between 30 and 45 cm range from 3.2 to 3.6 dB in the same frequency range. The smaller decaying rates, or larger deviations from the theoretical values for a point source, at the lower frequencies should be partly due to the poorer sound absorption expected at those frequencies. Another possible cause is that noise sources for lower frequencies in general are located more downstream and cover a larger region. Therefore, the model based on a point source is expected to induce more deviations at lower frequencies. It should also be noted that we measure the distance from the jet centerline to the microphone diaphragm, while the jet noise sources are located in the mixing region between the jet core and the ambient air.

In general, for frequencies above 1 kHz, those spectra show no sign of the testing environment significantly influencing the measurements made at 30 cm.

3.3. Sound Spectra at Typical Flow Rates

Figures 5–7 show noise spectra at the flow rate of 4 g/s for the three angles of 30°, 90°, and 135° respectively. As mentioned in section 3.2., the flow rate of 4 g/s is typical of work with nozzles with similar exit area. At this flow rate, shock cells are observed to form downstream the nozzle exits. But the shock cells have little influence on noise in the frequency range investigated in this work [8, 10].

In addition to the single-jet nozzle and the three conical nozzles, we also show the noise spectra for a multiple-jet nozzle with exits distributed on a flat surface. This nozzle was used in a previous work [1]. This nozzle has five 1-mm exits distributed on a 7.5-mm circle, denoted as 5 × 1 mm-Cap, whose combined exit area is equal to approximately one-half that of other nozzles tested in this work. Therefore, we use the flow rate of 2 g/s to obtain the same exit velocity. In addition, 3 dB is added to the sound pressure level in each frequency band to compensate for the smaller exit area.

The peak frequency of a jet sound spectrum can be estimated using a reference frequency that is defined as the exit velocity divided by the exit diameter. The peak frequency in general exceeds one-fifth of this reference frequency [6, 8]. If the exit velocity is 345 m/s, the peak frequency will exceed 70 kHz for a 1-mm exit and 22 kHz for a 3.2-mm exit. Therefore, for all the tested nozzles, the peak frequencies at choked flow rates are expected to be in the ultrasound range.

The three figures clearly demonstrate that, when the exit diameter is reduced, the shift of emitted sound power toward high frequency will lead to lower sound pressure levels in the frequency range below the peak frequency.

The quantity of noise reduction at frequencies below the peak frequency is related to the slope of the spectrum. The slopes above 8 kHz are very uniform for all the multiple-jet nozzles. At 30°, the slope is ~10 dB per octave. The slopes are smaller at 90° and 135°, ~8 and 6 dB per octave respectively. Therefore, noise reduction at audible frequencies with the use of multiple-jet nozzles will be most evident at 30°.

Consistent with most published results, the strongest sound radiation is in the downstream direction [6]. Although operators of hand-held air guns rarely work in this direction, in a reverberant environment, a significant portion of received sound power will come from the reflected sound, which will be dominated by the strong radiation in the downstream direction. In a large space, ultrasound radiation in downstream direction is expected to be significantly attenuated by air and surface absorption before it can reach the receiver after a few reflections.

Basically the spectra at the highest four or five frequency bands for the multiple-jet nozzles have similar slopes, which are close to those of the single-jet nozzle spectra shifted to the right (toward the high frequency). This suggests that

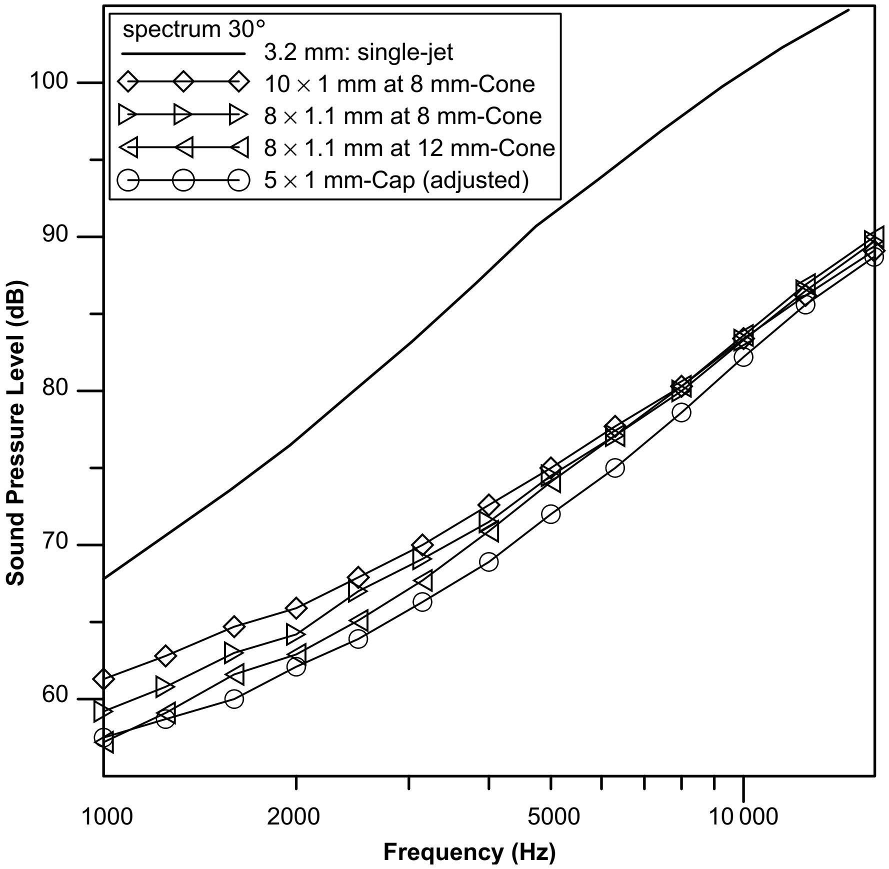

Figure 5. Sound spectra for the tested nozzles at 30°. Measuring distance = 30 cm. Mass flow rate = 4 g/s.

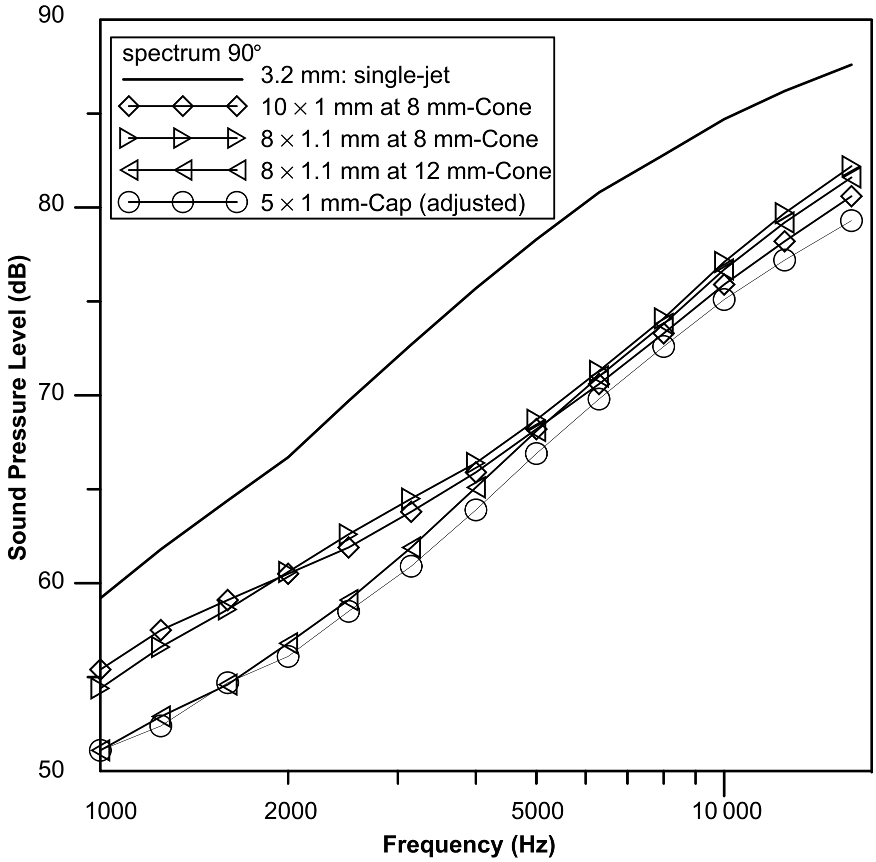

Figure 6. Sound spectra for the tested nozzles at 90°. Measuring distance = 30 cm. Mass flow rate = 4 g/s.

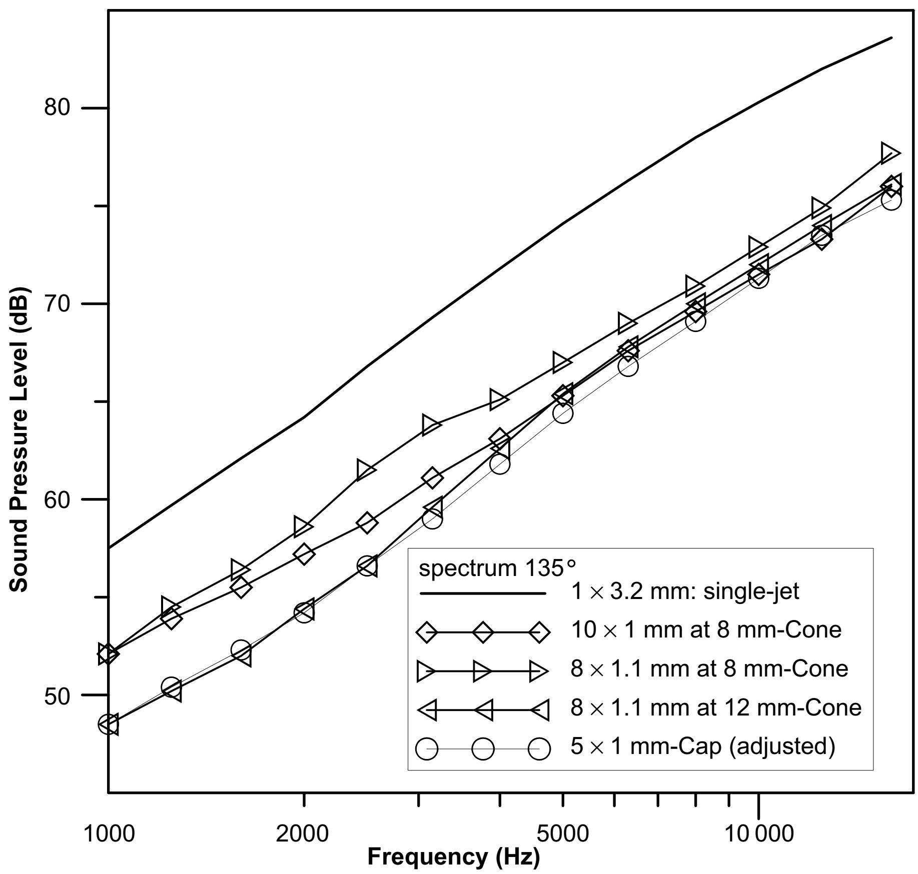

Figure 7. Sound spectra for the tested nozzles at 135°. Measuring distance = 30 cm. Mass flow rate = 4 g/s.

noise in this frequency range is generated in spatial locations where little mutual interaction exists between neighboring jet streams.

At the highest four or five frequency bands, the three conical nozzles have very similar sound levels at 30°. More significant differences among the three nozzles are observed at 90° and 135°. At these two directions, a few exits of the multiple-jet nozzles are not in the line of sight of the microphone. Therefore, it is possible that the more notable differences are partly due to the interference caused by the nozzle body. Because most sound power is radiated in the downstream direction, as suggested by the spectra at 30°, the emitted sound power for the three conical nozzles at this flow rate should be very close above 5 kHz.

As the frequency decreases, we note that the spectra for the two multiple-jet nozzles with more densely distributed exits begin to shift toward the low frequency, resulting in an increase in sound pressure levels in this frequency range. For nozzles with larger exit spacing, the 8 × 1.1 mm at 12 mm, this shift begins at lower frequencies and affects a smaller frequency range.

If the merging of adjacent jet streams increases the length scales of flow structures and leads to the generation of lower-frequency noise, that closely distributed jet streams will cause the sound spectrum to move toward the low frequency should be a reasonable consequence.

The shift toward the low frequency only increases the sound pressure levels at the relatively low frequencies. For the two conical nozzles with more densely distributed exits, we observe that, compared with the 8 × 1.1 mm at 12 mm nozzle, noise levels at frequencies most sensitive to humans, 3–4 kHz, and below show notable increases. But the overall sound pressure levels in the frequency range measured are mostly unaffected. However, if the exits are more densely distributed, the frequency range influenced may extend to higher frequencies, whose sources are located more upstream.

For exits distributed on a flat plane and on a conical surface, we do not observe significant differences. The 5-exit nozzle, whose exits are distributed on a 7.5-mm circle, has almost the same exit spacing as the 8 × 1 mm at 12 mm nozzle. Their spectra are similar from 1 to 16 kHz. Since the two types of nozzles have different profiles, which may influence sound radiation, the small differences between them are not large enough to make conclusive assessment.

3.4. Variations of Overall Sound Pressure Levels Versus Flow Rates

The spectra in section 3.3. at 4 g/s indicate that, below the peak frequency, sound pressure levels in general increase with frequency at a rapid rate. Because the corrections applied by the common *A*-weighting are quite uniform between 1 and 8 kHz, for the conical nozzles tested in this work, the *A*-weighted overall sound pressure level below 8 kHz, which is typically used to evaluate occupational noise exposure in commercial noise dosimeters, will be determined mostly by frequencies close to 8 kHz. Therefore, at this flow rate, the exit spacing used in this work, which shows only notable effect for frequencies below 5 kHz, will not significantly affect the *A*-weighted overall sound pressure levels.

Similar results are obtained at other flow rates, as demonstrated in Figures 8–10, which show variations of the *A*-weighted overall sound pressure levels versus flow rates at the three measuring directions. The evaluation of the overall sound pressure levels calculates only the one-third-octave frequency bands up to 8 kHz. The lowest flow rates correspond to exit velocity of ~260 m/s.

We note that the multiple-jet nozzles show consistent performance in reducing the overall noise levels below 8 kHz over a wide flow rate range. All the three conical profiled nozzles generate much lower sound pressure levels than the single-jet one. Because the noise spectrum is the steepest in the downstream direction, as demonstrated in Figures 5–7, the amount of noise reduction due to frequency shift is most evident at 30°. A reduction exceeding 17 dB for the three conical nozzles at 4 g/s is observed. Noise level reductions decrease to ~10 dB at 90° at the same flow rate.

The differences between the three conical multiple-jet nozzles are much less significant. This indicates that the effect of exit spacing has not influenced frequencies near 8 kHz. But it is possible that the frequency range influenced by exit spacing might extend to higher frequencies if the exits are more densely distributed. This situation may happen when a multiple-jet nozzle is used to replace a large diameter single-jet one. In this case, a large number of exits may be used, leading to densely distributed exits.

4. CONCLUSIONS

In this work, it is found that the noise characteristics generated by a conical profiled multiple-jet nozzle are similar to those generated by multiple-jet nozzles with exits distributed on a flat surface. Compared with a single-jet nozzle with similar exit area, the multiple-jet nozzle reduces the noise levels in the audible range by shifting radiated sound power to higher frequencies. If the peak frequency is located in the ultrasound range, this shift toward high frequency will reduce noise levels in the audible range. A conical profiled multiple-jet nozzle has the additional advantage of reducing the risk of accidental pressure built-up at the nozzle exits.

When the multiple exits are densely distributed, it is observed that the merging of neighboring jets will shift sound power back to lower frequencies, leading to increased sound pressure levels in a specific frequency range. It is conjectured that the coalescing of the multiple jet streams increases the length scale of flow structures, thus reducing the frequency for noise generated in the more downstream region where coalescing happens. Because human audible frequencies exist in a relatively low-frequency part of the jet noise spectrum for nozzle exits of the order of a few millimeters in diameter, exit spacing for a multiple-jet nozzle can be a potentially important factor in determining noise levels in the audible range.

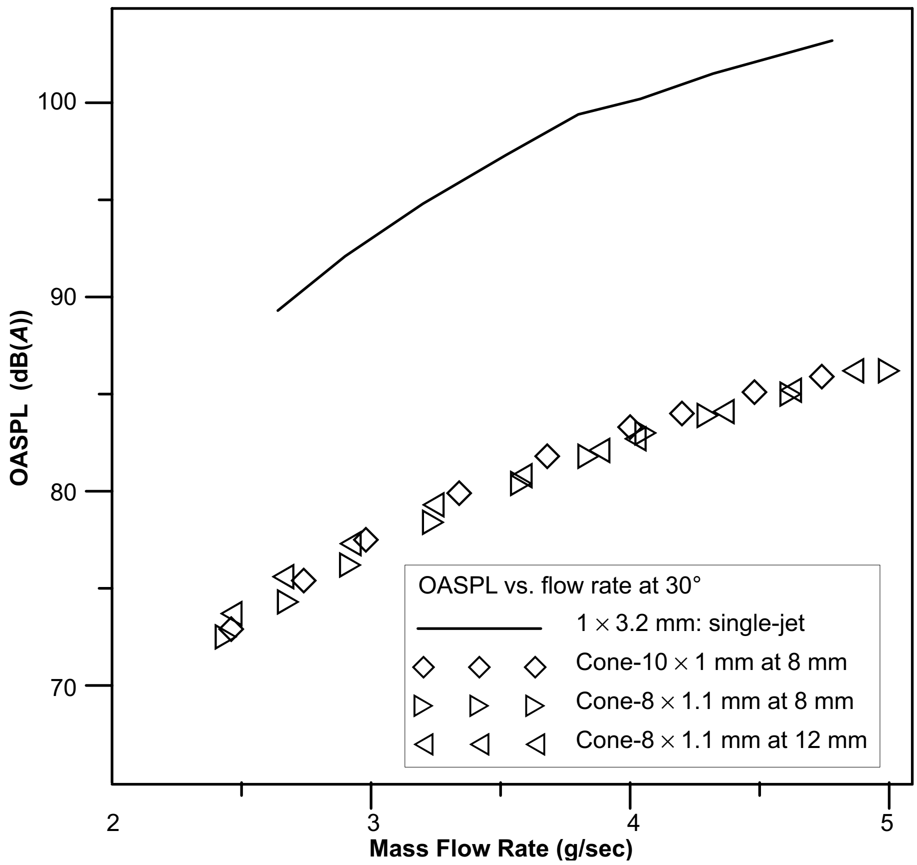

Figure 8. *A*-weighted overall sound pressure levels (OSPL) versus mass flow rates at 30°. Only frequencies below 8 kHz are evaluated.

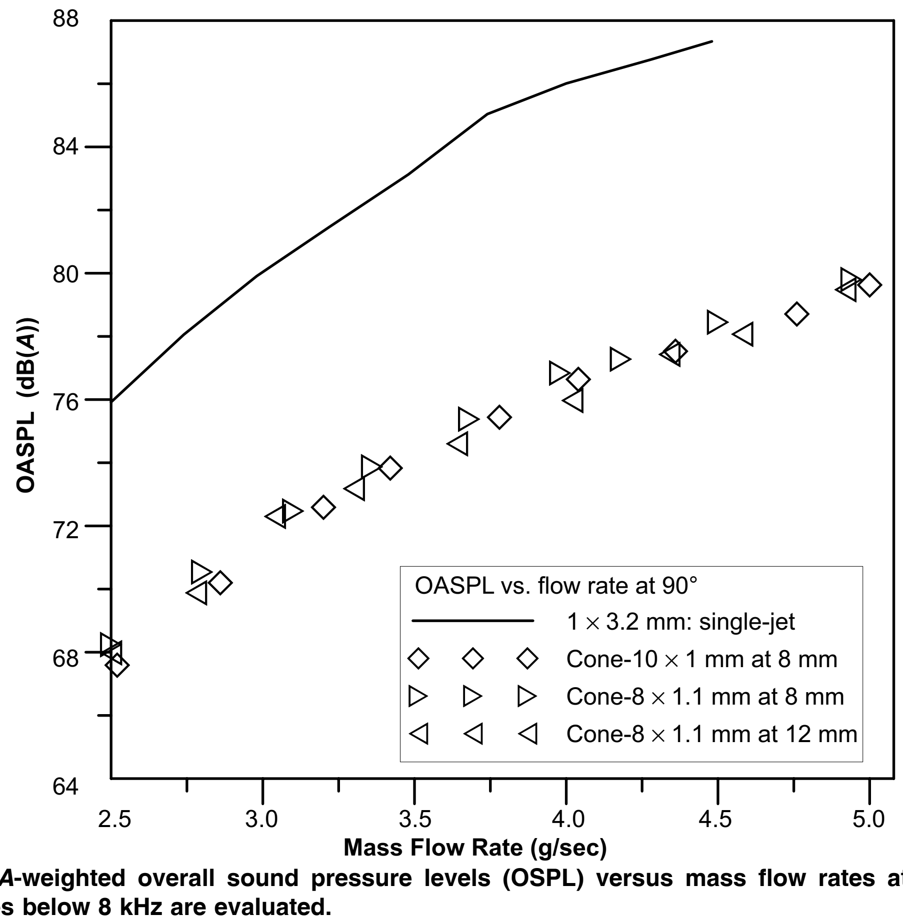

Figure 9. *A*-weighted overall sound pressure levels (OSPL) versus mass flow rates at 90°. Only frequencies below 8 kHz are evaluated.

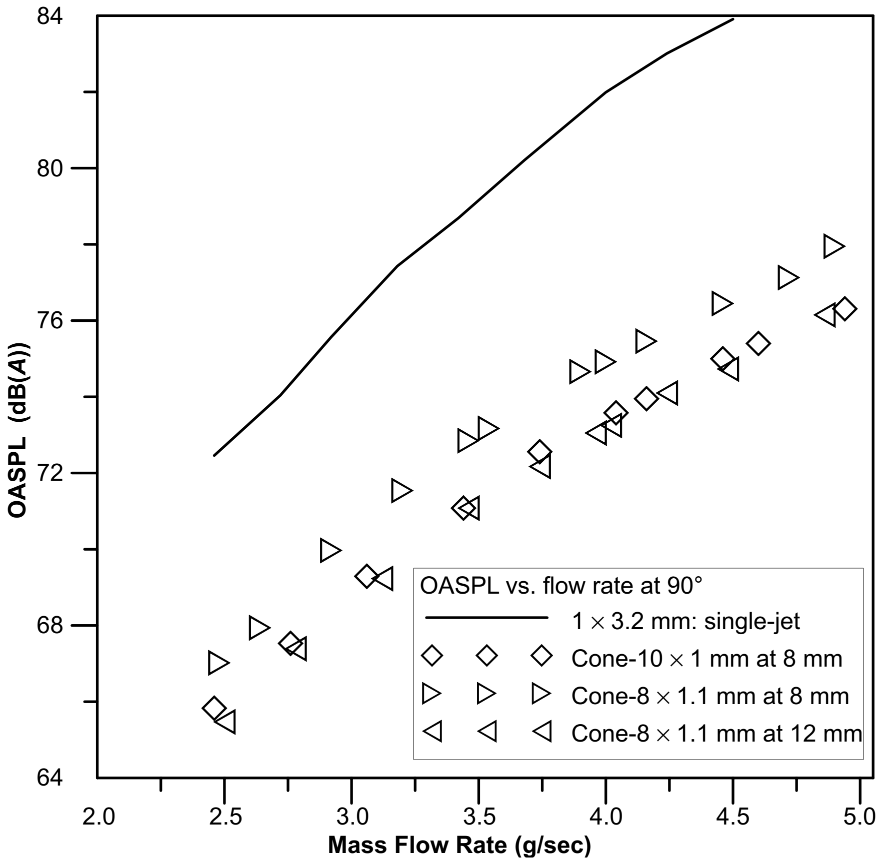

Figure 10. *A*-weighted overall sound pressure levels (OSPL) versus mass flow rates at 135°. Only frequencies below 8 kHz are evaluated.

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