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The Acoustic Performance of 3D Printed Multiple Jet Nozzles with Different Configurations

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Abstract: This work investigated multiple jet nozzles with various geometrical shape, number of exits, and material on reducing noise radiated from jet flows. Nozzles are categorized in two groups with few and many exit numbers, each with various exit shapes, slot and circular, and geometry. Firstly, nozzles are designed and then fabricated by a 3D printer, Form Labs, Form2USA, with polymeric resin. Also, the nozzle with the most noise reduction made of stainless steel. Noise and air thrust were measured at three air pressure gauges, 3, 5, 7 BAR and directions from nozzle apex, 30°, 90°, 135°. Nozzles with slot exit shape made of both plastic and stainless steel revealed the most noise reduction among all nozzles with few exit numbers, nearly 11–14 dB*(A)* and 11.5–15 dB*(A)*, respectively. On average, slotted nozzle noise reduction was nearly 5–6 dB*(A)* more than finned nozzle. However, nozzles with more exit numbers, finned and finned-central exit, illustrated much more noise reduction than nozzles with few exit numbers, by almost 16–18 dB*(A)*, they represented similar sound. All tested nozzles and open pipe demonstrated equal air thrust at each pressure gauges. The nozzles with slotted exit shape, either plastic or stainless steel, can provide reasonable noise reduction in comparison to other configuration with few exit numbers. In contrast, nozzles with more exit numbers demonstrated the most noise reduction.

Keywords: Jet noise; multiple jet nozzle; noise reduction; 3D design; exit shape; nozzle geometry

1 Introduction

Noise is considered as the most common occupational exposure around the world. This physical hazard is accompanied with numerous psycho-physiological problems on the workers [1, 2]. Jet noise, also called aerodynamic noise, is generated by venting high pressure air, steam, process gas, and liquid into atmosphere [3]. Manufacturing jet noise likely ranks third as a major cause of hearing damage after impact and material handling noise [4]. Compressed air guns, as a single jet nozzle, can produce sound pressure levels over the range of 88.8–105.2 dBA. Numerous industrial processes apply compressed air jet flows for tasks like cleaning, shooting, drying, moving, cooling, and ejection of work pieces or debris. Compressed air as a main utility within industrial facilities, account for more than 10 percent of energy consumption [5]. A particular combination of excessive noise and widely utilization make air jet nozzles as a major noise source within industrial workers.

Generally, air flow velocity discharged from industrial jet exits equals sound speed and jet nozzles working in this situation, are called choked nozzles. Peak frequency in jet nozzles with small exit diameters are included in ultrasonic range such that workers are exposed to a small portion of total emitted sound power by jet nozzles [6]. Noise spectrum characteristic for a shock-free single jet nozzle is a broadband noise and the peak frequency is estimated by a reference frequency which is defined as the exit velocity divided by the exit diameter. Generally, the peak frequency is more than one-fifth of the reference frequency. For example, for a choked nozzle with an exit diameter of 2 mm, this peak frequency will exceed 35 kHz [7].

There are various sources of jet noise generating mechanism in industrial nozzles. Vortex structures, shock cells and abrupt change of velocity inside the nozzle are the main noise generating mechanism in industrial jet nozzles which needs to apply different noise reduction approaches for each noise sources. Vortex structures are responsible for mixing noise that is a kind of quadrupole noise source. The sound power of mixing noise is proportional to the eight power of flow velocity. If pressure ratio, ratio of jet upstream pressure to ambient pressure, is more than 1.89, gas exit velocity will be equal to one mach. In this state, as well as noise generated due to turbulent flow, noise emission can be produced by shock waves [8].

Air jet nozzles have been proposed as a main measure to attenuate jet noise in industrial applications. Various jet nozzles have been designed, which reduce jet noise in terms of different approaches. Air shroud nozzle, multiple jet, coanda effect and co annular are instances of air jet nozzles. The selection of the low noise nozzle relies on its application. For cooling and drying purposes, a large flow rate with low thrust force is needed, like that of air shroud nozzle, while for ejection purposes, a high thrust directional force is needed, like that from multiple jet nozzle [6]. Air shroud nozzles are designed to mitigate mixing noise which is originated from vortex structures. Air shroud nozzle focuses on the jet flow's kinetic energy. Because, the noise level of jet flows is predominantly related to the discharge velocity, air shroud reduces the average velocity of jet flow with introducing a secondary flow that surrounds the jet core [8].

Jet nozzles with multiple and smaller openings is referred to as a multiple jet nozzle. This sort of nozzle, reduce the excessive noise without noticeably impairing air thrust. Open pipe nozzle could be replaced with multiple jet nozzle to reduce jet noise without significantly decreasing air thrust. Previous studies on multiple jet have shown that noise reduction mechanism is based on shifting noise spectrum to higher frequency contents, leads to reduce audible hearing sound [7, 9]. Jet noise peak frequency is inversely proportional to the exit diameter and as well as that it will probably be transferred to higher frequencies, ultrasound zone, so the emitted sound power below the peak frequency decreases in the audible frequency range. In addition to, high frequency noise is easier to control, by common traditional noise reduction methods such as sound absorbent material and sound barriers [5].

The key features in designing multiple jet nozzles involve number of exits, exits spacing, exits total area, exterior and interior nozzle geometrics, shape of exits, and the plenum volume [4, 10, 11]. Principally, multiple jet nozzles with smaller outlet diameter is recommended for jet noise control. It is assumed that the increase in the number of exits which is accompanied with smaller outlet diameter, leads to noise reduction. On the other hand, If the number of exits is mostly increased on a limited area, the space between jets will be decreased which cannot be feasible. Inversely, the merging of jets speeds up by closely distribution of exits, so this opposing effect results to shift sound spectrum backward to low frequency side [9]. In order to design multiple jet nozzles with the best acoustic performance, these two opposing effects should be considered to reduce noise levels in audible frequency range.

The main concern about replacing multiple jet nozzle with single jet nozzle or open pipe is the possible loss of thrust. Therefore, multiple jet nozzle must be designed with considering no major loss in air thrust. Based on the principle of momentum conservation, Eq. (1), multiple jet nozzle designations with the same exit area generate significantly comparable thrust, as long as there is no noticeable temperature variation between discharged flow and ambient air [8].

$$F = (\rho_e cA)c\left[1 + \left(1 - \frac{1}{Q}\right)/\gamma\right] \tag{1}$$

where F = thrust, c = exit velocity which equals the speed of sound for chocked flows, A = exit area, ρ_e = the density of discharged flow in exit, Q = a dimensionless pressure ratio of P_e to P_a (air pressure in exit and ambient air respectively), γ = the ratio of specific heat.

It is assumed that the configuration of jet nozzles can be effective on noise reduction. There are few studies about the effect of geometry on the acoustic performance of jet nozzles. Bridges's research has shown that exterior geometry of nozzle and size are effective on the sound and it was a function of noise frequencies [11]. Sheen investigations on multiple jet nozzles with conical profile and jets distributed on a flat surface showed that there is no difference in noise characteristics [8]. Furthermore, commercial manufacturers have produced jet nozzles with different configuration. For example, fins have been added between adjacent exits in some designs, but it is not clear what impact they have on noise reduction. Fins are seemed to prevent from injuries created by blocking exits, because the blockage of exits is another hazard associated with using high pressure air. In the context of noise, fins might prevent merging jets as soon as discharged from exits. Balakrishnan studied acoustic performance of non-circular jet nozzles with various shape of exits. Circular, elliptical, triangular, square, rectangular jet nozzles were investigated. In his research, noise spectrum was mostly studied in ultrasonic range and it was aimed to reduce ultrasonic noise [10].

This study aimed to design and compare multiple jet nozzles with various exterior geometrical shape and number of exits which are made of either metal or plastic to reduce jet noise propagated from single compressed air jet nozzles. All examined nozzles are designed with the same total exit area and fabricated by three dimensional printing.

2 Method

2.1 Nozzles Tested

Nozzles were categorized in two groups based on number of exits and geometry. Reference nozzle as a single jet nozzle is an open pipe with 6 mm internal diameter (1*6 mm). The geometry and distribution of exits, drawn to scale, for all tested nozzles are shown in Fig. 1, along with abbreviations used to denote the nozzles tested.

It is not correct to compare noise levels produced by nozzles with considerably various total exit areas, therefore all tested nozzles and open pipe have the same total exit areas. On the other hand, based on Eq. (1), in order to keep the same air-thrust in multiple jet nozzles and open pipe, they have to have equal exits area. There are four and two configurations of multiple jet nozzles in group 1 and 2 with few and many exit numbers respectively. The simple and slot nozzle configurations were not considered in the group 2 because it was possible to assess different configuration in nozzles with few exit numbers. The general specifications of the multiple jet nozzles designed in this study are presented in Tab. 1. All tested nozzles in group 1 and 2 have the same conical profile and total exit area. The length and diameter of all tested nozzles was designed to be 30 mm and 15 mm, respectively.

The first (Fig. 1a) and second nozzles (Fig. 1b) tested in group 1 are made with circular and rectangular (slot) exit shapes. The third (Fig. 1c) and fourth (Fig. 1d) nozzle tested in group 1 are the same circular exit

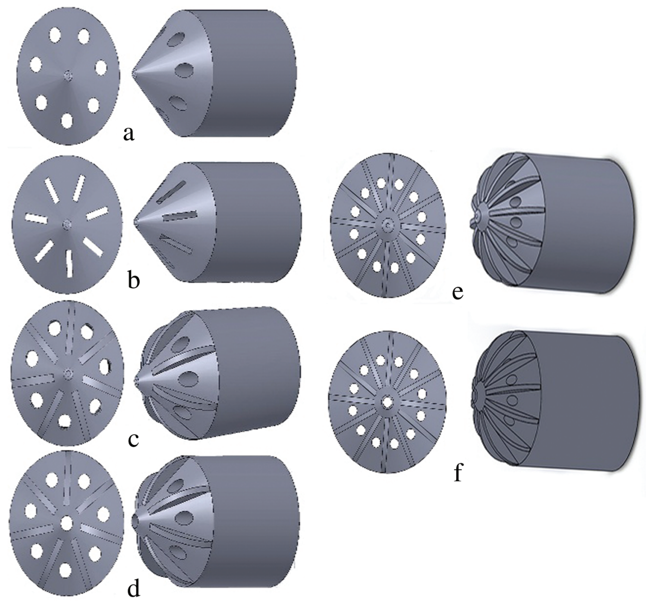

Figure 1: Isometric and top view of multiple jet nozzles. Group 1: (a) Simple nozzle with 7 circular exits (7C*2.27); (b) nozzle with 7 slot exits (7S*4*1.01); (c) nozzle with 7 circular exits and finned (7C*2.27*Finned); (d) nozzle with 8 circular exits, finned - central exit (8C*2.12*finned-central exit) and Group 2: (e) nozzle with 12 circular exits and finned (12C*1.7*Finned); (f) nozzle with 13 circular exits, finned - central exit (13C*1.65*finned - central exit)

Table 1: The general specifications of the multiple jet nozzles

Type of nozzle		Number of exits	Size of exits (mm)	Specifications Total exits area (mm^2)	Material	Shape of exits
Reference	Open Pipe	1	6	28.26	Plastic	Circular
Group 1	Circular Exits	7	2.27	28.31	Plastic	Circular
	Plastic – Slot	7	4 × 1.01	28.28	Plastic	Slot
	Finned	7	2.27	28.31	Plastic	Circular
	Finned – Central Exit	8	2.12	28.22	Plastic	Circular
	Steel – Slot	7	4 × 1.01	28.28	Steel	Slot
Group 2	finned	12	1.7	27.22	Plastic	Circular
	Finned – Central Exit	13	1.65	27.7	Plastic	Circular

configuration as first nozzle with various external geometry. Circular exits in the third nozzle are separated with fins and in the fourth one, as well as fins between exits, there is one more exit on conical tip of nozzle. The height and thickness of fins was considered to be 5 mm and 2 mm, respectively. All tested nozzles in group 2 are the same configuration as third and fourth nozzles in group 1 with more exit numbers.

The sketch and three dimensional (3D) design of nozzles is drawn by an engineering software, solid works software 2018, and nozzles are manufactured by a 3D printer (Form Labs, Form2USA). This printer was able to fabricate objects with great accuracy and as well as that there was widespread agreement between designed and printed nozzles. A sort of polymeric resin is used by 3D printer to print nozzles. Applicability of 3D printed nozzles with plastic polymeric resin in harsh and hot industrial environment is not practical and it would be possible to be deform or fracture. So, initially acoustic performance of 3D printed nozzles involved in group 1 was investigated and following that the nozzle with the most noise reduction was fabricated by CNC machine with stainless steel.

2.2 Noise Measurement

The compressed air is supplied by an air compressor with the capacity of 250 L and 2 hp. In order to reduce the noise interference caused by the operation of the compressor with measured sound, the compressor is placed outside the laboratory environment and the compressed air is supplied to the laboratory through piping. A schematic of laboratory set up is shown in Fig. 2. Noise pressure levels were measured in a laboratory by 6 m long, 4 m wide and 3 m high. In order to reduce reflections in the sound measuring environment, rock wool slabs as a sound absorbing materials with an average absorption coefficient of 80% are used on the floor and walls of laboratory around the sound measuring location. The ambient sound level of the laboratory was measured to be nearly 40 dB(*A*).

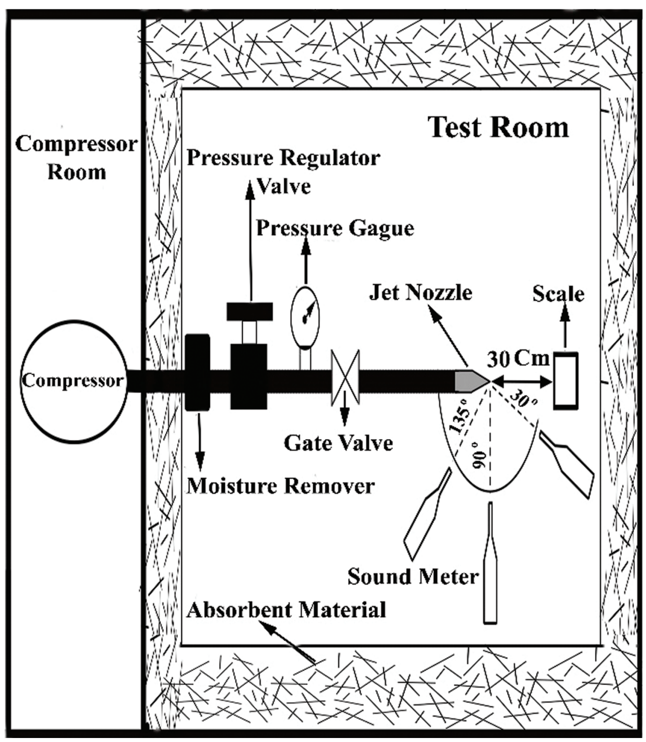

Figure 2: Laboratory set up for measurement of sound pressure level and air thrust

Both nozzles and sound level meter (SLM) are placed on different tripods at the same height of 85 cm. The distance between SLM's microphone and nozzle axis was considered to be 30 cm [7, 9]. SLM was equipped with a wind screen to reduce noise which might be generated from impinging exhausted compressed air on microphone. A PVC plastic hose with an internal diameter of 6 mm was considered as a reference sound source and all tested nozzles were examined after connection to the end of plastic hose. Noise measurement was performed by a Casella Cell 450 Type2, UK sound level meter and it was calibrated using a cell-110/2 calibrator before and after noise measurement. The time constant and frequency weighting network were adjusted at the slow response and *A*-weighting network, respectively. Also, Noise frequency analysis was done in octave band frequencies. What's more is that, noise measurement was made at various angles of 30°, 90° and 135° relative to the nozzles tip. At each angle, the level of sound pressure is measured three times. The logarithmic mean calculated from noise measured at various angles was considered as sound pressure level of each tested nozzle. At zero angle, microphone diaphragm is faced to the nozzle exit. In terms of air pressure, noise measurement was made at different air pressure of 3, 5 and 7 BAR and compressed air pressure was set by a pressure regulator. It was possible to observe pressure gauge during noise measurement in order to assure that noise is measured at a constant set pressure. Air thrust, at three pressures of 3, 5 and 7 BAR is measured using a digital scale (Pand model, Iran), located 30 cm away from the nozzle exit [12].

3 Results

The average A-weighted overall sound level for each nozzle in group 1 at the three directions from nozzle apex, namely, 30°, 90°, 135°, and three pressure gauges, 3, 5, 7 BAR is represented in Fig. 3. It was easily apparent from figure that, the overall sound level of all multiple-jet nozzles with various geometries was lower than open pipe nozzle at tested pressure gauges.

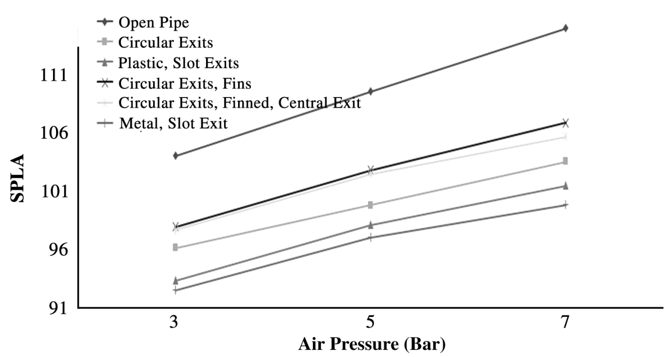

Figure 3: Average sound pressure level of nozzles in group 1 at various pressure gauges

Slotted and finned (without central exit) nozzles showed the lowest and highest measured sound levels respectively, among all fabricated nozzles with 3D printing. On average, printed slot nozzle effectively reduced sound level by 11, 11.5, and 14 dB(*A*) at pressure gauges 3, 5, and 7 BAR respectively. Meanwhile, finned multiple jet nozzle (without central exit) in group 1 reduced sound level by almost 6.3, 7, and 9 dB (*A*) at pressure gauges 3, 5, and 7 respectively. On average, slotted multiple jet nozzle noise reduction was measured to be nearly 5–6 dB (*A*) more than finned multiple jet nozzle. There was not significant differences between the sound level of finned nozzles with and without central exit. The measured sound level slopes for all tested nozzles in group 1 was the same as each other and open-pipe nozzle.

With regard material used to fabricate jet nozzles, there was not considerable differences between sound levels of metal and plastic slotted jet nozzles, although metal slotted nozzle had a bite slightly better acoustic performance. Noise reduction rate for slotted multiple jet nozzle fabricated with metallic material was measured to be around 11.5, 12.5, and 15 dB*(A)* at air pressures of 3, 5, and 7 BAR, respectively. Metallic slotted nozzle presented the most noise reduction among all tested nozzles in group 1.

The sound spectra at the direction of 90° and pressure gauges of 7 BAR for all tested nozzles in group 1 are shown in Fig. 4. Also, the overall sound pressure levels are listed in the figure legends. The spectrum slopes decrease the same order as sound pressure level. In comparison with low frequencies, noise reduction in high frequencies was more evident for all tested nozzles with various configurations. There is some similarity in noise spectrums of all tested nozzle in group 1 and open pipe nozzle in low frequencies. Metal and plastic nozzles with slotted exits exhibited the best acoustic performance in all octave band frequencies. Additionally, the effect of frequency shifting to higher frequencies for nozzles with slotted exits was more than other tested nozzles in group 1. Slotted exit nozzle reduced sound level by 5 dB*(A)* more than finned nozzle in all octave band frequencies.

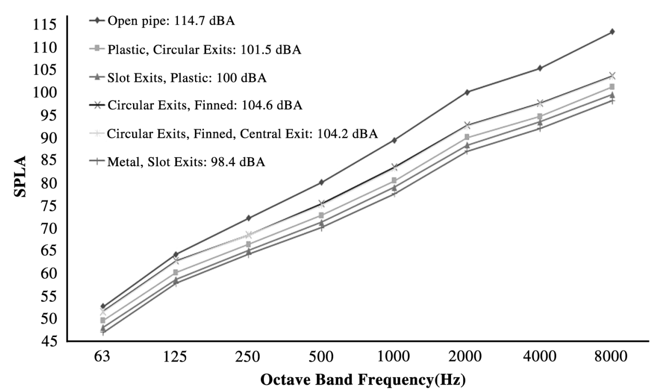

Figure 4: Sound spectra in octave band frequencies for nozzles in group 1. Polar angle = 90; Air pressure = 7 BAR

Compressed air thrusts for nozzles in group 1 in various air pressure gauges are illustrated in Fig. 5. Air thrust in each examined air pressures was approximately equal for all tested nozzles with various configurations and as well as that it was slightly lower than open-pipe nozzle.

The average sound pressure level for both groups of nozzles with few (group 1), only finned nozzles, and many (group 2) exit numbers, at different air pressure are displayed in Fig. 6. Average sound pressure level is actually the logarithmic mean of SPLs at various polar angles of 30°, 90° and, 135° from nozzles apex. All multiple jet nozzles generated much lower sound pressure level than the reference open-pipe nozzle. In group 1, noise reduction was measured to be 6.3, 7 and 9.2 dB*(A)* at various air pressure 3, 5 and 7 BAR,

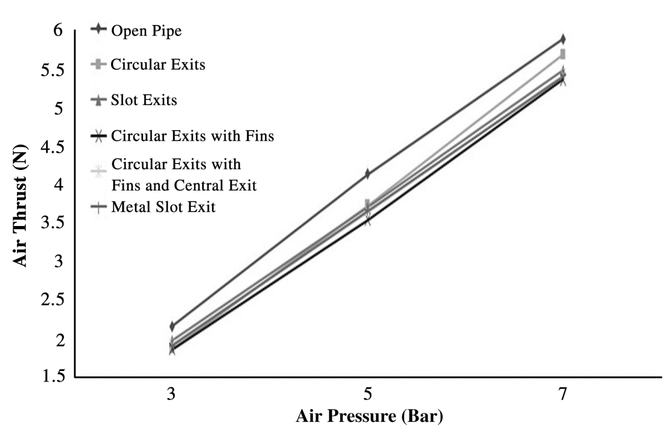

Figure 5: Air thrust *vs*. air pressure gauge for nozzles in Group 1

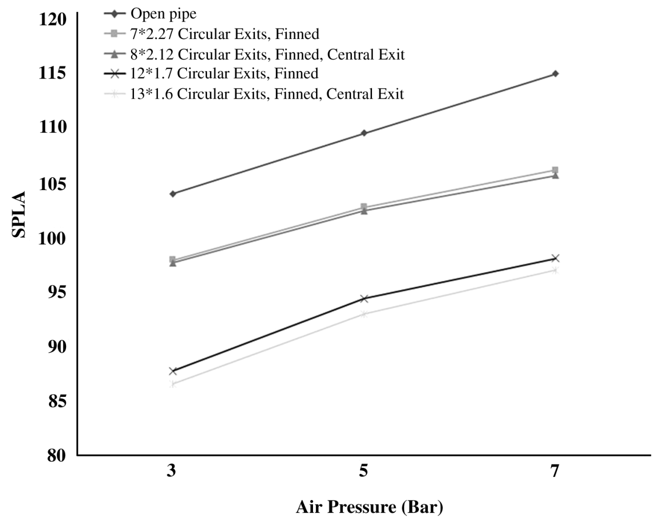

Figure 6: Average sound pressure level of nozzles in group 2 at various pressure gauges

respectively. On the other hand, in group 2, noise reduction was measured to be approximately 17, 16 and 18 dB*(A)* at various air pressures of 3, 5 and 7 BAR respectively. It is evident that multiple jet nozzles with more exit numbers revealed significantly lower sound pressure level in comparison with nozzles with less exit numbers. In group 2, noise reduction was measured to be nearly twice more than group 1. Overall, multiple jet nozzles with more exit numbers (denoted as 12*1.7 fin and 13*1.6 mm fin-central exit) produced significantly lower SPL than group 1 and single jet nozzle.

According to Fig. 6, the comparison between multiple jet nozzles in each group showed that nozzles with different geometry generated approximately similar SPL at various air pressures. However, nozzles with fin and central exit generated roughly lower sound pressure level. The differences between the two multiple jet nozzles in each group are much less significant. This indicates that the effect of nozzle exterior geometry has not influenced sound pressure level. Adding central exit to finned nozzles did not influence on acoustic performance even in nozzles with many exit numbers.

Noise spectrum in octave band frequencies for both group of nozzles at compressed air pressure of 7 BAR, which is usual of many industrial setting to blow, clean, dry, and shoot, are demonstrated in Fig. 7. Compared with nozzles in group 1 and open pipe nozzle, nozzles in group 2 exhibited the best noise reduction in all octave band frequencies. Frequency shifting effect to higher frequencies was more clear for nozzles in group 2. Multiple jet nozzles in both groups generated significantly lower noise level in all octave band frequencies, especially at higher frequency range. It can be noticed that there was high frequency content in the measured sound pressure levels. In low frequency range, less than 1000 Hz, there are less difference in noise levels between multiple jet nozzles and open pipe nozzle. In other words, sound pressure levels of nozzles in group 1 and 2 and open pipe was more similar to each other in low frequency range. Geometric shape did not have an important effect on sound level of nozzles in group 2.

The relationship between air thrust and air pressure for the two groups of multiple jet nozzles, namely all tested nozzles in group 2 and finned jet nozzles in group 1, and open pipe nozzle is shown in Fig. 8. This figure shows that nozzles with the same total exit area generate quite similar air thrust. Nozzles with more and less exits number generate equal air thrust at different air pressures.

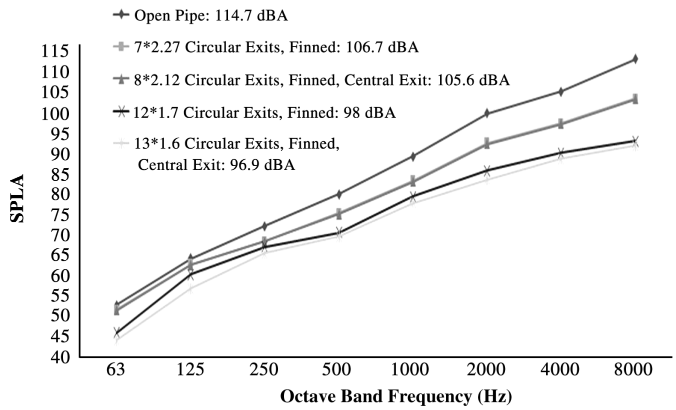

Figure 7: Sound spectra in octave band frequencies for nozzles in group 1 and 2. Polar angle = 90; Air pressure = 7 BAR

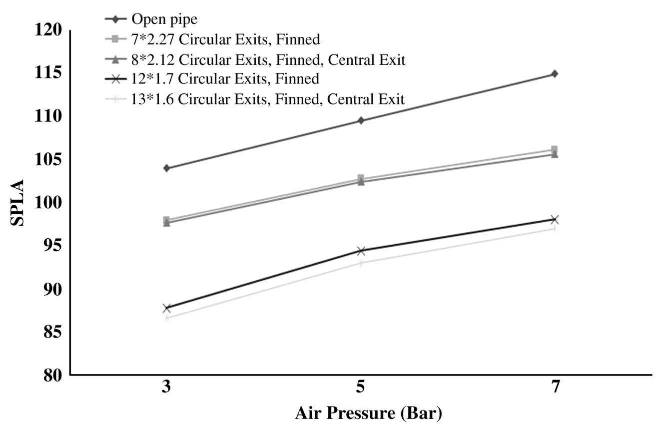

Figure 8: Air thrust *vs*. air pressure gauges for nozzles in group 1 and group 2

4 Discussion

In this study the acoustic performance of multiple jet nozzles with various geometric shape, which was categorized in two groups having few and many exit numbers, was investigated. Material (plastic, metal), exit shape (slotted, circular) and, surface geometry (finned, fin-central exit) were considered as key factors to fabricate and examine the acoustic characteristics of nozzles.

The lowest sound pressure level for nozzles in group 1 was connected to the slotted nozzles made with both metal and plastic material. In addition, the noise reduction of nozzles with many exit numbers was far better than few exit numbers. However, noise measurement results were presented for each angle separately in previous studies [8, 9]. In the current research, the average sound pressure level measured in three directions of 30°, 90°, and 135° relative to nozzle axis was considered as a measure to assess acoustic performance of tested nozzles. The sound pressure levels decreases as the direction of sound propagation from nozzle apex increases, which was consistent with reports in the literatures [7]. In other words, the sound pressure levels were highest at 30° and lowest at 135°.

There was slightly difference about 2 dB*(A)* between sound levels of slotted and circular nozzles fabricated using 3D printer (Fig. 3). In one hand, the measured sound level for both 3D printed nozzles with slot and circular exit, was exceeded occupational health and safety association (OSHA) noise exposure limit. On the other hand, metallic nozzles are preferred to plastic ones in industrial rough environments and what's more is that manufacturing process for machining circular exit is easier and cheaper than slot one. Hence, using metal nozzles with circular exit can be regarded as an appropriate alternative for plastic nozzle with slot exit.

Nozzles with circular exit shape revealed more noise reduction than finned nozzles. In the both above mentioned nozzles, exit shape and number of exits were equal and the only difference was related to fins. Adding fins between circular exits lead to deteriorate acoustic performance of circular exit nozzles. In other words, adding fins between exits caused sound level to increase in finned nozzles. It was expected that adding fins to simple circular exit nozzles prevent merging jets which are close together and following that more noise reduction will be achieved but such effect was not observed. In terms of occupational safety, working with compressed air pressure can be hazardous if there is a contact between discharged compressed air and workers body [12]. Nozzle exits might be accidentally blocked if it touches some part of human body. It would be possible to protect workers from blockage of nozzle exits by using guard. So, it seems that the role of fins in preventing hazardous events are more influential than increasing acoustic performance. Accordingly, fins specification and dimension on noise reduction should be examined more in future studies.

Finned and finned-central exit nozzles represented the same acoustic performance in both groups with few and many exit numbers (Fig. 6). A rise in the number of exits from 7–8 to 12–13 lead to substantial noise reduction. Central exit did not influence on acoustic performance of finned nozzles. Noise reduction in nozzles with more exit numbers was more than nearly twice as much as nozzles with few exit numbers. It is proven in previous studies that, if the number of exits are increased sharply in a limited area on nozzle body as if they are located very close together, more noise reduction would not be experienced. The reason for this is that as the distance between exits decrease, merging discharged jet flows will happen faster in a closer distance to exits which lead to more noise generation [8]. It is exhibited in previous research that acoustic performance of jet nozzles will be declined if there is a distance equal with one diameter of exit between two exits next to each other [9]. So, according to these opposing effects, exit numbers and exit diameter, there would be an optimum number of exits for consideration in which the best acoustic performance is provided.

Noise reduction was roughly similar in both slotted multiple jet nozzles, which were made of plastic or metal (Fig. 3). It should be mentioned that in industrial processes with probably no potential damage to the nozzles due to physical impacts or heat, plastic nozzles produced by 3d printer, a cheaper and faster process for the fabrication of nozzles, can be worth considering. But, in contrast, it is essential to apply metal nozzles in harsh industrial environments, which is associated with extreme heat, physical damage and falling down nozzles on the ground. For instance, air blow guns equipped with jet nozzles are used to clean metal debris in some metallic industries like production of engine parts. It is likely to be hit and cause damage to nozzles during cleaning process or falling down on the ground from worker hands. So, it would be required to use firm and resistant nozzles that are made of stainless steel in the above mentioned jobs.

According to Eq. (1) nozzles with the same total exit area, which includes group 1, group 2, and single jet nozzle, should produce equal thrust. As it can be showed in Figs. 5 and 8, the results are in accordance with the above mentioned equation and the previous studies confirmed it [3, 8]. Practically, it is useful to reduce noise without sacrificing air thrust. Otherwise, applying compressed air for tasks such as cleaning, shooting, drying and, sorting would not be performed appropriately. Decreasing nozzles outlet diameter from 6 mm to 1.7 mm did not considerably change thrust. Although the total cross-sectional area of the nozzle openings in group 1 was considered to be equal to open pipe, with an internal diameter of 6 mm, air thrust in jet nozzles was fairly less than open pipe. This apparent lack of complete correlation can be attributed to precision of 3d printing and manufacturing process of nozzles. For instance, polymeric resin particles may be remained in openings of nozzle during printing process. Therefore, nozzle openings have been fabricated a little bit smaller than designed sketches. What's more is that printed nozzles should be washed with a solvent to remove remained polymeric resin from nozzle openings. These remained particles might not be cleaned completely which can be caused to smaller openings.

Nozzles with smaller exit size tend to shift noise peak frequency to higher frequencies which is called frequency shifting and following that noise will be reduced in hearing zone frequencies [8-10]. In octave band frequencies, band width is large, so frequency shifting effect is not clear sufficiently but noise reduction in nozzles with smaller outlet size is apparently clear. Generally, noise spectrum curve is shifted to the right based on the outlet diameter ratio between single jet nozzle and multiple jet nozzle. Multiple jet nozzles' noise spectrum looks very similar to single jet nozzle but their noise spectrum is lower than single jet nozzle.

Slotted multiple jet nozzles either plastic or metal one represented the highest noise reduction and shifting to higher frequencies. As previously mentioned, peak frequency would be largely shifted to higher frequencies in nozzles with smaller size openings [3, 7]. In spite of the fact that total cross-sectional area of all nozzles in group 1 were the same, frequency shifting effect was higher in nozzles with slot shapes. However, the diameter of the finned-central exit nozzle (2.12 mm) was less than circular exits nozzle (2.27 mm), shift to higher frequencies was higher in nozzles with circular exits. These results revealed that, in addition to exit size, geometrical shape of exits can play a key role in frequency shifting effect. Another issue worth noting is that, it is difficult to make comparison slotted and circular nozzles based on size because of various exit shapes but it sounds that the smallest dimension of slotted exit, 1 mm in width, has a vital role in frequency shifting.

Based on frequency shifting effect, nozzles in group 2 will shift to higher frequency more than group 1, because exits hole size in group 2 is less than group 1. Exit hole size ratio between single jet nozzle and multiple jet nozzle determine the amount of frequency shifting to the right. This effect is evident in Figs. 4 and 7. The shift of noise frequency towards higher frequencies was more evident in group 2, especially at frequencies more than 1000 Hz (Fig. 7). The reason for this, might be a significant decline in size diameter of exits in group 2 nozzles. At frequencies below 1000 Hz, the noise spectrum in nozzles with more exit numbers was nearly similar to nozzles with fewer exit numbers like slotted nozzles in group 1. Moreover, the noise spectrums of open pipe nozzle and all multiple jet nozzles included in both groups were similar in low frequencies. In group 2 nozzles, there was a considerable decline in exit spacing with increasing the number of exits. According to previous investigations, noise spectrum would probably be shifted to lower frequencies with a decrease in exit spacing [9]. In other words, increasing the number of exits and decreasing the diameter of exits cause to shift noise spectrum to higher frequencies and in contrast, decreasing the exit spacing leads the noise spectrum to be shifted to lower frequencies. Therefore, in order to have a nozzle with the best acoustic performance, the most appropriate number of exits and exit spacing should be designed considering these opposite effects. The overall sound level of nozzles in group 2 has been greatly reduced compared to nozzles in group 1, so it seems that increasing the number of exits and subsequently reducing the distance between exits in group 2 nozzles was desirable and there was no negative impact on nozzle acoustic performance. Moreover, it should be noted that the sound power of frequencies below 2000 Hz has a small contribution to the overall sound pressure level, hence the shift of sound to lower frequencies does not have a significant effect on the overall sound pressure level [5].

According to the conservation law of mass momentum and energy, jet nozzles with equal air thrust generate similar flow fields downstream from the nozzle. Because, low frequency noise sources of jet nozzles are emitted from downstream and nozzles with equal air thrust have similar flow fields in this area, it would be reasonable to have the same noise spectrum in low frequencies. Moreover, previous researches have shown that jet nozzles with the same thrust generate similar noise spectrum in low frequency [9]. So, it can be concluded that multiple jet nozzles are not effective in low frequencies.

Shaw-Ching Sheen noted that noise spectrum in multiple jet nozzles with more exit numbers, which had exit spacing equal to the size of one diameter, was the same as open pipe in frequencies below 2000 Hz. The current study does not completely support its research in this area. In fact, we found that there was a similarity in noise spectrum in frequencies lower than 250 Hz. The reason for this rather contradictory result is still not entirely clear but it might be connected to geometrical shape of nozzle and its exit.

5 Conclusion

Our work has led us to conclude that slotted multiple jet nozzle made of both metal and plastic material revealed the best acoustic performance in nozzles with few exit numbers, although there was not a substantial difference between sound pressure levels of nozzles with various geometrical shapes. Finns as an add-in in finned nozzles did not lead to more noise reduction in nozzles with circular exits. In contrast, we have obtained comprehensive results demonstrating that noise reduction in nozzles with more exit numbers was considerably larger than nozzles with fewer exit numbers. Despite multiple jet nozzles with few and many exit numbers showed different noise reduction, our results highlight the similarity in air thrust between all tested multiple jet nozzles.

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References

1. Safari Variani, A., Ahmadi, S., Zare, S., Zaroshani, V., Ghorbanideh, M. (2018). Water pump noise control using designed acoustic curtains in a residential building of Qazvin city. *Iran Occupational Health, 15(1),* 126–134.
2. Zare, S., Baneshi, M. R., Hemmatjo, R., Ahmadi, S., Omidvar, M. et al. (2019). The effect of occupational noise exposure on serum cortisol concentration of night-shift industrial workers: a field study. *Safety and Health at Work, 10(1),* 109–113.
3. Safari Variani, A., Ahmadi, S., Zare, S., Beheshti, A. S., Abdolahei, F. H. et al. (2018). Air blow guns noise reduction through design and fabrication of a multiple jet nozzle. *Iran Occupational Health Journal, 15(3),* 11–18.
4. Li, P., Halliwell, N. A. (1985). Industrial jet noise: coanda nozzles. *Journal of Sound and Vibration, 99(4),* 475–491. DOI 10.1016/0022-460X(85)90535-8.
5. Prieve, K., Rice, A., Raynor, P. C. (2017). Compressed air noise reductions from using advanced air gun nozzles in research and development environments. *Journal of Occupational and Environmental Hygiene, 14(8),* 632–639. DOI 10.1080/15459624.2017.1316384.
6. Dahl, M. D., McDaniel, O. H. (1985). The performance of jet noise suppression devices for industrial applications. *Journal of Vibration and Acoustics, 107(3),* 303–309. DOI 10.1115/1.3269261.
7. Sheen, S. C. (2011). Noise generated by multiple-jet nozzles with conical profiles. *International Journal of Occupational Safety and Ergonomics, 17(3),* 287–299. DOI 10.1080/10803548.2011.11076895.
8. Sheen, S. C., Hsiao, Y. H. (2007). On using multiple-jet nozzles to suppress industrial jet noise. *Journal of Occupational and Environmental Hygiene, 4(9),* 669–677. DOI 10.1080/15459620701513466.
9. Sheen, S. C. (2011). Effect of exit spacing in a multiple-jet nozzle on noise levels at audible frequencies. *Journal of Occupational and Environmental Hygiene, 8(6),* 349–356. DOI 10.1080/15459624.2011.576331.

10. Balakrishnan, P., Srinivasan, K. (2019). Impinging jet noise reduction using non-circular jets. *Applied Acoustics, 143,* 19–30.
11. Bridges, J., Hussain, F. (1995). Effects of nozzle body on jet noise. *Journal of Sound and Vibration, 188(3),* 407–418.
12. Silvent. (2019). Silvent catalog. *https://www.silvent.com/us* (accessed June 20 2019).