Using the Absorptive-Dissipative Silencer in Air Conditioning Systems of an Office Environment in Order to Provide Acoustic Comfort

Zahra Moradpour[1], Sajjad Farhadi[2], Mohsen Mohsenabadi[3], Mahdi jalali[4], Ghasem Hesam[1]*

1) Department of Occupational Health Engineering, Occupational and Environmental Health Research Center, School of Public Health, Shahroud University of Medical Sciences, Shahroud, Iran.
2) Center of Excellence for Occupational Health, Research Center for Health sciences, School of Public Health, Hamadan University of Medical Sciences, Hamadan, Iran.
3) Department of Ergonomics, School of Public Health, Mazandaran University of Medical Sciences, Mazandaran, Iran.
4) Department of Occupational Health Engineering, School of Public Health, Neyshabur University of Medical Sciences, Neyshabur, Iran.

**Author for Correspondence:* ghasem_hesam@yahoo.com

Received: 28 July.2017, Revised: 29 Jun.2018, Accepted: 08 Mar. 2018

ABSTRACT
Air conditioning systems are the main source of background low frequency noise in administrative buildings, restaurants, classrooms, and hotels. There are different ways to reduce the low frequency noise. Silencers are generic tools which are utilized for controlling noise produced by air conditioning systems. Sound assessment and frequency analysis were performed in accordance with standard methods to evaluate the exposure of workers in separate work stations. In the next step, an absorptive- dissipative silencer which its inner side was covered by convoluted acoustical foam was implemented in the ventilation system. The exposure of employees was re-evaluated. Moreover, Preferred Noise Criterion (PNC) and Speech Interference Level (SIL) were two acoustic indices used for assessing the effectiveness of the silencer. Before implementing the silencer, the sound pressure level in the rooms was between 57.8 and 61.1dBA with a peak frequency at 125Hz. The implemented silencer with dimensions of 1.4 ×1×1m, and inlet and outlet area of 0.45×0.45m was able to reduce the sound pressure level of about 13 to 14.2dB. Further, the PNC and the SIL indices were reduced to 14.33 and 15.31dB, respectively. The implemented absorptive- dissipative silencer reduced the sound pressure level of about 13.6dBA. Moreover, PNC and SIL indices are two important indices which can be used for assessing the level of comfort in office buildings.

Key words: Noise Pollution, Silencer, Air Conditioning System, Acoustic Comfort

List of Abbreviations
PNC: Preferred Noise Criterion
SIL: Speech Interference Level
dB: decibel
Hz: Hertz
CFM: Cubic feet per minute
SPL: Sound pressure level
ISO: International Organization for Standardization
CAF: Convoluted Acoustical Foam

INTRODUCTION
Noise pollution is one of the most important annoying factors in residential and occupational environments which in addition to the physiological effects, may cause reduction in the ability of understanding speech, disturbance in the concentration, and consequently reducing employees' performance [1]. The most common type of sound that employees are expected to be exposed in office buildings is known as background low frequency noise. This type of sound can cause such complaints from employees as vocal annoyance, stress and anxiety, fatigue, headache, sleep disturbance and decreased mental performance. Sounds with 20 to 250 Hz, are known as low frequency noise. Recent studies indicate that low frequency noise, especially in jobs with complex tasks demanded a lot of mental activity requirements, can cause negative effects on human performance. Thus, potential negative effects of low frequency noise are crucial at work stations which involve in mental information processing and high concentration duties,

especially on control panel rooms and administrative environments [2].

Uncontrolled sound in offices, buildings, and classrooms may negatively impact the acceptable level of employee performance. Even if the noise is not dangerous and do not annoy residents, it would be unpleasant if it interferes with the conversations among people [3]. Air conditioners are the main problem and source of background low frequency noise in administrative buildings, restaurants, classrooms, and hotels [4, 5]. The exact sources of these noises are the combination of different parts of the air conditioning system such as bearings, motors, conveyors, fans, and the movement of high speed air and its turbulence in channels [6].

Silencers are common tools used for controlling noise produced by air conditioning systems [5,7]. "Silencer" is a generic name referred to an equipment which can reduce the noise level of a high pressure gas or air discharge. They are classified into two categories as absorption and expansion silencers [8]. The former group is mainly used for controlling high frequency noise, while the latter is an effective tool in controlling low frequency noise [9]. In the cases that high level of control is needed, both these types of silencers are combined together and a system utilizing the advantages of both types of silencers is built which can be able to reduce the noise level in a wide range of frequencies [10].

Normally, many people are working in office environments and their performance demand a high level of mental abilities. Low frequency noise is a contributing factor which is playing a significant role in influencing the level of employees' performance. In order to optimize administrative environments and create a convenient atmosphere in such workplaces, certain standards such as the "maximum permissible noise level" for indoor environments of offices have been developed [11]. The purpose of developing such exposure limits is not only to prevent hearing loss caused by noise, but also, the main purpose of them is for providing comfort for employees to increase efficiency, improve performance, and prevent fatigue. Therefore, according to the aforementioned issues, the present study, was designed to investigate the efficiency of an absorptive-dissipative silencer in controlling the noise emitted from air conditioning systems.

MATERIALS AND METHODS

The current study was conducted in a governmental building in Shahroud, Iran, 2016. The building was composed of ten rooms located alongside each other in a U-shape pattern (Fig.1). In order for providing thermal comfort in the summer season, water cooled air conditioner system with the capacity of 6500 CFM had been implemented.

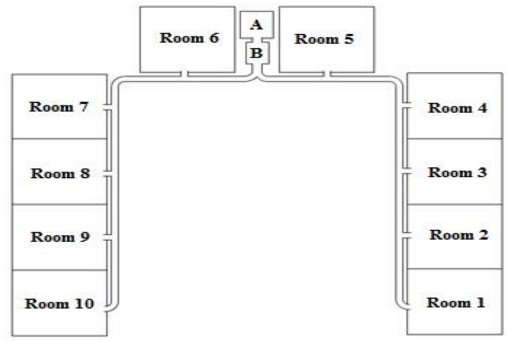

Fig. 1: Rooms plan and the air conditioner system (A: Water cooled air conditioner B: Silencer)

Although the use of such a system produced a thermal comfort for residents, it faced them with a new challenge, the noise pollution from the ventilation system. Following the request of the mentioned organization, we performed an initial evaluation on the building and the air conditioning system noise.

In this step, a sound level meter (Cel-450, Casella) was used for measuring the sound pressure level for assessing the workers exposure. Since the sound was not appreciably changed over time, the sound pressure level (SPL) was recorded at the work stations in each room. For doing this, according to the method developed by ISO 9612 standard, Slow, A-Weighted Sound Level was measured. For octave band analysis in each work station, scale setting was one and C-weighted (12, 13). To ensure calibration of noise level meter, an acoustic calibrator (CEL-282) was used. This calibrator creates the sound of 114 dB in 1000 Hz frequency (3, 8, 10).

Then, Preferred Noise Criterion (PNC) and Speech Interference Level (SIL) were evaluated in each room to assess acoustic comfort ability. The PNC index was determined using its curves and the SIL index and the maximum distance between the speaker and the listener were calculated using Equation 1 and Equation 2, respectively [3].

$$\boldsymbol{SIL = \frac{SPL_{250}+SPL_{500}+SPL_{1000}+SPL_{2000}}{4}} \quad \text{Eq. 1}$$

Where:

SPL250, SPL500, SPL1000 and SPL2000 are the octave band sound pressure levels at 250, 500, 1000 and 2000 Hz, respectively.

$$\boldsymbol{SIL = K - 20\log r} \quad \text{Eq. 2}$$

Where:

K = constant (54dB for men and 50dB for women in Normal voice), r = maximum distance between the speaker and listener

As it became clear that the sound pressure level has been crossed over the permissible limits for background noises [11], we tried to reduce the noise. Since the noise of the system was caused by the high volume of air passing through the channel, the silencer was the best choice in this respect. To achieve a better control, two important characteristics of silencer, i.e. absorption and expansion, were considered to be used simultaneously.

According to the physical properties of the air flow passing through the channel and the sound absorbents commercially available in the market, Convoluted Acoustical Foams (CAFs) with a thickness of 3 inches were selected to be used for covering the inner surfaces of the silencer. This open-cell absorbent was made of polyurethane, and its cone-shape structure increases its surface area up to four times higher than flat absorbents (Fig. 2).

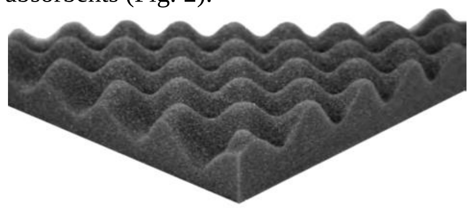

Fig. 2: Convoluted Acoustical Foam

The foam has an acceptable ability in absorbing low and medium sound frequencies. The sound absorption coefficients of the foam in various frequencies are as shown in Table 1, adopted from the catalog published by the manufacturer [14].

Table 1: The sound absorption coefficients of the Convoluted foam in various frequencies

Convoluted Foam Style	Thickness	Sq.Ft. / Set	NRC, by Octave Band Frequency (Hz)						NRC
			125	250	500	1000	2000	4000	
CVF-3-2754	3” Peak	20.25	0.24	0.46	1.03	1.05	0.93	0.90	0.90

In the next step, dimensions of the silencer were computed considering the required sound reduction level by using Equation 3 [8, 10]. In order to increase the absorbing surface area, an aerodynamic blade covered by the acoustic foam was designed and implemented inside the silencer.

$$\boldsymbol{NR(dB) = -10log\left[S_e\left(\frac{cos\theta}{2\pi d^2} + \frac{1-\alpha}{\alpha S_w}\right)\right]} \quad \text{Eq. 3}$$

Where:

α= sabine absorption coefficient of the lining (unit less)

Se= plenum exit area (ft^2 or m^2)

Sw= plenum wall area (ft^2 or m^2)

d= distance between entrance and exit (ft or m)

θ= angle of incidence at the exit (rad)

After computing the dimensions of the silencer, the silencer was built using a 1mm galvanized metal sheet resistant against corrosion, then it was placed at a distance of 40cm from the water cooled conditioner system.

Fig. 3 shows the scheme of the designed silencer and the real silencer is given in Fig. 4. According to the calculations, the dimensions of the silencer were as follows, 1.4m length; 1m wide, and 1m height. Moreover, the silencer's inlet dimensions were 0.45×0.45m, and the outlet was of the same dimensions as the inlet. The length of the aerodynamic blade located inside the silencer was 0.9m and its widest part was equal to 0.3m. Moreover, the total absorptive surface area of the silencer was equal to 8.9m^2 that is shown in Fig. 5.

Finally, all indices, including SIL and PNC, which had been measured before the Implementation of silencer, were measured again to assess the efficiency of the system. At last, the data were analyzed using the SPSS software package.

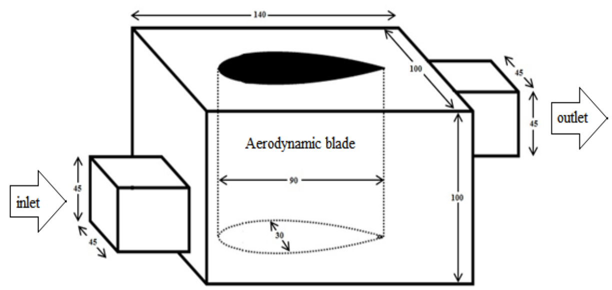

Fig. 3: The scheme of designed silencer

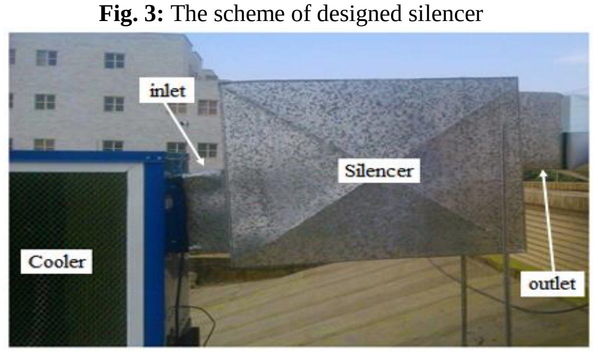

Fig. 4: Real shape of produced silencer

RESULTS

The sound pressure levels in different sections of the indoor environment measured before and after implementing the control system. The results are presented in Table 2. Before implementing the control system, the sound pressure levels were between 57.8 to 61.1 dBA and after implementing the controlling system, the sound pressure level was declined between 13 to 14.2 dBA.

The results of the sound frequency analysis for some rooms before and after applying the control system are shown in Fig. 6. Moreover, this figure demonstrates that noise pick had been at 125 Hz.

The results of PNC and SIL indices before and after the implementation of the control system are presented in Table 3. Before implementing the control system, the PNC and SIL indices were between 55 to 60dB and 54.85 to 58.58dB, respectively. After implementing the control system, the PNC and SIL indices were between 39 to 45dB and 39.9 to 44.3dB, respectively.

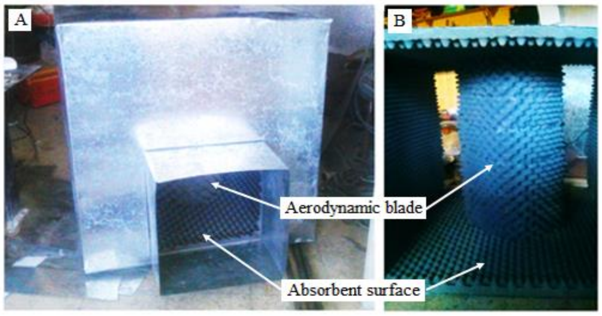

Fig. 5: Aerodynamic blade and absorbent surface outside (A) and inside (B) the silencer

Table 2: The sound pressure levels measured before and after applying the control system, and also the noise reduction ratio.

Stations	SPL before intervention (dB)	Noise reduction, (dB)		SPL after intervention (dB)
		Theoretical	Actual	
Room 1	60.4	18	13.6	46.8
Room 2	57.8	18	13.5	44.3
Room 3	58.3	18	14.1	44.2
Room 4	57.9	18	13.0	44.9
Room 5	61.1	18	13.8	47.3
Room 6	61.1	18	13.1	48.0
Room 7	58.5	18	13.4	45.1
Room 8	58.1	18	13.5	44.6
Room 9	58.3	18	13.8	44.5
Room 10	60.0	18	14.2	45.8

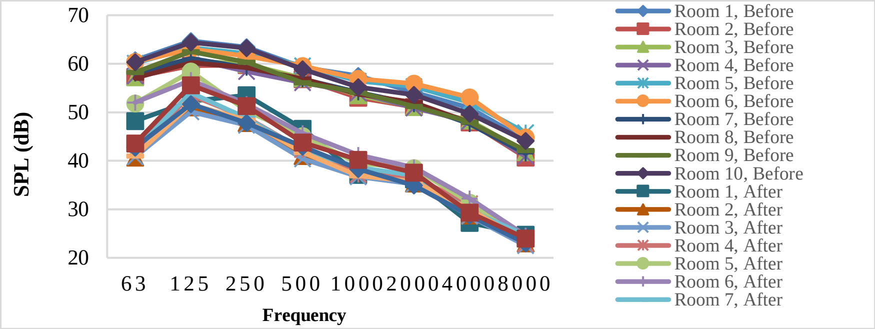

Fig. 6: sound frequency analysis for rooms

Table 3: The results of PNC and SIL indices, before and after applying the control system

Stations	PNC before intervention (dB)	PNC after intervention (dB)	SIL before intervention (dB)	SIL after intervention (dB)	r before intervention (m)		r after intervention (m)	
					men	women	Men	Women
Room 1	58	44	58.58	43.35	0.59	0.37	3.41	2.15
Room 2	55	39	55.15	40.63	0.87	0.55	4.66	2.94
Room 3	55	40	55.38	39.9	0.85	0.54	5.07	3.20
Room 4	55	41	54.85	41.23	0.91	0.57	4.35	2.74
Room 5	59	45	58.35	43.35	0.61	0.38	3.41	2.15
Room 6	60	44	58.48	44.3	0.60	0.37	3.05	1.93
Room 7	56	41	55.45	41.63	0.85	0.53	4.15	2.62
Room 8	56	40	55.45	40.68	0.84	0.53	4.63	2.92
Room 9	55	39	55.43	40.98	0.85	0.53	4.48	2.82
Room10	58	42	57.73	43.23	0.65	0.41	3.45	2.18

DISCUSSION

According to the measurements, the sound pressure level was between 57.8-61.1 dBA, before implementing the silencer. Although the SPL was lower than the occupational exposure limit (85 dBA), it was 12.8 to 16.1 dBA more than maximum acceptable background sound level in the offices (45 dBA) [11]. SPL values in the rooms located near the fan (room 5 and 6) as well as rooms in which the ventilation channels ended (room 1 and 10) were higher than other rooms. The higher SPL in the rooms' number 5 and 6 can be due to the transmission of fan noise via the channel into these rooms. Likewise, the higher SPL in rooms' number 1 and 10 can be the result of the high volume of air remained at the end of the channel that arrived in these rooms with a high velocity without any obstacles.

As expected, the frequency of sound emitted from the system was located in the low frequency range, which is consistent with other studies [4, 6, 7, 9, and 15]. Therefore, we decided to choose a sound absorbent with capability of controlling the low frequency noise. Yousefi *et al.* reported that the maximum reduction of sound pressure levels is in the 125 Hz frequency by absorbent in 5cm thickness and 80 Kg/m^3 density [16]. The convoluted acoustical foam was a good choice because of its acceptable sound reduction coefficient for controlling low frequency sounds located within this range and according to its other excellent features, such as stability in harsh environment with high moisture and temperature, resistivity against oil and acids, and high surface because of its cone style absorbent cells [14]. Gery assessed the effect of absorbent surface style on the level of sound reduction, and concluded that having a triangle or pyramid shape, because of its surface development, improved the efficiency of the silencer in reduction of sound level [17].

In addition to implementation of absorbent on the silencer surfaces, an aerodynamic blade added inside the silencer which it covered by the sound absorbent in order to enhance the efficiency of the silencer in the sound damping. Thus, the used area of the absorptive surface increased. Also, placing this blade in the air conduction path, made the sound to impact directly to the blade, which this can result in better sound absorption on the blade. Moreover, the aerodynamic shape of the blade, leads to better sound absorption by the absorbents on the silencer surfaces and the blade. Therefore, aero-dynamical shape of the blade, caused less pressure drop. The same approach was applied by Gery in silencer designing and the results had been shown that this modification improves the functioning of the silencer.

Furthermore, Gery has reported that the use of an aerodynamic blade alongside the coverage of walls with the absorbent, is more efficient than having covered walls without the blade or having covered the blade with simple walls. In addition, he represented that using an aerodynamic blade is more effective in reducing the low frequency sound level than using an un-aerodynamic one [17]. In another study, Zare *et al.* used a silencer equipped with parallel plate absorbent to reduce the sound of the Cooling Tower pump [18].

The value of PNC and SIL indices calculated before the implementation of silencer, emphasized that the PNC index is much higher than the recommended value for administrative rooms (35-45 dB) [3,19]. Since the PNC index is higher than 50 dB, so a difficulty in the lingual communication between people is expected. Farhang Dehghan *et al.* have demonstrated that a PNC index of about 62 dB causes adverse effects, including fatigue, sleepiness, vertigo, concentration loss, headache, and a feel of uncomfortably during the day [20]. The maximum distance between the speaker and listener before implementing the silencer showed that if the residents wanted to talk on a usual sound pressure level, they should lower the distances to 0.91m for men and lower 0.57m for women, which are very short and unacceptable.

Finally, sound assessments demonstrated that the SPL achieved a reduction level about of 13 to 14.2 dBA by implementing the silencer, which is equal or lower than the permissible level for administrative rooms. Moreover, the frequency analysis revealed that PNC index was reduced up to 14 to 16 dBA, achieving permissible PNC limits for offices. Also, SIL decreased 13.62 to 15.48 dBA, and led to maximum distance between speaker and listener which increased up to 5.07m for men and 3.20m for women. Lower SIL levels can provide safer communications in comparison with the longer distances [21].

CONCLUSION

The absorptive-dissipative silencer covered by Convoluted Acoustical Foam was used to reduce the sound caused by the ventilation system. The results of the study demonstrated that using designed silencer is capable to reduce the SPL about 13.6 dB, in average, and also the PNC and SIL indices to permissible limit recommended for office rooms. Finally, the study confirmed that the silencer with the inner aerodynamic blade is an effective tool for reducing sound emitted from air conditioning and industrial ventilation systems.

ETHICAL ISSUES

The Shahroud University of medical sciences ethics committee approved the study protocol.

CONFLICT OF INTEREST

We affirm that this article is the original work of the authors and have no conflict of interest to declare.

AUTHORS' CONTRIBUTION

All authors were participated in all stages of the research.

FUNDING/ SUPPORTS

The project was supported financially by Shahroud University of medical sciences.

ACKNOWLEDGEMENT

The authors would like to appreciate Shahroud University of Medical Sciences for funding and supporting this project.

REFERENCES

[1] Nezami T, Golmohammadi R, Aliabadi M, Soltanian A. Investigation acoustic comfort indexes in staff of open plan offices in state banks in Hamadan city. Journal of Occupational Hygiene Engineering. 2015; 1(4):60-67.

[2] Gholami T, Piran Veyseh P, Aliabadi M, Farhadian M. Evaluation of noise pollution and its effects on subjective fatigue of staffs in the governmental banks of Hamadan city. Iran Occupational Health. 2014; 11(5):65-73.

[3] Barron FB. Industrial Noise Control and Acoustics. New York: Marcel Dekker; 2003.

[4] Kaczmarska A, Łuczak A. A study of annoyance caused by low-frequency noise during mental work. Int J Occup Saf Ergon. 2007; 13(2):117-25.

[5] Larsson M, Johansson S, Håkansson L, Claesson I, editors. A system implementation of an active noise control system combined with passive silencers for improved noise reduction in ducts. Fan Noise; 2007 September 17- September 19; Lyon.

[6] Choy Y-S, Lau K-T, Wang C, Chau C, Liu Y, Hui D. Composite panels for reducing noise in air conditioning and ventilation systems. Compos B Eng. 2009; 40(4):259-66.

[7] Choy Y, Huang L. Multiple drumlike silencer for low frequency duct noise reflection. Appl Acoust. 2009; 70(11):1422-30.

[8] Golmohammadi R. Noise and Vibration Engineering. 3rd ed. Hamadan-Iran: Daneshjoo Publishing; 2006 [In Persian].

[9] Wang C, Cheng L, Huang L. Realization of a broadband low-frequency plate silencer using sandwich plates. J Sound Vib. 2008; 318(4):792-08.

[10] Bell LH, Bell DH. Industrial noise control: fundamentals and applications. New York: Marcel Dekker Publishing; 1994.

[11] Mohammadpour H, Moussavi Najarkola SA, Jalali M, Hosseini Asl A, Rahmati A. GIS-Based Noise and Hearing Loss Screening in Publishing Factory. Health Scope. 2013; 2(3):156-61 .

[12] ISO 1999. Determination of occupational noise exposure and estimation of noise-induced hearing impairment. Geneva: International Standard Organization Press; 1990.

[13] ISO 9612. Guidelines for Measurement and assessment of exposure to noise in working environment. Geneva: International Standard Organization Press; 1997.

[14] Jaouen L, Renault A, Deverge M. Elastic and damping characterizations of acoustical porous materials: Available experimental methods and applications to a melamine foam. Appl Acoust. 2008; 69(12):1129-40.

[15] Yousefi HA, Forouharmajd F, BolghanAbadi S. Noise reduction efficiency of Helmholtz resonator in simulated channel of HVAC system. Int J Environ Health Eng. 2014;3(1):33-39.

[16] Jahangiri M, Golmohammadi R, Aliabadi M, Jalali M. Noise control of feed water pumps in a thermal power plant. Iran occupational health. 2017; 14 (1):81-92 [In Persian].

[17] Grey A. Induct Dissipative Bar-silencer Design [MSc thesis]. Canterbury: University of Canterbury; 2004.

[18] Grey A. Induct Dissipative Bar-silencer Design [MSc thesis]. Canterbury University; Mechanical Engineering Department; 2004.

[19] Pandey G, Carney GC. Environmental Engineering. 1st ed. India: McGraw Hill Education; 2001.

[20] Farhang Dehghan S, Monazzam M, Nassiri P, Haghighi Kafash Z, Jahangiri M. The Assessment of Noise Exposure and Noise Annoyance at a Petrochemical Company. J of Health and Safety at Work. 2013; 3(3):11-12.

[21] Okcu S, Ryherd E, Zimring C, Samuels O. Soundscape evaluations in two critical healthcare settings with different designs. J Acoust Soc Am. 2011;130(3):1348-58.