Subjective Assessment Research of Middle Pressure Regulator Boxes in Urban Gas Industry

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Abstract. In urban gas industry there are many middle pressure regulator boxes which locate in noise sensitive areas like Class 1 and Class 2 acoustic environment functional areas in where exist strict noise emission limit requirement. Compared with high pressure regulation stations these middle pressure ones generate lower level noise but they are still complained because of the boundary noise excessive emission caused by direct exposure outdoors and lack of noise control treatment like acoustic enclosures, sound barriers and walls’ baffle. Most of the existing research focused on the parameters like noise sound pressure level, sound power level and so on of these regulator boxes, and there is little achievement about the subjective assessment of the noise generated by them. But the values of noise subjective assessment are the major reasons and influential index of the surrounding environmental complaints. In this paper, some objective values of subjective assessment base on several typical middle pressure regulator boxes noise emission during gas supply peak are measured, calculated and analyzed, the results offer the scientific evidence for the noise control and subjective feeling improvement of these boxes.

1. Introduction

In recent years, as tougher environmental protection policies are implemented, clean energy is widely used in China. As the driving force of clean energy, the usage and penetration of natural gas have also increased, which has promote the rapid development of the urban gas industry.

A large number of middle-pressure regulator boxes are indispensable to gas operation network in every city, and are distributed in noise-sensitive areas such as residential areas and hybrid areas of commerce and residence. These areas are divided, according to the acoustic environment classification[1], as Class 1 and Class 2 area where noise emissions must meet strict standard limits. According to the Environmental Protection Tax Law of the People’s Republic of China, taxes of excessive noise emissions are levied based on excessive decibels and the number of locations[2]. Therefore, being aware of the situation of noise emissions from middle-pressure regulator boxes and reducing noise-related complaints have become one of the problems faced by urban gas operators.

2. Status of middle-pressure regulator boxes

2.1. Noise Sources

The middle-and-low-pressure regulator boxes in the city shares similar noise sources with the high-pressure ones, but sound power and the size of sound sources of the former one are much smaller.
With regard to noise generation mechanism: First, gas is transmitted at high speed inside the gas pipeline, which generates high flow-induced noise that spreads outward through the fluid-solid coupling with the pipeline; meanwhile, the original flow field mutates in manifolds or other structures, thereby generating new noises. Second, regulator boxes also produce noises, specifically including noises of rotating machines and fluid dynamic noises. The former one refers to the noise generated by mechanical rotation, natural frequency vibration, and fluid pressure fluctuations caused by the oscillating displacement of the valve core, which are attributable to the design of the regulator boxes, components and materials, processing technology, and assembly quality. The latter noise is produced by the turbulence and vortex flow after the fluid passes through the valve port of regulator boxes, that is, the noise generated by the interaction of the turbulent fluid with the regulator boxes or with the inner surface of the pipeline [3].

In addition, there is a rigid connection between the box structure and pressure regulators as well as filtering pipelines. The vibration of the pipelines will be effectively transmitted to the box structure through this connection, and causes the box structure to vibrate and produce secondary radiated noise, which intensifies noise pollution.

2.2. Noise characteristics

Compared with high-pressure regulator boxes in the city, although middle-pressure ones produce lower decibel of noises, most of these boxes are exposed outdoors, and lack noise-related control measures such as acoustic enclosures, sound barriers, and fences. As a result, noises emitted by the factory boundary often exceed standards, and many related complaints have been received. Through the observation, measurement and statistics of middle-pressure regulator boxes of Beijing in heating season and non-heating season, noise characteristics of middle-pressure regulator boxes in the urban gas system are summarized as follows:

- During the peak period of gas consumption, the noise level inside the middle-pressure regulator boxes ranges from 65 to 75dBA. Generally speaking, the larger the tanks and the internal equipment are, the higher the internal noise level will be. The noises produced by regulator boxes within factory boundary range between 53 and 65dBA, changing with the noise level inside the regulator boxes.
- During the non-peak period of gas consumption, the noise level inside the middle-pressure regulator boxes ranges from 55 to 65dBA. Generally speaking, the larger the tanks and the internal equipment are, the higher the internal noise level will be. The noises produced by regulator boxes within factory boundary range between 42 and 53dBA, changing with the noise level inside the regulator boxes.
- According to statistics, the daytime excessive noise of the middle-pressure regulator boxes with excessive emissions ranges from 5 to 10dBA, while the night time excessive noise ranges between 8 and 15dBA.
- Other regulator boxes of this type which meet or partially meet the emission standards (the daytime standards) have also received noise complaints from nearby residents.

2.3. Research challenges

Previous researches focus on how to deal with noise problems of the high-pressure regulator boxes or stations in the city gas system, while studies on the noises emitted by the middle-pressure regulator boxes are almost restricted to the sound pressure level or spectrum analyses and few researches are published concerning the subjective evaluations of noise. The evaluations act as the main factor in causing complaints of surroundings and of middle-pressure regulator boxes that fulfill or partially fulfill the emission standard requirements (the daytime standards). Therefore, it is important to discuss the subjective evaluations of the noise emitted by the middle-pressure regulator boxes in the city.
3. Objective indicators for subjective assessment of noise

3.1. Subjective assessment of noise
In addition to objective indicators such as sound pressure level, NC and NR, among other evaluation curves, subjective assessment indicators of the noise include objective indicators and subjective ratings. The objective indicator is the value calculated by noise data based on the characteristics of human hearing and perception, while subjective ratings allow the listeners to score their feelings of certain noise and the result is influenced by their educational background, life experience, physical conditions, living environment, etc.

3.2. Objective indicators of subjective assessment
Frequently-used objective indicators for subjective evaluation include: sharpness, fluctuation strength, roughness and psychoacoustic annoyance.

- Sharpness [4] describes how sharp the sound is, which is one of the features used to assess sound quality. The higher the frequency is, the sharper the sound is.

\[
S = 0.11 \int_{0}^{24\text{Bark}} g(z) dz \int_{0}^{24\text{Bark}} dz
\]  

Here, \(g(z)\) is a weighting function when the sound is in a higher frequency band.

- Fluctuation Strength[4] reflects the amplitude modulation of the sound.

\[
F = \frac{0.008 \int_{0}^{24\text{Bark}} dL(Z) dz}{(\frac{\text{mod}}{24\text{Hz}}) \int_{0}^{24\text{Bark}} dz}
\]

Here, \(dL(Z)\) represents the modulation depth in dB, while \(f_{\text{mod}}\) is the modulation frequency.

- Roughness[4] reflects the amplitude modulation of the sound.

\[
R = 0.3 \int_{0}^{24\text{Bark}} dL(Z) f_{\text{mod}} dz
\]

- Psychoacoustic Annoyance (PA) describes to which extent people are bored with the sound[5][6]. According to the Zwicker model[7], the calculation formula is as follows:

\[
PA = N_S \left(1 + \sqrt{W_5^2 + W_{FR}^2}\right)
\]

\[
W_5 = \begin{cases} 
(S - 1.75) \times 0.25 \log(N_S + 10) & S > 1.75 \\
0 & S \leq 1.75 
\end{cases}
\]

\[
W_{FR} = \frac{2.18}{N_S^{0.64}} (0.4F + 0.6R)
\]

Here, \(W_5\) is the coefficient of sharpness, \(W_{FR}\) the coefficient of fluctuation strength and roughness, and \(N_S\) the cumulative percent level of loudness in Sone.

4. Experiment design

4.1. Selection and characteristics of middle-pressure regulator boxes
In order to select typical middle-pressure regulator boxes with noise pollution, five boxes of different sizes and types are chosen to study on the subjective evaluation of noise, including those, receiving most complaints, from Beijing Gas Group, and those from noise-sensitive areas (such as residential areas, villas, hospitals, etc.). The specific features of the five regulator boxes are as follows:

- Box A, located in the green belt between two residential buildings of a residential area, is relatively old, with a length of 1.6 meters, a width of 0.7 meter and a height of 1.7 meters. The box is shown in the figure 1 and 2.
• Box B, located in the green belt between two residential buildings of a residential area, is relatively newer and bigger, with a length of 2 meters, a width of 1.8 meters and a height of 2 meters, as shown in the figure 3 and 4.

• Box C, situated in the hospital, provides gas during the heating season, and gas for such power equipment as air conditioning. Directly installed on the ground, it is moderately new and has a larger volume, with a length of 2.55 meters, a width of 1.55 meters and a height of 2.05 meters, as shown in the figure 5 and 6.
• Located in the villas, box D has been overloaded during the heating season, because a large number of residents modify heating boilers. With low-frequency resonance, the box is old, with a length of 2.06 meters, a width of 0.9 meters and a height of 1.55 meters, as shown in the figure 7 and 8.

• As Box E, located in a residential area in a busy area, is next to the wall, the reflection of the wall aggregates the noise pollution problems with a large radiation area. It is small and old, with a length of 1.87 meters, a width of 0.8 meters and a height of 1.78 meters, as shown in the figure 9 and 10.
4.2. Experimental arrangement
In mid-December 2019, microphones were installed in the middle of the above-mentioned five boxes in the noon and evening, the peak period of heating gas consumption. Ten-minute noise data was collected from each box in each period.

4.3. Data Processing
The data, from the five middle-pressure regulator boxes in the peak period (the period with the most noise pollution), was calculated and further analyzed, including average A-weighted sound pressure level, frequency spectrum, sharpness, fluctuation strength, roughness and psychoacoustic annoyance.

5. Data Analysis

5.1. Results on objective indicators of subjective assessment
The collected data was calculated, and the results are as follows:

- The noises emitted from middle-pressure regulator box A was concentrated in the one-third octave bands between 1000 and 8000 Hz, while the peak existed in the one-third octave band of 8000 Hz. There was a small difference in the noise spectrum between noon and evening. The rest of the data is shown in Table 1.

| Average dBA | Ns | Sharpness | Fluctuation Strength | Roughness | Psychoacoustic Annoyance |
|-------------|----|-----------|----------------------|-----------|--------------------------|
| Data value  | 74.41 | 26.95     | 5.18                 | 0.83      | 1.71                     | 69.11       |
| (noon)      |     |           |                      |           |                          |             |
| Data value  | 80.78 | 22.52     | 3.86                 | 0.99      | 1.67                     | 49.28       |
| (evening)   |     |           |                      |           |                          |             |

- The noise energy emitted from regulator box B in the noon was in the one-third octave bands of 1250-8000Hz, while the peak existed in the one-third octave bands between 4000 and 5000Hz. As the peak value of the low-frequency sound pressure decreased in the evening, it was in the one-third octave bands of 3150-5000Hz. Other data is shown in Table 2.

| Average dBA | Ns | Sharpness | Fluctuation Strength | Roughness | Psychoacoustic Annoyance |
|-------------|----|-----------|----------------------|-----------|--------------------------|
| Data value  | 71.38 | 36.34     | 2.75                 | 0.68      | 1.76                     | 65.68       |
| (noon)      |     |           |                      |           |                          |             |
The noises emitted from middle-pressure regulator box C as well as its peak level in the noon and evening were concentrated in the one-third octave bands between 1000 and 8000 Hz, which revealed small difference. The rest of the data is shown in Table 3.

Table 3. Results on objective indicators of middle-pressure regulator box C

| Average dBA | N<sub>5</sub> | Sharpness | Fluctuation Strength | Roughness | Psychoacoustic Annoyance |
|-------------|--------------|------------|----------------------|-----------|--------------------------|
| Data value  |              |            |                      |           |                          |
| (noon)      | 91.67        | 20.75      | 4.81                 | 0.86      | 50.54                    |
| (evening)   | 91.16        | 21.53      | 4.43                 | 1.26      | 51.87                    |

The noise energy emitted from regulator box D was in the one-third octave bands ranging from 2500 to 10000Hz, while the peak existed in the one-third octave bands between 3150 and 8000Hz. There was a small difference in the noise spectrum between noon and evening. The noise energy from regulator box D was affected by the low-frequency traffic noise around the site. Other data is shown in Table 2.

Table 4. Results on objective indicators of middle-pressure regulator box D

| Average dBA | N<sub>5</sub> | Sharpness | Fluctuation Strength | Roughness | Psychoacoustic Annoyance |
|-------------|--------------|------------|----------------------|-----------|--------------------------|
| Data value  |              |            |                      |           |                          |
| (noon)      | 74.41        | 20.01      | 2.78                 | 0.81      | 38.66                    |
| (evening)   | 75.41        | 21.48      | 2.79                 | 0.84      | 42.26                    |

The noise energy emitted from regulator box E was in the one-third octave bands within 10500-8000Hz, while the peak existed in the one-third octave bands between 1600 and 3150Hz. There was a small difference in the noise spectrum between noon and evening. The rest of the data is shown in Table 5.

Table 5. Results on objective indicators of middle-pressure regulator box E

| Average dBA | N<sub>5</sub> | Sharpness | Fluctuation Strength | Roughness | Psychoacoustic Annoyance |
|-------------|--------------|------------|----------------------|-----------|--------------------------|
| Data value  |              |            |                      |           |                          |
| (noon)      | 81.85        | 39.13      | 2.50                 | 0.94      | 70.03                    |
| (evening)   | 82.84        | 38.31      | 2.47                 | 0.87      | 69.20                    |

5.2. Correlation analysis of Psychoacoustic Annoyance and other indicators
Figure 11 shows the change in psychoacoustic annoyance according to the Zwicker psychology model when the single variable was changed and the other variables were the average of ten experimental samples (cumulative percentile level of loudness was 28.646, sharpness 3.499, fluctuation strength 0.869, roughness 1.736).
According to the Zwicker psychoacoustic annoyance model, psychoacoustic annoyance was affected by loudness, sharpness, fluctuation strength and roughness[8]. The correlation coefficients between psychoacoustic annoyance and loudness, sharpness, fluctuation strength as well as roughness are defined as follows:

\[
K_{\text{Loudness}} = \frac{\text{PA's rate of change}}{\text{Loudness' rate of change}}
\]

(7)

\[
K_{\text{Sharpness}} = \frac{\text{PA's rate of change}}{\text{Sharpness' rate of change}}
\]

(8)

\[
K_{\text{Fluctuation Strength}} = \frac{\text{PA's rate of change}}{\text{Fluctuation Strength's rate of change}}
\]

(9)

\[
K_{\text{Roughness}} = \frac{\text{PA's rate of change}}{\text{Roughness rate of change}}
\]

(10)

It is known from figure 11:

- When the cumulative loudness increases from 10 to 40, the psychoacoustic annoyance grows from 23.262 to 80.005, which reflects linear growth. The correlation coefficient \( K_{\text{Loudness}} \) was 0.813.

- When the sharpness is measured less than 1.75, the change in sharpness does not affect the psychoacoustic annoyance. If it rises from 1.75 to 3, the psychoacoustic annoyance increases from 51.311 to 55.400. In this process, the psychoacoustic annoyance increases slowly, and the correlation coefficient \( K_{\text{Sharpness}} \) hits 0.111. When the sharpness increases from 3 to 9, the psychoacoustic annoyance grows from 55.400 to 114.111, which shows linear growth, with the correlation coefficient \( K_{\text{Sharpness}} \) hitting 0.529.
When the fluctuation strength increases from 1 to 5, the psychoacoustic annoyance sees an increase from 59.082 to 91.906, which indicates a linear growth with the correlation coefficient $K_{\text{Fluctuation Strength}}$ hitting 0.138.

When the roughness sees a surge from 0.5 to 2, the psychoacoustic annoyance also grows from 50.659 to 60.438, which reflects slow growth with the correlation coefficient $K_{\text{Roughness}}$ reaching 0.064. When the roughness increases from 2 to 10, the psychoacoustic annoyance witnesses an increase from 60.438 to 134.017. In this process, the latter increases linearly, and the correlation coefficient $K_{\text{Roughness}}$ is 0.304.

In conclusion, loudness is the main factor in influencing the psychoacoustic annoyance. If the sharpness is measured more than 3, it is also an important factor for the psychoacoustic annoyance. Otherwise, other factors should be considered. Roughness and fluctuation strength exert few influence on the psychoacoustic annoyance, especially the change of the latter.

6. Conclusions
In this experiment, the value of average roughness of the ten data sets is 1.7, while the fluctuation strength is measured less than 1, except for the box D whose value of fluctuation strength exceed 1. Besides, the cumulative loudness of all regulator boxes is above 20. Based on the experimental analysis, the psychoacoustic annoyance of the middle-pressure regulator boxes is affected by the sharpness and loudness. When the sharpness is measured less than 3, the loudness is the most important factor.

The noise energy emitted by the five regulator boxes exists in the one-third octave bands of 1000Hz-8000Hz, most of which are high-frequency. As the box D is close to the roadside, low-frequency noise exist when large trucks pass slowly. The sharpness of the box A and the box C is obviously higher than that of boxes in other locations, which is consistent with the on-site personnel’s feelings. The frequency bands of each regulator box during the day and night is basically the same, but there are small changes in the sound pressure level.

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