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Experimental study on both cleaning effect and motion performance of the duct-cleaning robot

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ABSTRACT

With increasing consideration on public health, the cleaning industry for central air-conditioning systems has been flourished in China with the rapidly developed of both duct-cleaning technology and cleaning robots. By testing the performance on the experimental platform, this paper presents the cleaning effect and motion performance of the duct-cleaning robot designed by our expert group. The result indicates that the cleaning effect is not satisfied at corners and elbows, where the pollution is relatively serious. At the end of this paper, it points out the development direction for China's duct-cleaning robot and its experimental platform, which can provide an important basis to standardize the test platform, tools and methods for the evaluation of robot's performance.

1. Introduction

With the rapid development of economy, the central air-conditioning and ventilation system has been widely used to improve the indoor air quality. The pollution of ventilation system in public buildings with different functions in both south and north regions was investigated (Song et al., 2010; Zhao et al., 2011), and the conclusion was that the amount of dust, bacteria and fungi on the inner surfaces of duct had reached to 288.48 g/m^2, 1575 cfu/cm^2 and 1440 cfu/cm^2 respectively. Researchers pointed out that the contaminated ventilation system not only fails to dilute the pollutant concentration by air supplying, but also diffuses the spread of contamination (Chen, Zhao, & Yang, 2009). The cleaning of duct systems and equipments is an effective way to reduce pollution and improve indoor environment quality. With its automatic control system and visual function, the duct-cleaning robot performs well in cleaning work, which brings a great convenience to the cleaning of central air-conditioning and ventilation systems (Li, Zhang, & Li, 2009). The duct cleaning equipment was first developed in US in 1950s, and the technique was introduced to China in 2000s. The duct-cleaning robot is newly appeared in the market, and with using advanced control systems, it has advantages of intelligent and humanized. However, in China, there is no relevant technical standard to evaluate the performance of the cleaning robot to make the domestic industry of duct-cleaning robot extensive widely (Luo, Cao, & Song, 2009; Yang, 2004). This may threaten the robot's quality and performance. In this situation, our group has developed the robot-integrated system and set up an experimental platform for the robot's performance test. Based on the tests for robot's cleaning effect and motion performance, this paper presents the standardization of the test platform, tools and methods applied in the evaluation of robot's performance. The systematic study on key problems revealed in cleaning work is also included in this paper.

2. Design scheme of the experimental platform of the duct-cleaning robot performance

The test platform consists of rectangular and round ducts in various dimensions and elbows to better simulate different kinds of complicated conditions of the robot working process. Sorts of experiments such as tests for robot's adaptability in ducts, cleaning effect, turning and climbing performance can be operated on this platform (Luo, 2009; Yong, Yunyou, Dan, & Lisi., 2009).

The principle layout and size of the experimental platform is shown in Fig. 1 and the real picture is shown in Fig. 2. In the installation, one side of the rectangular duct and a quarter of the round duct were replaced by transparent boards which is made

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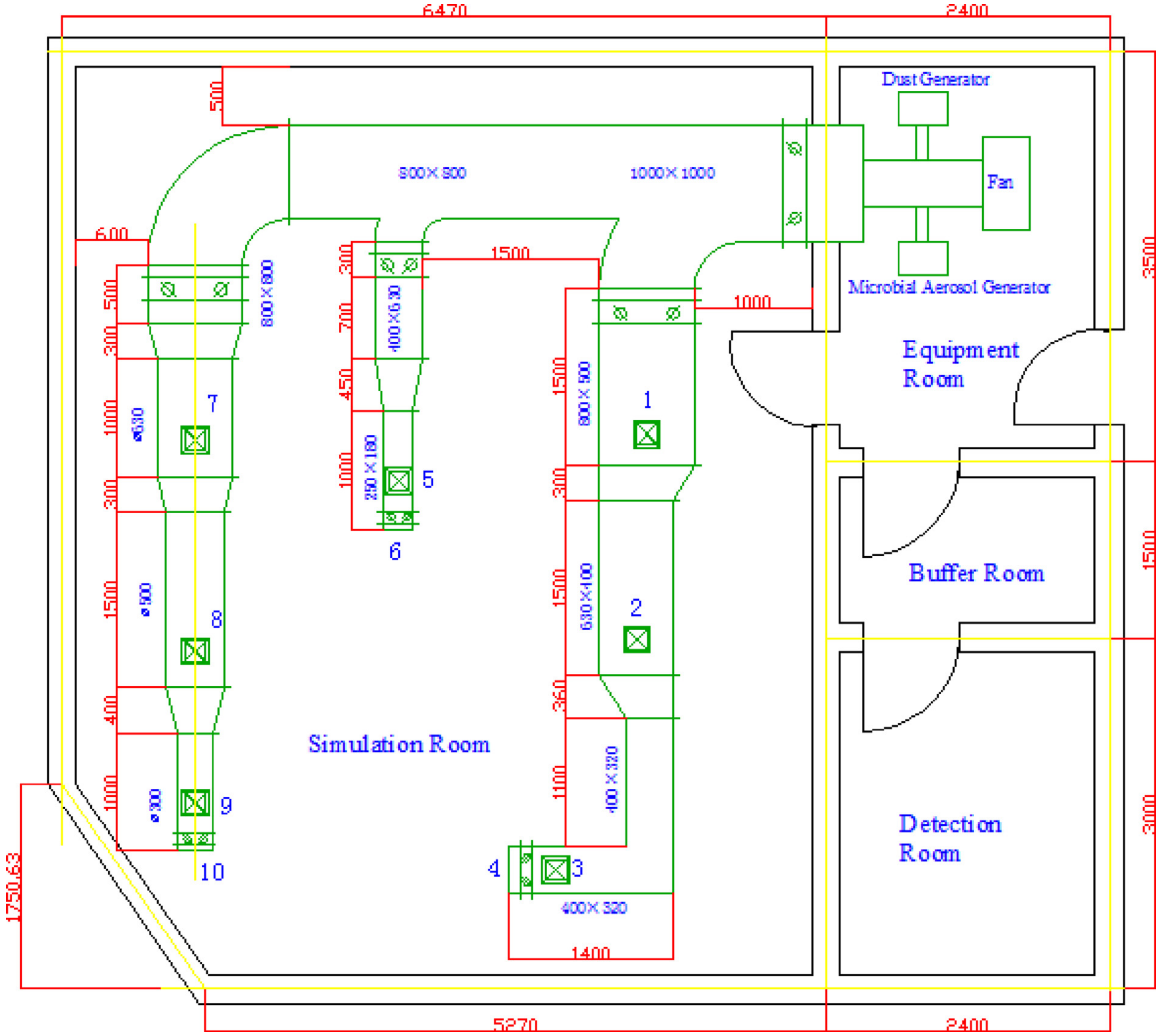

Fig. 1. Principle layout of the experimental platform.

by plexiglass and the ducts were set 0.8 m high to the ground so that the working process of the robot can be observed outside. Square holes were opened as an access for the robot and sampling. HEPA filters were installed on the ends of branch pipes and 4 exhaust vents. When the experimental dust is emitted, the other exhaust vents are turned off and the air flows out from the filers only so that the dust can uniformly be deposited on the inside surface, and the pollution outside ducts can be avoided at the same time.

Fig. 2. Picture of the experimental platform.

3. Experiment scheme of cleaning effect of the duct-cleaning robot

The pollution inside ducts was distributed by artificial approach. By using the dust generator and microbial aerosol generator, the pollution was generated, and the fan blew the pollution into the ducts then the robot was sent to clean. The robot consists of 4 parts, including the moving body, the cleaning brush, the control system and the monitoring system. The moving body of cleaning robot is shown in Fig. 3. The moving body carries the cleaning brush and moves in the ducts, the brush cleans the inner surface of the ducts. The working scene is shown in Fig. 4. Wiping method was adopted in the dust sampling, and the microbial sampling uses the swab-wiping method. After that, the microbe was generated and analyzed after collected. The TSI DUSTTRAK 8520 smart dust detector and the six-level sieve air-percussive samplers were respectively utilized in the sampling of inhalable particulates and microbe from

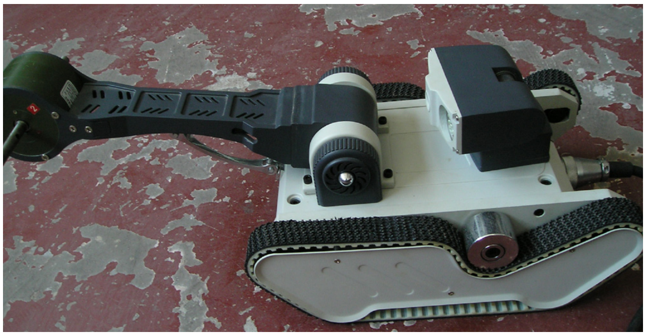

Fig. 3. The moving body of duct-cleaning robot.

air distributors. The technical indexes of the equipment are shown in Table 1.

Table 1
Index of the sampling equipment.

TSI DUSTTRAK 8520 smart dust detector	Six-level sieve air-percussive sampler
The measuring principle: 90° angle light scattering	Model: FA-1
Measurement range: 0.001–100 mg/m^3	Capture rate: >98%
Particle size range: 0.1–10 μm	Capture particles range:
Resolution: 0.001 mg/m^3	Level 1: >7.0 μm, aperture: 1.18 mm
Flow range: 1.4–2.4 L/min	Level 2: 4.7–7.0 μm, aperture: 0.91 mm
Ambient temperature: 10–50 °C	Level 3: 3.3–4.7 μm, aperture: 0.71 mm
	Level 4: 2.1–3.3 μm, aperture: 0.53 mm
Ambient humidity: 0.95% RH (non-condensate)	Level 5: 1.1–2.1 μm, aperture: 0.34 mm
	Level 6: 0.65–1.1 μm, aperture: 0.25 mm
	Sampling flow: 28.3 L/min (adjustable)

3.1. Experiment 1: test for robot's general cleaning effect

According to the standards (Ministry of Health, 2006a; Ministry of Health, 2006b), 8 sampling points on the inner surface were selected to investigate and compare the amount of dust and microbe before and after cleaning.

3.2. Experiment 2: test for robot's cleaning effect in ducts with different shapes and diameters

In both rectangular and circular ducts, 3 points were selected in ducts of different diameters, and the amount of dust was measured before and after cleaning. The test and sampling were taken repeatedly to obtain the average value of the ducts which the analysis of the cleaning effect was tested.

3.3. Experiment 3: test for robot's cleaning effect in the special position

Special positions such as round elbow, rectangular and round reducer were selected in this experiment. The test and sampling were taken repeatedly to obtain the average value of the ducts which the analysis of the cleaning effect was tested.

3.4. Experiment 4: test for the concentration of inhalable particulates after cleaning

In this experiment, 5 outlets were chosen and the concentration of inhalable particulates was detected every half-hour. Then the change of the concentration after 5 h cleaning can be investigated.

Fig. 4. The duct-cleaning robot in working.

Fig. 5. Comparison of the lower inner surface before (left) and after (right) cleaning.

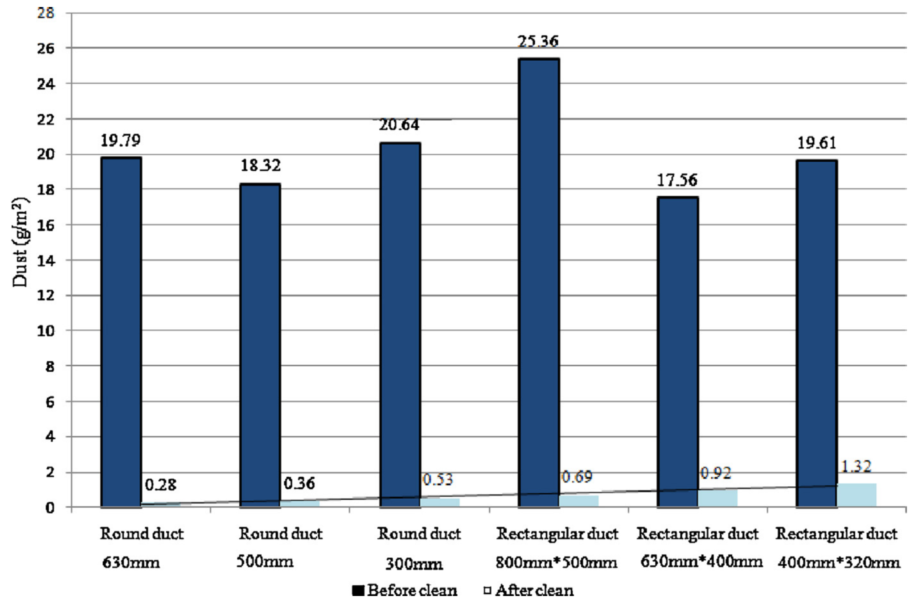

Fig. 6. The cleaning effect of ducts with different shapes and diameters.

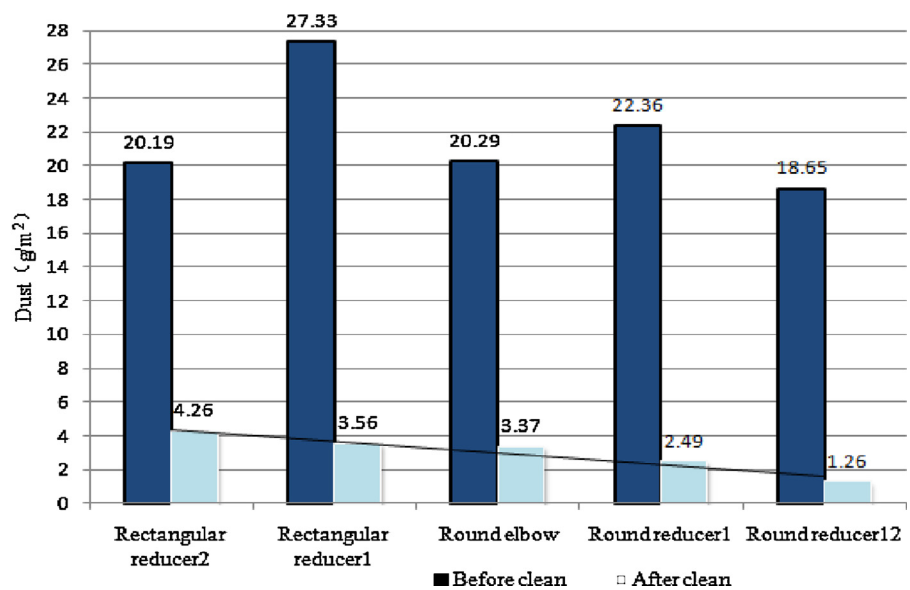

Fig. 7. The cleaning effect in special positions.

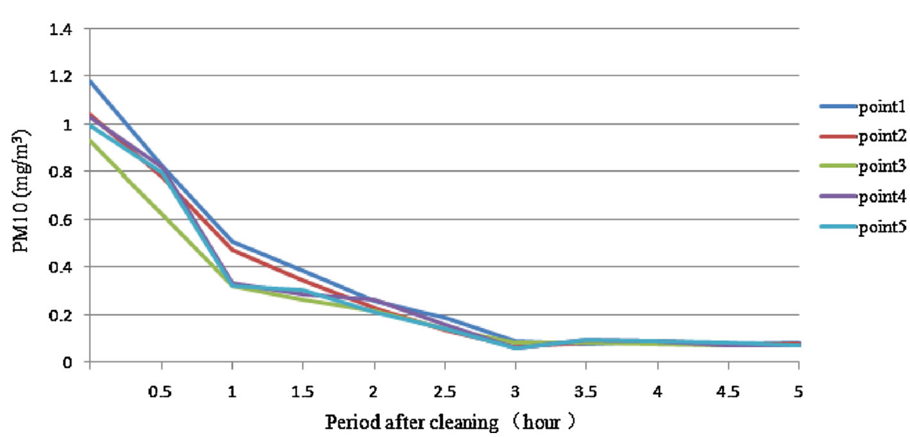

Fig. 8. The change of the concentration of inhalable particulate in air supplying after cleaning.

Table 2
The result of general cleaning experiment.

Measure	Dust (g/m^2)		Bacteria (cfu/cm^2)		Fungi (cfu/cm^2)	
Point	Before cleaning	After cleaning	Before cleaning	After cleaning	Before cleaning	After cleaning
1	16.29	0.85	567	65	433	71
2	17.24	0.66	369	57	370	34
3	30.88	0.51	432	46	429	65
4	18.10	1.17	415	55	417	54
5	18.90	0.58	409	98	369	70
6	15.52	0.96	398	87	405	74
7	15.45	0.92	360	68	345	65
8	7.56	0.85	258	53	256	48
Pass rate (%)	87.5		100		100	

4. Experiment scheme of the moving performance of the duct-cleaning robot

4.1. Experiment 5: climbing test

The robot, which was no-load and towing less than 2 m, was put on a slope with adjustable angle. The slope angle was gradually increased until the robot stopped moving upward.

4.2. Experiment 6: speed test

In this experiment, the robot was with no-load and its speed was maximized when it moves for 2 m in a horizontal pipe. Then we calculated the robot's speed and repeated this test.

5. The result and analysis of cleaning effect

The result of Experiment 1: Table 2 indicates that the pollution was serious before cleaning, but after cleaning, 87.5% area of inner surface satisfied the dust standard, and it was 100% for fungi and bacteria. It shows that the cleaning effect was good. Fig. 5 shows two pictures of inner surface which were taken before and after cleaning respectively.

The result of Experiment 2 was shown in Fig. 6, and it indicates that the rectangular duct was more difficult to be cleaned than the round duct, and the bigger duct could be cleaned easier. The remaining dust was under 0.53 g/m^3 in the round ducts and above 97.4% of the dust were removed, while more than 0.69 g/m^3 in the rectangular ducts, and under 97.2% were removed.

The result of Experiment 3 was shown in Fig. 7, and it indicates that the cleaning effect was not so good in special positions such as elbows and reducers. 78.9–93.2% of the dust were removed in special positions. Compared to the round reducer, the rectangular reducer was the more difficult to clean, and the percentage of removed dust is lower.

The result of Experiment 4 was shown in Fig. 8, and it indicates that the concentration of inhalable particulates was still beyond the standard requirement even after cleaning for long time. The concentration was about 0.1 mg/m^3 and stayed stably after cleaning for 3 h and satisfied the requirement at the same time".

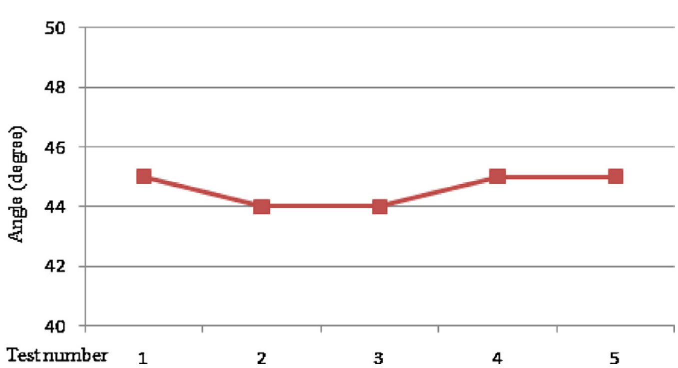

Fig. 9. Test for robot's maximum creep angle.

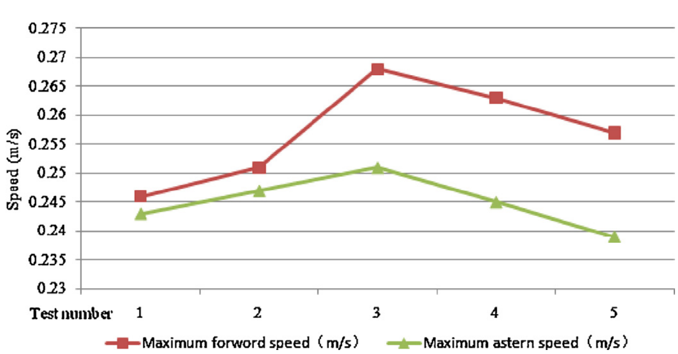

Fig. 10. Test for robot's maximum speed.

6. The result and analysis of moving performance of duct-cleaning robot

The analysis of Experiments 5 and 6: As is shown in Figs. 9 and 10, the average value of robot's maximum creep angle is 44.6°. The maximum moving speed is 0.257 m/s in average, and the maximum astern speed is 0.245 m/s in average.

In the 5 experiments, the parameters stayed relatively stable, indicating the excellent moving performance of the robot.

7. Conclusions

(1) The general performance of the robot designed by our group is good, while some common problems do exist. For instance, the robot is inefficient to clean the elbows and corners, and its performance in the rectangular duct needs to be improved.
(2) Dust and bacteria are much easier to accumulate at some positions like elbows, corners and reducers, and also hard to be cleaned. While those special positions, where the pollution is more serious, are currently neglected by relevant specifications. Therefore, this issue is very necessary to be taken into consideration in the design of robot, and in the preparation or amendment of the specification.
(3) In China, most robots design follows the step of foreign countries, where round ducts are dominant in ventilation system. That is the reason our robot performed better in round ducts than others. However the irregular rectangular duct is more widely used in China, the design of robot's cleaning component should be improved to adjust this kind of duct.
(4) Because of the dust raised by cleaning, the concentration of PM10 increases apparently. The concentration of PM10 reaches

to the peak after 30 min cleaning and decreased to a low level after 3 h. So a pre-run for 3–4 h or even half a day is necessary before the system put to use.

(5) In the installation of the current test-platform, factors like duct shape and size were already taken into consideration. Different materials for ducts would be considered in the further improvement to make the test-platform work better.

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