IMPROVEMENT OF VENTILATION SYSTEM DURING CONSTRUCTION IN HSUEHSHAN TUNNEL AND ITS INTELLIGENT OPERATION STRATEGY

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ABSTRACT

In this study, an innovative computer-aided design methodology for the ventilation system design of the 12.9 km long Hsuehshan tunnel during construction has been developed. 3D CFD analysis has been performed with full-scale experiment to validate the design effectiveness with successful result. An optimal operation strategy has also been developed which saves operation cost and energy significantly.

Keywords: Ventilation System During Construction, 3D CFD Analysis, Full-scale Experiment

INTRODUCTION

When a long tunnel is under construction, the ventilation problem becomes more serious as it penetrates deeper and deeper, especially when Drill-and-Blast method was used for excavation. The local Code for Labor Health Protection necessitates the oxygen content to exceed 18 % during tunneling all the time, with air speed no less than 0.3 m/s at the working surface of excavation. Normally, this is accomplished by a soft mechanical ductwork leading all the way from tunnel portal to the working surface.

The ventilation system is designed by considering the air flow rate needed to dilute the pollution generated by blasting and excavation, transportation vehicles, etc. so that the concentration of the exhaust gases can be controlled within the threshold limit, or as shown in table 1.

To facilitate this design process more effectively, a computer-aided design program “ RSEA DUCT-1” has been developed in this study for the 12.9 km long Hsuehshan tunnel

Table 1 The Threshold Level of Pollutant Concentrations in Working Environment, Taiwan

Gases	Concentration (ppm)	Density (kg/m^3)
CO_2	5,000	9,000
CO	35	40
H_2S	10	14
SO_2	2	5.2

THE DESIGN PROCEDURE

In order to take advantage of the #3 vertical shaft, which is now completed for ventilation during construction, it is considered more efficient to divide the total tunnel length into 4 segments, each with a maximum length of 3.5 km to be equipped with a Single-Headed Soft Ductwork, or SHSD system.

The airflow rate of the SHSD system has been calculated through the computer with the following equations:

(1) During normal working

$$Q_1 = q \times N \tag{1}$$

where q = ventilation rate for each person (cmm/person)

N = number of persons

(2) During Blasting

$$Q_2 = K \times P / \alpha \times t \tag{2}$$

where P =gas production rate during blasting (m^3)

α =pollutant concentration threshold level (ppm)

t =time for ventilation before re-entry (s)

K =constant

(3) During Shotcreting

$$Q_3 = P / \alpha \times t \tag{3}$$

where P =dust production rate (mg)

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α = pollutant concentration threshold level (mg/m3)

t = time for ventilation before re-entry (s)

(4) Ventilation rate for Transportation Vehicle

$$Q_4 = (H_s \times q_s \times \alpha_s) + (H_d \times q_d \times \alpha_d) + (H_e \times q_e \times \alpha_e) \qquad (4)$$

where Hs = rated output of vehicles (ps)

q_s =ventilation rate per specific vehicle (cmm/ps)

α_s =utilization percentage per specific vehicle (%)

The calculated airflow rate needed and pressure loss should be further corrected by the air leakage rate per 100 meter duct length, or

$$Q_f = Q / (1 - m) \qquad (5)$$

The result generated by the RSEA DUCT-1 program yielding a ventilation system with a 1.8 m diameter soft ductwork and a 220-kw fan at the portal with 2,500 cmm air flow rate. The soft ductwork can be extended in stages while always keeping the duct outlet 40 m from the working surface.

3D CFD SIMULATION

In order to simulate the effectiveness of this design, 3D CFD analysis has been performed. As shown in figure 1, the push-pull effect of the airflow can be experienced as expected so that the air speed at the working surface “A” is near 1.5 m/s, much higher than the 0.3 m/s needed. The pressure distribution as indicated by figure 2 further validated that the pollutants was purged out longitudinally along the tunnel. In other words, the airflow is essentially making an U-turn at the working surface and scavenging pollutants generated by the blasting and transportation vehicles successfully.

DEVELOPING THE OPTIMAL OPERATION STRATEGY

Conventionally, a constant speed fan was adapted for this application, creating a problem of inadequate airflow rate when the tunnel penetrated deeper and deeper. Figure 3 shows the main reason that when the duct length increases, so is the pressure drop and losses. The increasing resistance moves point A to point B where air flow rate Q b will be supplied, leading to inadequate air velocity near the working surface.

Therefore, the conventional design always chooses the peak flow resistance for fan selection and yielding an over-sizing problem. An innovative design method has been developed in this study; to utilize a variable speed drive (VSD) fan to coup with various stages of blasting and excavation, with different air flow demand. The computer problem “RSEA DUCT-2” has been compiled for this purpose where figure 4 shows its performances. Right after blasting is completed, maximum airflow will be provided so that pollution level can be brought down to acceptable threshold level, normally within 15 to 30 minutes. In this case, the ventilation system is operating at point A as shown in figure. Following that, the system works at points B and C for excavation, shotcreting, or drilling and charging the blast holes with explosives process while much less air flow is needed and supplied so that tremendous amount of energy and operation cost can be saved. It is estimated that over 40 % savings can be expected in case of Snow Mountain Tunnel.

FULL-SCALE EXPERIMENTAL VALIDATION

In order to validate the system performances, a full-scale experiment has been performed first to measure the air leakage rate m per 100 meter duct length, or the m value as shown in equation 5. The experimental set-up is shown in figure 5.

Furthermore, a series of full-scale experiments has been performed in the Hsuehshan tunnel east portal to validate the ventilation system performances under different operation modes, including the following 6 cases:

Case 1: No Ventilation is provided before and after blasting, as a comparative basis

The result shown in figure 6 indicated that in zone A and B, there are essentially no sensible air velocity can be measured as expected. While in Zone C, the situation improved due to the 2m diameters duct air supply. In zone D, the situation improved further due to the #3 vertical shaft producing a significant chimney effect.

Case 2: Ventilating with existing system in a supply mode before blasting only

The result in figure 7 indicated that in zone A, the air velocity is minimal and approaching zero due to the serious air leakage of the existing duct. The other areas are showing some good result, especially in zone C and D, due to the 2m Diameter duct and the #3 Vertical shaft. After blasting, it takes 45 minutes ventilation before transporting of debris can be proceeded. This is also showing that the inadequate ventilation has become the bottleneck and constraint for a faster working shift.

Case 3: Ventilating with existing system in a supply mode before blasting, and with the new SHSD system in an exhaust mode

This case can be considered an improved strategy of case2, or the existing system. Test result in figure 8 indicated that in zone A, the situation is not improved since the existing duct in a supply mode is still the predominant factor. While in zone B, an air velocity can be experienced now, showing the situation is improving when compared with case 2. The result is that the transporting of debris can now take place, in 22 minutes after blasting -- that is, an improvement of almost 50 % in shortening the working shift period.

Case 4: Ventilating with the new SHSD system in a supply mode before blasting only

As the second option for improvement to the case 2, the result in figure 9 is quite encouraging, with a significant air velocity of 0.6 m/s measured in zone A. In zones B, C and D, significant improvement had all been experienced due to the low air leakage rate of the new venting system and with a push-and-pull mode to form a much better air flow pattern for pollutant removal..

Case 5: Ventilating with the new SHSD system in a supply and exhaust mode before blasting

Due to the low air leakage rate of the new venting system and with a push-and-pull mode to form a much better air flow pattern for pollutant removal, the result in figure 10 is significantly improved indicating that satisfactory and pleasant working environmental conditions has been maintained.

Case 6: Ventilating with the new SHSD system in a supply and exhaust mode after blasting

Following the successful operation strategy of the push-and-pull mode before blasting, the same mode has been again applied after blasting. The result is a significantly improved situation, that the transporting of debris can take place in 10 minutes.

CONCLUSIONS

The ventilation of a long tunnel under construction stage might present a major problem when the tunnel penetrated deeper and deeper, with many excavation surfaces created simultaneously. In fact, inadequate and in-efficient ventilation system can become the most crucial hindrance when a tight working schedule is to be maintained. The design methodology developed in this study in utilizing a variable speed driven SHSD system is successful in providing a good working environment with optimum operation strategy where significant power consumption and thus operation cost can be saved. The experimental investigation validated that the SHSD system is convenient to install, and with a very low air leakage rate. It has also been validated that the push-and-pull ventilation system, such as case 5 and case 6, is successful in achieving this goal and is recommended for all long tunnel ventilation systems during construction period in the future.

ACKNOWLEDGEMENT

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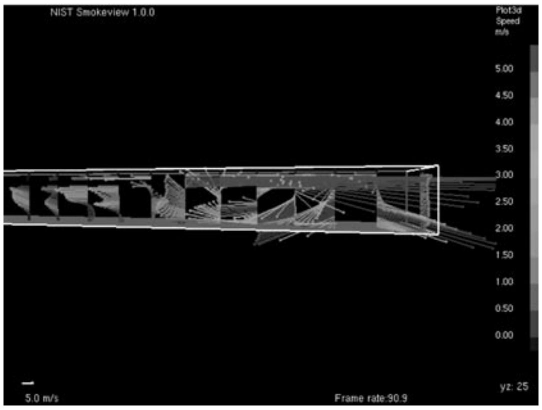


Figure 1 The push-pull effect of the airflow at the working surface

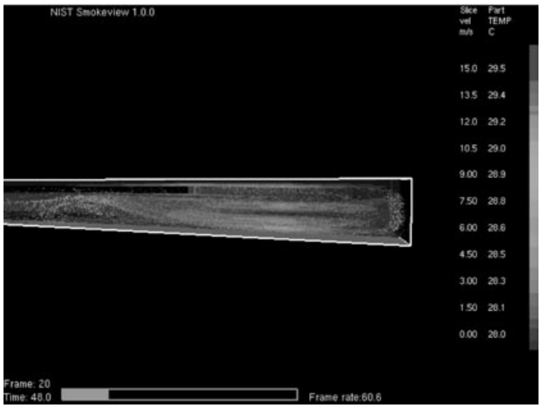
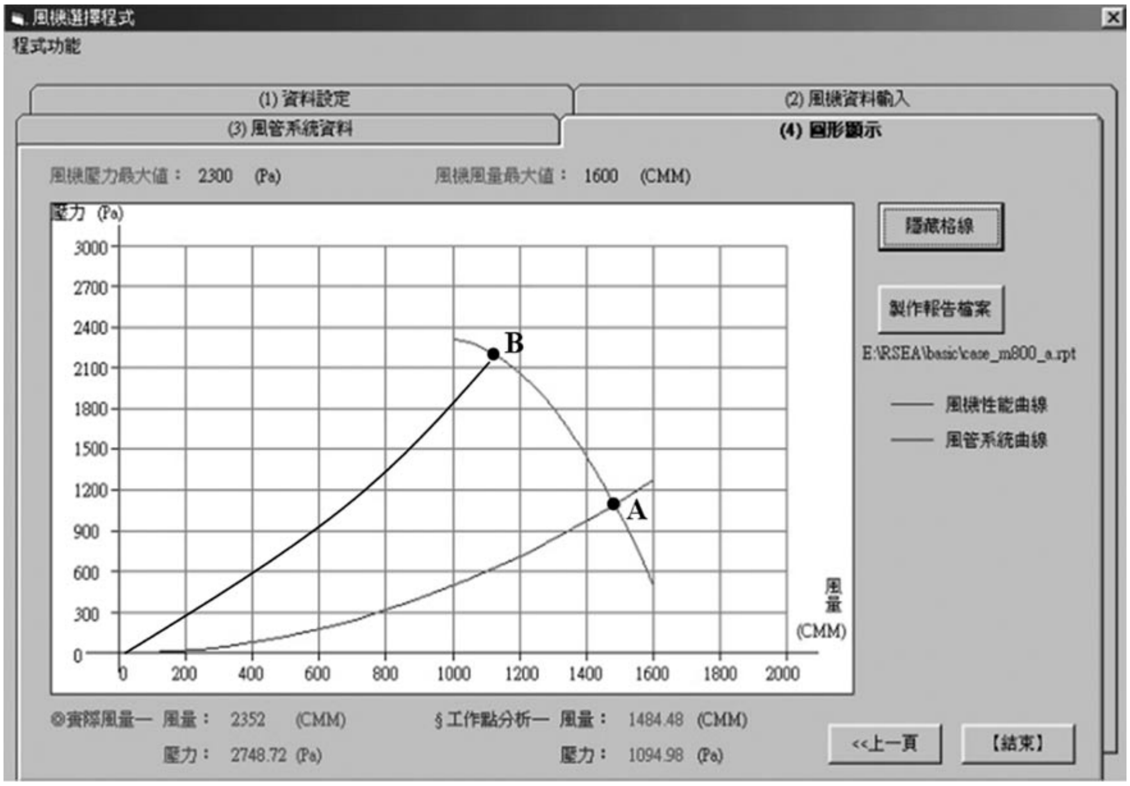


Figure 2 The pollutant was purged out longitudinally along the tunnel



風機壓力最大值： 2300 (Pa)　風機風量最大值： 1600 (CMM)

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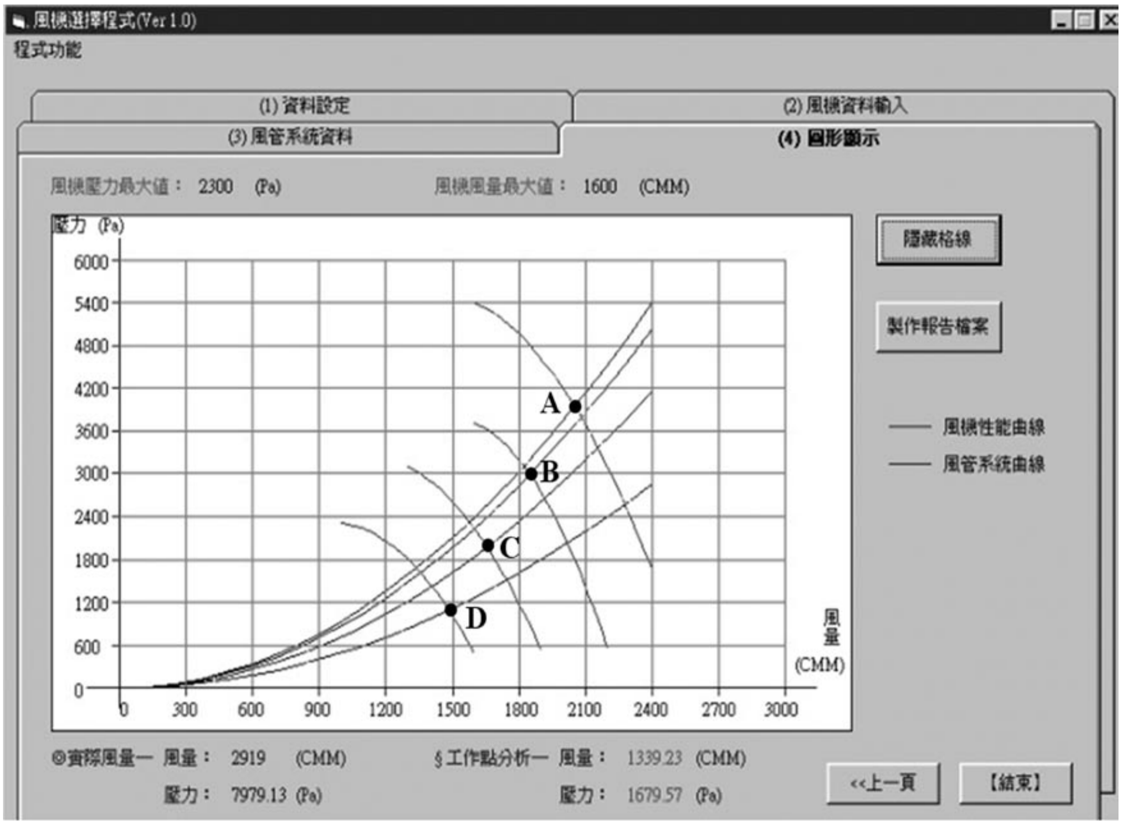
◎實際風量— 風量： 2352 (CMM)
壓力： 2748.72 (Pa)

§工作點分析— 風量： 1484.48 (CMM)
壓力： 1094.98 (Pa)

Figure 3 The increasing resistance moves point A to point B leading to inadequate air velocity near the working surface



風機壓力最大值： 2300 (Pa)　風機風量最大值： 1600 (CMM)

◎實際風量一 風量： 2919 (CMM)
壓力： 7979.13 (Pa)

§工作點分析一 風量： 1339.23 (CMM)
壓力： 1679.57 (Pa)

Figure 4 To utilize a variable speed drive (VSD) fan to coup with various stages of blasting and excavation

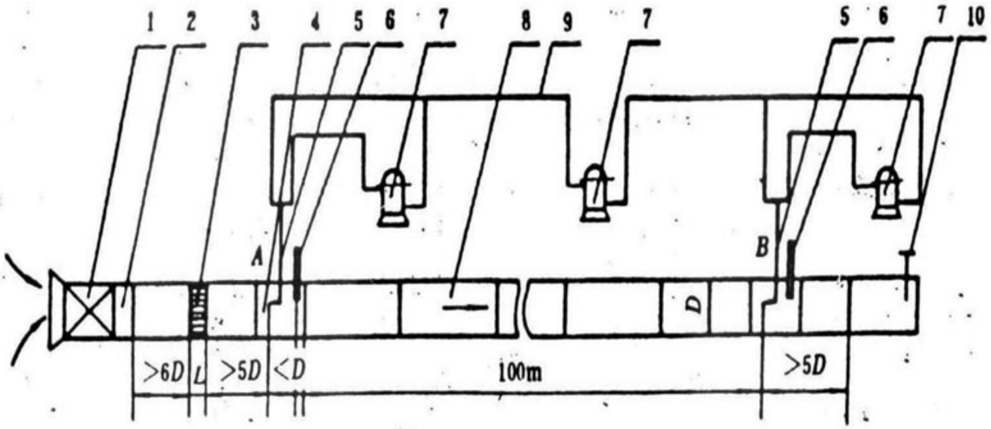


Figure 5 The experimental set-up to measure the air leakage rate m per 100 meter duct length

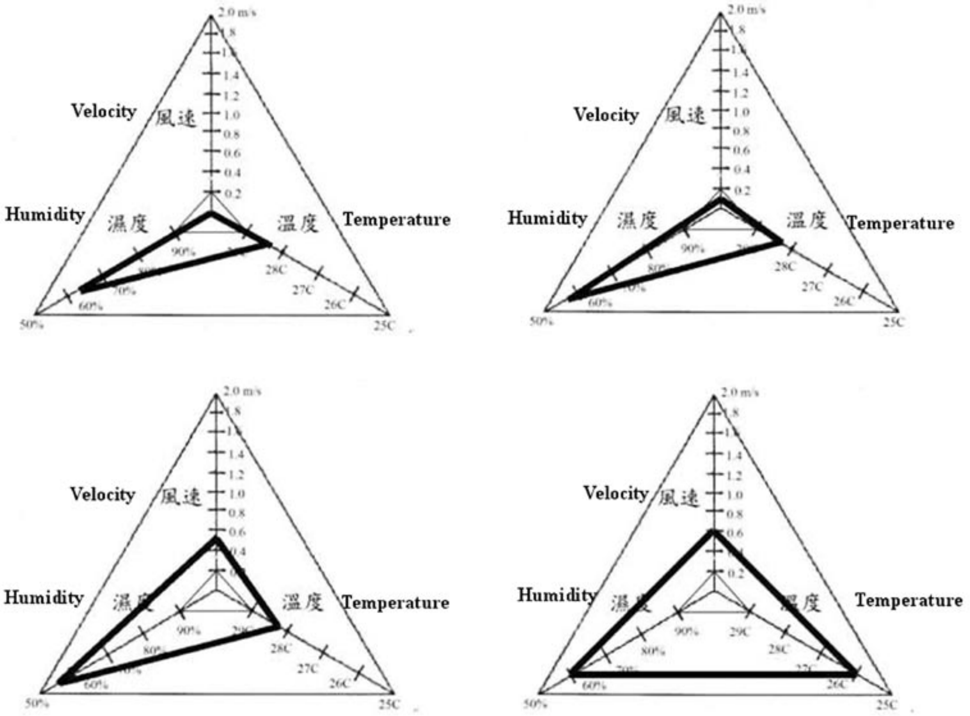


Figure 6 The full-scale experimental results in case 1

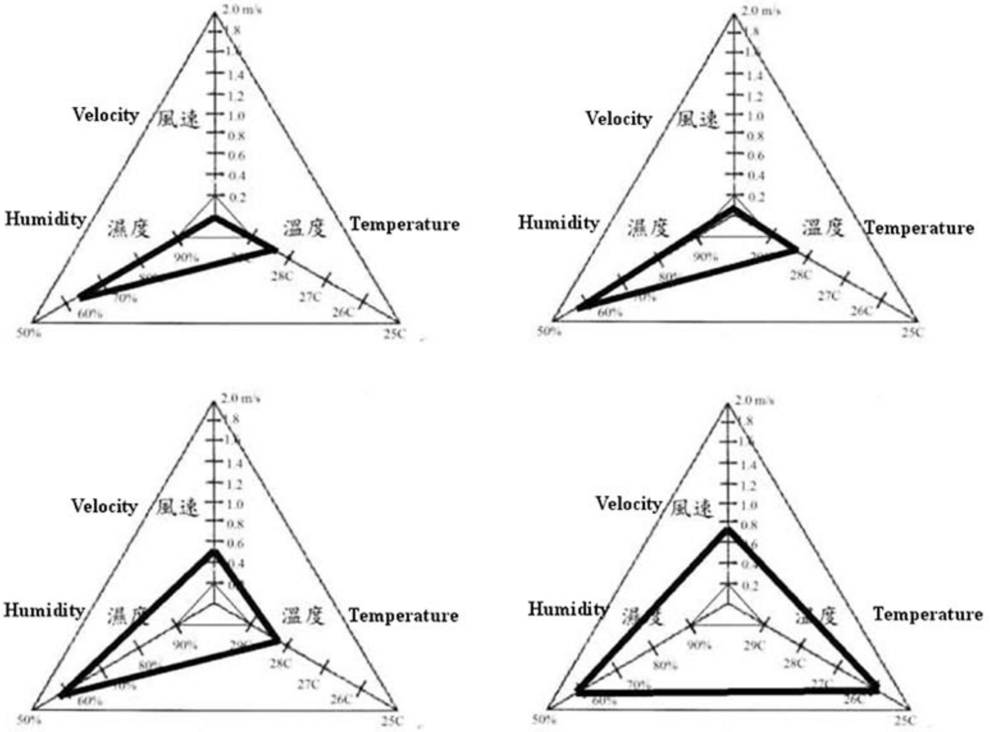


Figure 7 The full-scale experimental results in case 2

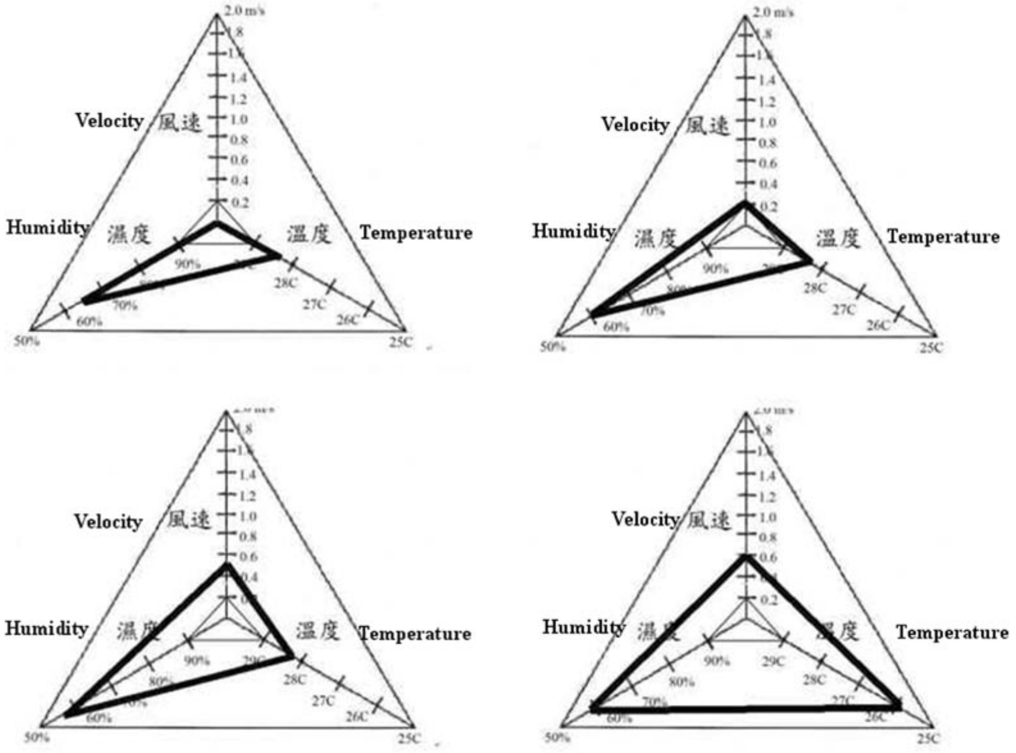


Figure 8 The full-scale experimental results in case 3

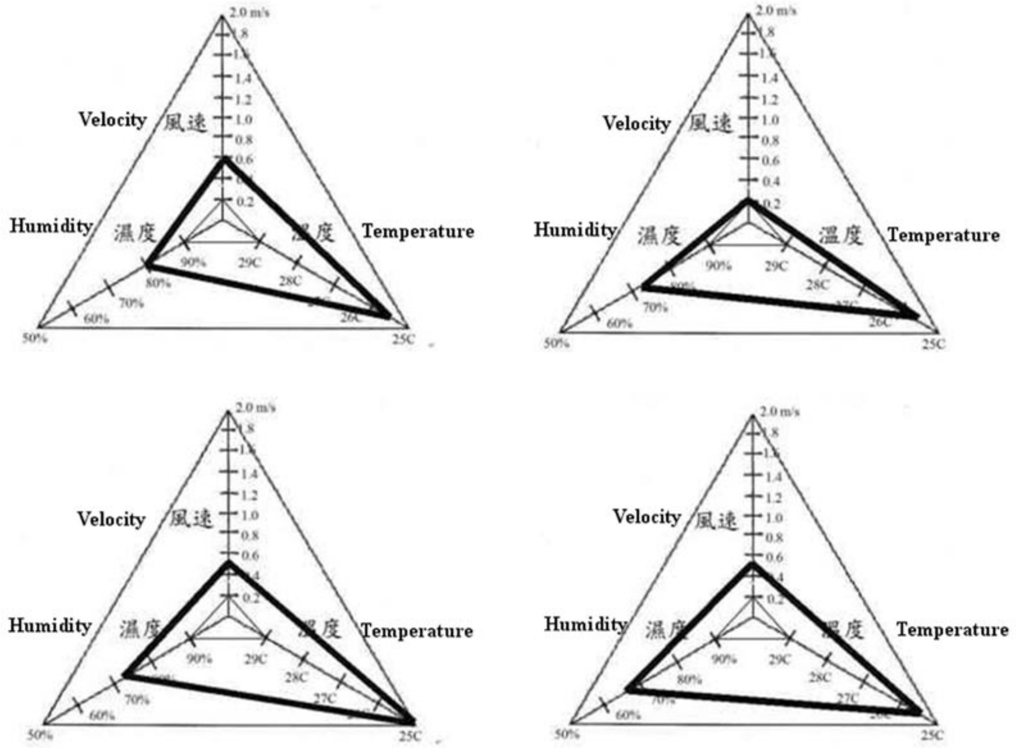


Figure 9 The full-scale experimental results in case 4

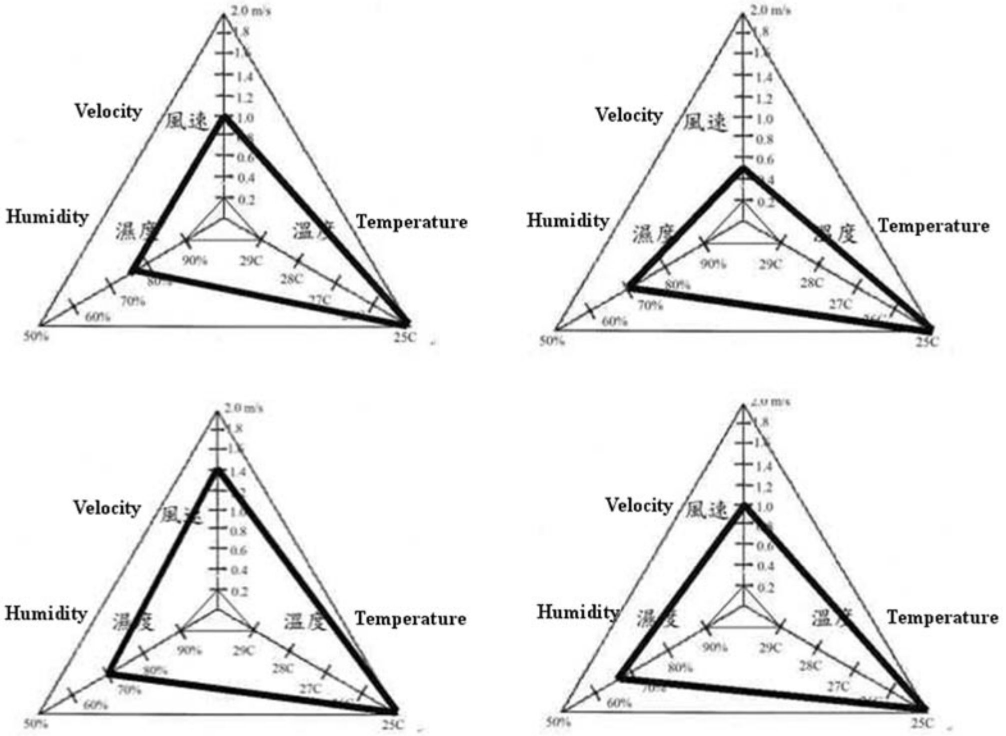


Figure 10 The full-scale experimental results in case 5

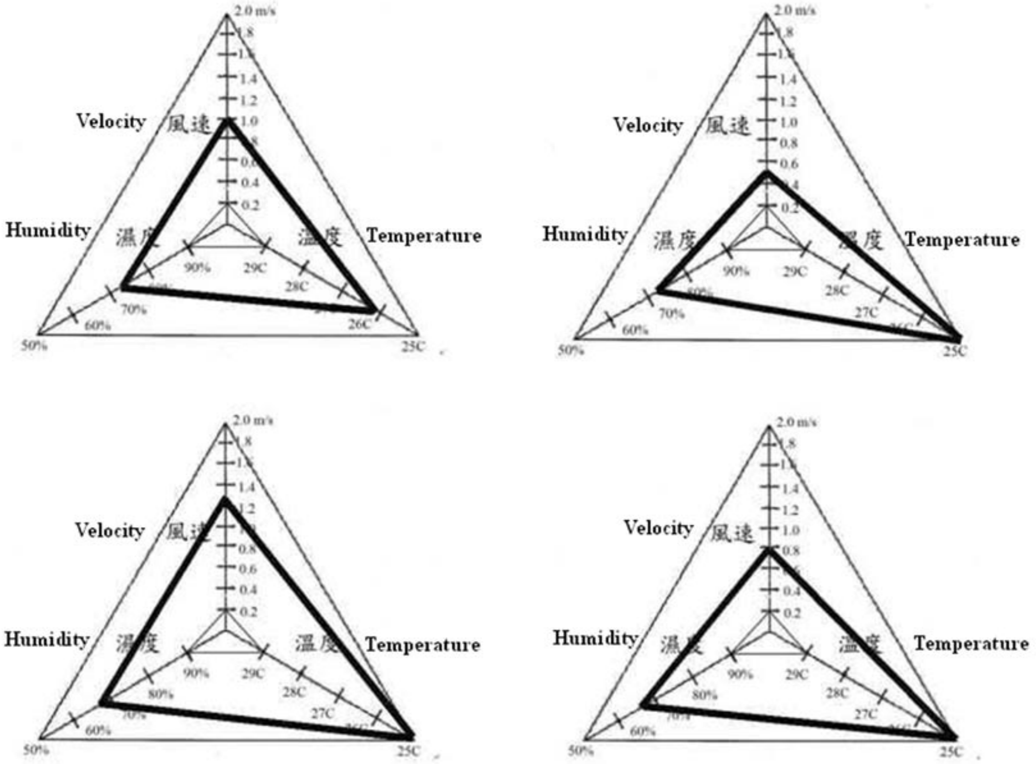


Figure 11 The full-scale experimental results in case 6