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Effect of Nozzle Air Supply Temperature and Volume on Flow Field of a Typical Nozzle for a Seated Passenger in Aircraft Cabin

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Abstract
A nozzle's flow characteristics determine its effect on a passenger's thermal comfort in an aircraft. However, it has not previously been considered in detail. In this research, temperature and air speed of more than 220 points in both non-isothermal jets and isothermal jets were measured in a simulated three-row cabin. The non-isothermal jets were with four temperature differences of nozzle air supply-0, ±5, 10 ℃. The isothermal jets were with three different volumes-0.67, 0.96 and 1.59L/s. The results showed both temperature and air speed distributions of nozzle jet are axial symmetry. Attenuation of nozzle jet is rapid. The temperature difference of nozzle air supply less than 10 ℃ leads a little effect on temperature field surrounding passengers from head to waist. The pipe coefficient of nozzle, α=0.64, calculated by least square method is different from circular pipes. The equation of air speed distribution for the main sector of nozzle jet is obtained to calculate air speed at any point in nozzle air flow field with different volumes. Temperature difference has little effect on air speed field of the main sector of nozzle jet in aircraft, whilst air volume has significant effect on air speed field of nozzle jet. This indicates the nozzle's effect on passengers' thermal comfort is not due to temperature difference of nozzle air supply. These flow field results could support for the following study on effect of nozzle air supply on thermal comfort.

Keywords - aircraft cabin; nozzle air supply; air speed; air temperature;

1. Introduction

In recent years, civil aviation industry is developing rapidly. The environment in aircraft cabin has become a focus and attracted more and more researchers' attention.

Environmental control system of the aircraft cabin is critical to passenger safety and comfort. Most studies focused on main air supply system controlling cabin environment for thermal comfort and air quality in aircraft[1]-[4]. Only a few studied new individual air supply systems rather than nozzles widely used in real airplane, and focused on its effect on air quality[5]-[10]. Dai et al[17] measured characteristics of jet flow of an aircraft gasper in MD-82 with the jet distance 185.22mm. Nozzles are widely used in Boeing and Airbus aircrafts as personal air supply outlets. However, a nozzle's structure is relatively complex and its flow characteristics have not previously been considered in detail. Its air supply characteristics determine its effect on a passenger's thermal comfort. A passenger can adjust his nozzle's flow rate and direction in order to achieve their preferred environment.

In our previous paper [11], it has been proved that nozzle air speed distribution of different cross-sections is axisymmetric in isothermal jet with the nozzle fully open in isothermal jet with approximate 20 m/s at nozzle outlet. As a further study, this paper aims to research a nozzle's flow field characteristics with different air supply temperatures and volumes. Measurements on temperature and air speed in nozzle's non-isothermal jet were carried out in a simulated cabin in this research. The flow field results could support for the following study on effect of nozzle air supply on thermal comfort.

2. Method

2.1 A Three-row Aircraft Cabin

Measurement on nozzle flow field was carried out in a three-row (18-seat) aircraft cabin in Chongqing. The cabin was built to meet the requirements of ASHARAE 161[12]and ASHRAE Handbook- HVAC Applications [13] based on the cross sectional size of Airbus A320. Details can been seen in previous paper [11][14]. Air speed at nozzle outlet (Figure 1) was from 0 m/s to 25 m/s. Flow meter was installed in front of nozzle (see Figure 1). Because of the flow meter's resistance, air speed at nozzle outlet cannot be more than 20m/s. Thus another system (Figure 1) was created to obtain the relation between nozzle air volume and air speed at nozzle outlet. In this system, the nozzle and its pipe were disassembled from the cabin and connected with a fan (CZR-LY80). Different speeds were adjusted by a valve in front of the flow meter.

2.2 Experimental Conditions

Four experimental conditions focusing on nozzle air supply temperatures and three conditions focusing on nozzle air supply volumes were arranged in this research. Cabin air speed was controlled less than 0.15m/s during the experiments. Relative humidity was approximately from 60% to 70% in cabin. And the relative humidity of nozzle supplied air was also approximately from 60% to 70%. The air temperature of personal airflow outlets is normally somewhat lower than cabin temperature during cooling conditions and may be somewhat higher than cabin temperature during heating conditions [12]. The air temperature of personal airflow outlets is commonly 5℃ lower than cabin temperature [15]. In existing studies, temperature of personal airflow outlets is commonly in the range from 19℃ to 21℃ [5][9]. Temperature differences between nozzle air supply temperature and cabin temperature were set as 0, ±5 and 10℃ (see Table 1). Nozzle flow field in these four conditions were measured in January, 2014. The designed local velocity is less than 0.36m/s for seated passengers and crew in ASHREA161-2007. And for draft sensitive bare body areas, the velocity is designed less than 0.30m/s and recommended less than 0.20m/s. The designed local air speed at head level is more than 1.0m/s with PAO turned on and 0.1m/s with PAO not installed. The minimum volume for a PAO is 0.94L/s referred to ASHRAE 161. However, no recommended value of maximum volume for a PAO can be seen in existing standards, neither in existing papers.

Based on the preceding introduction about air volume of a PAO and local air speed, three isothermal conditions were with different volumes (0.67, 0.96 and 1.59L/s, see Table 1) in this research. Air speed at head level was approximately 1.0m/s when a nozzle's volume was 0.67L/s in three-row aircraft cabin. Nozzle flow field in these three conditions were measured in September, 2014. Approximated to the minimum volume in ASHRAE 161, 0.96L/s was created in three-row aircraft cabin. Air speed at head level was approximately 1.5m/s in this condition. Air speed at head level was approximately 2.5m/s when nozzle air supply volume was 1.59L/s. During all the experiments, the nozzle was fully open.

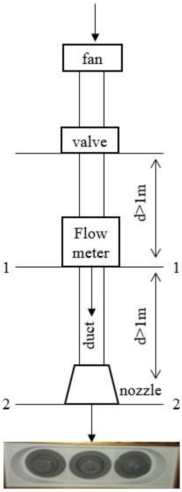
Table 1 Experiment conditions for testing nozzle jet

No.	Cabin temperature, T_a (℃) [a]	Nozzle air supply temperature, T_0 (℃) [a]	Temperature difference, $\triangle T_0$ (℃) [a]	Speed at nozzle outlet, U_0 (m/s)	Air volume, Q_0 (L/min)
1	12.90±0.08	12.36±0.04	-0.54±0.07	20	78.6
2	12.97±0.07	17.84±0.24	4.89±0.24	20.1	79.1
3	14.36±0.20	24.49±0.43	10.13±0.37	20.8	82.3
4	27.07±0.23	22.52±0.13	-4.55±0.26	20.6	81.4
5	26.07±0.17	Null	0	11.7	40.5
6	26.03±0.22	Null	0	16.5	57.7
7	26.02±0.22	Null	0	22.6	90.6

[a] Data are presented as mean ± standard deviation.

2.3 Measuring Points for Nozzle Flow Field

In condition 1, 2, 3 and 4, nozzle jet flow is vertical. In condition 5, 6 and 7, nozzle jet flow is toward chest of a seated passenger. Angle between nozzle jet flow axis and vertical is 16.2 °in terms of a Chinese reference man who is 62kg and 1.7m. Measuring points were set axisymmetric on eight different cross-sections from 0.3m to 1.0m away from the nozzle. Vertical distance was 0.1m between adjacent cross-sections. Horizontal distance was 0.01m between adjacent points on each cross-section were set. Measuring points are more than 220 shown in Figure 2.



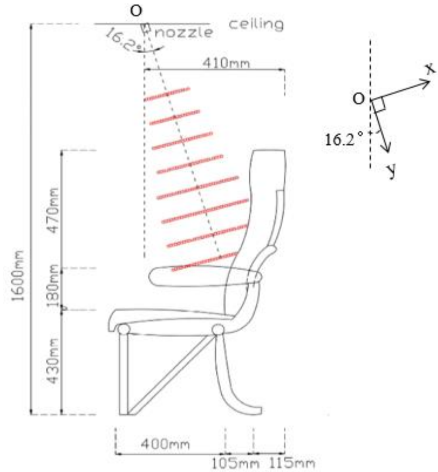


Figure 1 Air supple nozzles Figure 2 Layout of measuring points

2.4 Tested Parameters and Instruments

Velocity ($v_{x，y}$) and temperature ($T_{x，y}$) at measuring points were tested by AirDistSys 5000 with sample rate 8Hz. It spent 4 minutes to collect 1920 samples for every measuring point. In order to compare a nozzle's temperature field with cabin ambient temperature field, temperatures under a closed nozzle were tested at 0.6m, 1.1m, and 1.6m away from cabin floor by MP150. A nozzle's air supply volume Q_0 was measured by a digital mass flow meter (MF5712). Air speed U_0 and temperature T_0 of air leaving a nozzle were also measured. Cabin environmental parameters including air temperature T_a, relative humidity RH_a and velocity U_a were tested far away from outlets of main air supply system and personal air supply system. Detailed information of instruments are shown in Table 2. The average air temperature surrounding a representative occupant is the numerical average of air temperature at the ankle level, the waist level and the head level. These tested levels are 0.10m, 0.61m and 1.09m provided by ASHRAE 161.

Table 2 Measurement instruments and specifications

Parameters	Instruments	Measurement range	Measurement accuracy
Q_0	MF5712	0…200L/min	±2.5% of readings
U_0	KIMO VT100	0.15…3.00 m/s	±0.1m/s±3 % of readings
		3.10…30.0 m/s	±0.1m/s±3 % of readings
T_0	MP150 (TSD202B)	10…50℃	±0.0002℃
$v_{x,y}$	AirDistSys 5000	0.05…5m/s	±0.02m/s±1% of readings
$T_{x,y}$	AirDistSys 5000	-10…50℃	±0.2℃
T_a	MP150 (TSD202B)	10…50℃	±0.0002℃
	LSI (BSU102)	-25…150℃	±0.1 ℃
RH_a	LSI (BSU102)	70%…98%	±0.5%
		40%…70%	±1%
		15%…40%	±2%
U_a	LSI (BSV101)	0…1 m/s	±0.04m/s
		1…50m/s	±4% of readings

2.5 Statistical Analysis

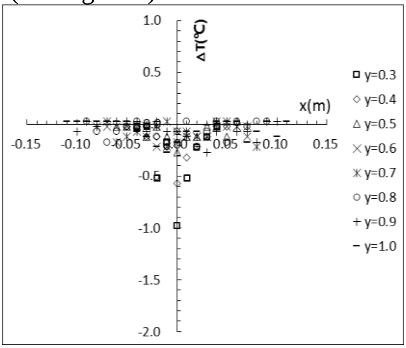
Average value during the tested 4 minutes are reported as the velocity and temperature of every measuring point. The velocity distribution was performed with MATLAB R2014a (version 8.3). R-squared values were used to assess the power of the regression models. R-squared value is defined as the proportion of the total sample variability as explained by the regression model. The statistical analysis was performed with SPSS 21.0. Confidence level, 95 percent, is adopted in statistical analysis in this paper.

3. Results

3.1 Air Temperature Field

Condition 1 is isothermal air supply. Its nozzle jet air temperature field is the same as ambient cabin temperature. Temperature differences (△T) between nozzle jet flow and ambient cabin environment are shown in Figure 3 and

Figure 4 when $\triangle T_0=\pm 5$℃. $\triangle T_0$ is the difference between nozzle air supply temperature and cabin temperature. The air temperature distribution of different cross-sections is axisymmetric. The air temperature decreases quickly with increasing cross-sectional distance. △T at the axis is the maximum. △T decreases as x increases. When x≥0.07m with $\triangle T_0=\pm 5$℃, △T equals 0℃ approximately. In Figure 3, when y≥0.4m (y is the distance from a cross-section to nozzle), all the temperature differences (△T) are less than 1℃. When nozzle air supply temperature is 5℃ lower than ambient cabin temperature, nozzle jet axis temperature at y=0.3m is obviously different from ambient cabin temperature with △T=1.2℃. When nozzle air supply temperature is 5℃ higher than ambient cabin temperature, all the temperature differences (△T) are less than 0.5℃ with the range from 0.3m to 1.0m being the distance between a cross-section and nozzle (see Figure 4).



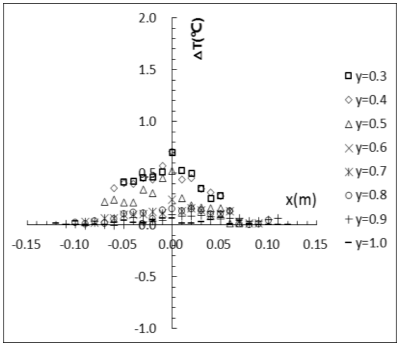
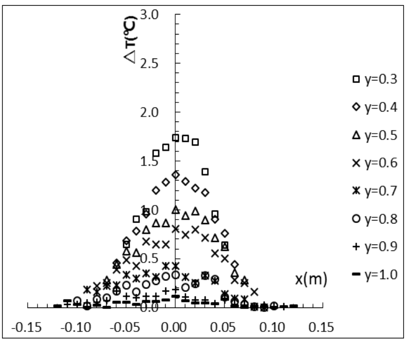


Figure 3 Air temperature field in condition 4 Figure 4 Air temperature field in condition 2 （The symbols ‘y=0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0’ represent the distances from cross-sections to the nozzle）

Nozzle air temperature field when ΔT_0=10℃（condition 3） is shown in Figure 5. The air temperature distribution of different cross-sections is axisymmetric. The air temperature decreases quickly with increasing cross-sectional distance. On the same cross-section, ΔT at the axis is the maximum. Air temperature in nozzle jet field is obviously different from ambient cabin temperature. Compared with ΔT_0=±5℃, ΔT is higher when ΔT_0=10℃ and approximately equals to 0℃ when x≥0.10m. When y≥0.7m, ΔT is less than 0.5℃. When 0.5 ≤y≤0.6, ΔT is less than 1℃. When 0.3 ≤y≤0.4, ΔT is less than 2.0℃.



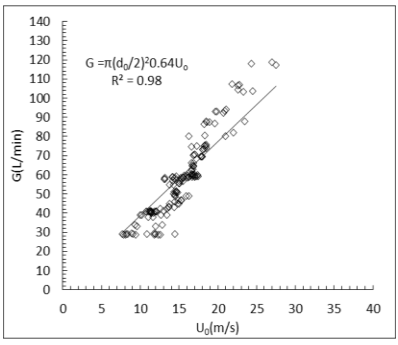


Figure 5 Air temperature field in condition 3 Figure 6 Relation between G and U_0

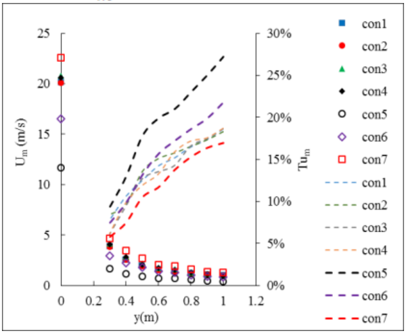
3.3 Air speed field

The air can be treated as steady and incompressible fluid for nozzle air supply system in aircraft. Based on equation of continuity for a steady and incompressible fluid flow, air volume has the same value at every position along a tube that has a single entry and a single exit. Air volume is equal to the product of the cross section area (A) and the average speed at the cross-section (U). The relation between maximum speed (U_0) and average speed (U) is given by U =α* U_0. The ratio of average to center velocity, α, is frequently called the "pipe coefficient" or "pipe factor". Air volume of the nozzle is given by $G=\pi(d_0/2)^2\alpha U_0$. The liner relation between nozzle air volume and center velocity at nozzle outlet is significant as shown in Figure 6. The calculated pipe coefficient of nozzle, α, is 0.64. According to Reference [16] the pipe coefficient, α, increases with the Reynolds number (Re). The Reynolds number calculated in this study, ranges from 6000 to 21000. For a circular pipe, α ranges from 0.75 to 0.78 with corresponding Re from 6000 to 21000. But α for an aircraft nozzle is lower than a circular pipe, calculated by experimental data in this study.

During the measurements of velocity field, cabin air speed is (0.04±0.02) m/s, and cabin air turbulence is 45.06%. Figure 7 shows axis velocity (U_m) and turbulence (Tu_m) of nozzle jet. The dotted lines and scatters in Figure 7 represent separately axis velocity and turbulence of the seven experimental conditions. The axis velocity decreases with increasing y. The axis turbulence increases as y increase. Conditions from No.1 to No.4 are with different temperature differences of nozzle air supply. These four conditions have a similar air supply volume and a similar velocity at nozzle outlet. The air volume is approximately 80L/min. The velocity at nozzle outlet is approximately 20m/s. Axis velocity and turbulence at a same cross-section are similar with each other among these four conditions. This indicates the temperature difference of nozzle air supply has no obvious effect on velocity field of nozzle jet. Conditions from No.5 to No.7 are with different volumes of nozzle air supply. The air is supplied with same temperature as cabin air. Significant difference appears in axis velocity and turbulence among these three conditions. Velocity at nozzle outlet in condition 5 is the least among the seven conditions. The maximum one is in condition 7. For this reason, axis velocity is the least in condition 5 and the most in condition 7. This shows air supply volume has significant effect on velocity field of nozzle jet. The effect decreases as y increases. Axis velocities are approximately 0.5m/s in condition 5 and 1m/s in other 6 conditions at the waist level of a seated passenger. The waist level corresponds y=1.0m. When $y \geqslant 0.3$m, axis velocities are much less than the velocity at nozzle outlet. This shows velocity attenuation is very fast due to the nozzle's special structure. When $y \leq 0.8$m, axis velocities are significantly different among the seven conditions. When $y > 0.8$m, velocity attenuation is slower than $y \leq 0.8$m.

The attenuation rule of the axis velocity has been obtained in isothermal jet with the nozzle fully open based on experimental data in isothermal jet with approximate 20 m/s at nozzle outlet[11], shown as the black curve in Figure 8. It is also applicable to different volumes and different temperatures for the nozzle shown in Figure 8.

The velocity distribution of nozzle jet is axial symmetry. This phenomenon is similar to the velocity distribution of a circular jets. For the reason that the first four conditions approximately have same velocity at nozzle outlet and same volume, the average velocity is adopted to represent the velocity distribution shown in Figure 9. The air speed distribution of nozzle jet is highly in line with Tollmien series solution for circular jets. Equation (2) is fitted with experimental data for the nozzle's distribution. In which, $r_{0.5u_m}$ is the distance to the axis from the point $U=0.5U_m$.



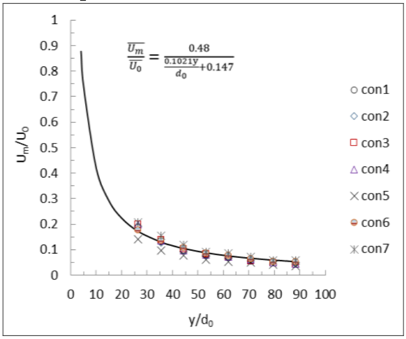
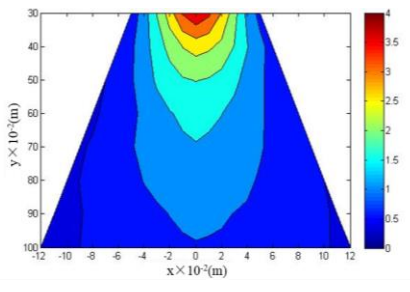


Figure 7 Axis velocity and turbulence Figure 8 Dimensionless attenuation of axis velocity

$$\eta = \frac{r}{r_{0.5u_m}} \quad (1)$$

$$\frac{u}{u_m} = \left(0.83 + \frac{0.16}{1+\eta}\right) \exp(-0.61\eta^2) \quad (R^2=0.97) \ (2)$$



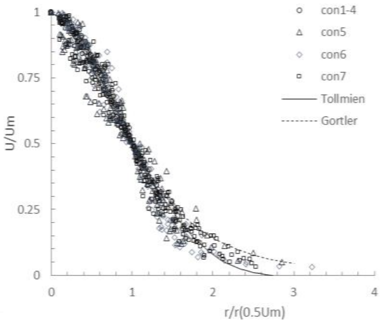


Figure 9 Velocity field of nozzle jet Figure 10 Dimensionless velocity distribution

4. Discussions

The limitation of this study should be addressed. In this study, measurements were carried out in a three-row aircraft cabin rather than in a real airplane. The nozzles used in the experiments were from Airbus. The results may not be applied for other nozzle types. The experiments were not carried out in low humidity and low pressure because they are really hard to simulate in laboratories. It is still not clear what the effect of low humidity and low pressure is. The results may need to be revised for application in low humidity and low pressure. The effects of seats/bulkheads and passengers on nozzle jet were not included in the experiments. This should be further studied.

Air temperature in the first three conditions were lower than in real cabin to obtain the aimed temperature difference of nozzle air supply. If cabin air temperature was maintained at a common level (26℃) by the main air supply system, the conditions with △T=5℃ (nozzle air temperature higher than cabin air) and △T=10℃ cannot be created with the limitation of air-conditioning of nozzle air supply system. Because of this reason, air temperature was approximate 12℃ without air-conditioning of main air supply system to achieve △T=5℃ (condition 2) and △T=10℃ (condition 3). As a control group for condition 2 and condition 3, condition 1 was set with both main air supply system and nozzle air supply system turned off. This is why the first three conditions in Table 1 were set at approximate 12℃ different from the real cabin temperature. If air temperature was maintained at 26℃ by the main air-conditioning system, the lower air temperature at nozzle's outlet could only reach 21.5℃, though it was 18℃ after cooling by air-conditioning. Because the air temperature increased as flowing through the pipe. Due to the limitation of air-conditioning system, the condition with △T＜-5℃ could not be created.

The waist level and head level are 0.61m and 1.09m from the floor for a seated occupant provided by ASHRAE 161. The head level corresponds y=0.99m in the cabin. The waist level corresponds y=0.51m in the cabin. The area with 0.5m≤y≤1.0m covers a seated passenger's body from head to waist. This area is the focus of thermal comfort in nozzle study. The limit value is 4.4℃ for horizontal operative temperature variation and 2.8℃ for vertical operative temperature in ASHRAE 161. Horizontal temperature variation and vertical temperature variation are not more than 1.2℃ when $\triangle T_0=\pm 5$℃ (Figure 3 and Figure 4) and not more than 2℃ when $\triangle T_0=10$℃ (Figure 5). This meets the temperature variation requirements in ASHRAE 161. The temperature difference of nozzle air supply leads little effect on passengers' surrounding temperature field when $|\triangle T_0| \leqslant 10$℃. This means that cooling and heating of nozzle air supply are not obvious with $|\triangle T_0| \leqslant 10$℃. This indicates the nozzle's effect on passengers' thermal comfort is not due to temperature difference of nozzle air supply.

5. Conclusions

Temperature distribution of nozzle jet is axial symmetry. Its attenuation is very fast. The temperature difference of nozzle air supply leads little effect on temperature field surrounding passengers' area from head to waist when $|\triangle T_0| \leqslant 10$℃. This means that cooling and heating of nozzle air supply are not obvious with $|\triangle T_0| \leqslant 10$℃. Temperature difference of nozzle air supply has little effect on air speed field of the main sector of nozzle jet in aircraft. Air volume of nozzle air supply has significant effect on air speed field of the main sector of nozzle jet. This indicates the nozzle's effect on passengers' thermal comfort is not due to temperature difference of nozzle air supply.

The pipe coefficient of nozzle, α=0.64, is calculated by least square method based on experimental data in this study. The value of α is different from circular pipes. It makes the relationship between nozzle air volume and air speed at nozzle outlet clear. The attenuation of air speed of nozzle jet is sharp. Air speed distribution of nozzle jet is axial symmetry and basically in line with circular jets. The equation of air speed distribution for the main sector of nozzle jet is obtained. This equation could calculate air speed at any point in nozzle air flow field with different volumes. This is useful to analyze the effect of nozzle air supply on passengers' thermal comfort in the next paper.

Acknowledgment

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