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2D-PIV Experimental Study on the air distribution with Natural Convection Effect of Passengers in an Air Cabin Mockup

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Abstract

Many previous studies have mentioned the critical effect of natural convection caused by passengers heat transfer on the air distribution inside the air cabins, but No study focused on it to make a further experimental or numerical analysis. In fact, the air flow field inside the air cabin with narrow interior space and passengers seated intensively is the result of interaction between natural convection from the passengers and forced convection from the supply air diffusers, including the air jet which plays the most essential part on the flow pattern. This study has measured the air flow jet in a 7-row cabin mockup with 2D-PIV (two dimension Particle Image Velocity) measurement system, and to make comparison of the air jet under isothermal and cooling conditions to analyze qualitatively the impact of natural convection inside the cabin mockup, which is to increase the air jet entrainment and weaken the attaching effect which can also enhance the velocity distribution uniformity. With the variety of air flow volume in a reasonable range of design parameters, we measured the different air velocity fields to quantify the effects of natural convection on the air jet. It can be concluded that the air jet decay rate becomes slower with the enhancement of natural convection.

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Keywords: Natural convection; Air cabin; Archimedes number; Air jet

1. INTRODUCTION

The current total amount of global passengers transported by aircrafts has exceeded 1 billion (World Tourism Organization, 2013). The aircraft is an increasingly popular choice for people living in the time with the rapid development of the economy and society. And there are also growing requirements for a healthy and comfortable cabin thermal environment. The cabin thermal environment is mainly related with the velocity and temperature distribution with mixing ventilation which is the most common.

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In fact, the air jet actually plays the most essential part on the thermal environment. And the occupied zone is overlapping the air jet in the cabin with narrow interior space and passengers seated fully. So the air jet with mixed ventilation is just the interaction result of forced convection, driven by the air jet itself, and natural convection, driven by the temperature difference resulting of the intense heat dissipation from passengers. Zhang et al. (2005) and Zhang et al. (2009) found out the existing of intense natural convection around passengers forcing the air flow upward. Cao et al. (2014) compared the detailed flow field under isothermal and cooling conditions respectively and pointed out that natural convection enhanced the air jet entrainment and lower the attaching effect. Kühn et al. (2008) specifically made experimental study of the natural convection inside cabins and deemed that the impact of the natural convection differs under different ventilation methods significantly.

In fact, many studies have referred to effects of natural convection in cabins, but the topics and concerns are nothing about it. Previous studies only made qualitative comparison of isothermal and cooling air jet in cabins, which is usually an account for the presentation, but this paper will make use of 2D-PIV air flow measurement system placed inside 7-rows cabin mockup, and set up a series of different experimental conditions on the basis of qualitative comparison, so as for further quantitative analysis of the impact of natural convection on the air jet.

Nomenclature

Ar	Archimedes number
g	Gravitational acceleration, 9.8m/s^2
β	Air thermal expansion coefficient, $2/\Delta T$ K^{-1}
ΔT	The temperature difference between supply air and floor, K
h	Diffuser height, m
u	Air supply velocity, m/s
Ar_w	Corrected Archimedes number
ΔT_i	The temperature difference between supply and exhaust air, K
H	The height of wall equipped with diffusers, m
L_p	The air jet penetration distance, m
L	The half of the cross section width, m
Re	Reynold number
υ	Air movement viscosity, m/s^2
ω	Vorticity of airflow
V	X-direction velocity component, m/s
U	Y-direction velocity component, m/s
T_d	The air supply temperature, ℃
T_e	The air exhaust temperature, ℃
C_w	The air-jet centerline velocity decay coefficient
U_m	The he air-jet centerline velocity, m/s

2. RESEARCH METHODS

2.1. 7-rows cabin mockup

A full-scale single-aisle aircraft cabin mockup was constructed inside a thermostatic chamber as a replica of a section of Boeing 737-200. Due to different materials of walls from the real aircraft bulkheads, the temperature of thermostatic chamber should be controlled at 18±1℃ based on the load calculation to ensure the interior walls temperature of cabin mockup at 19.5℃, which is the same as that when aircrafts fly at the altitude of 10,000 meters. 7-rows cabin mockup was arranged symmetrically with the middle aisle as the axis of symmetry and occupied with six seats on each row and a total of 42 manikins on 7 rows (Fig. 1. (a)). All manikin was wrapped with 2mm diameter nickel-chromium wires with a resistance of 32Ω/m. The total heat capacity of 75W should be ensured to reflect the real heat load from passengers, which was turned off under isothermal condition instead.

Only side supply air ducts mounted at the luggage compartment level were turned on and the air exhausted from the outlets at the foot level on side walls. The diffuser on each row consisted of 105 slots on both sides respectively, and each slot was 50mm long and 3.5mm wide (Fig. 1. (b)). The air supply temperature is controlled at 19℃ and the exhaust is 22.5℃ with the total air supply volume of 1420m3/h under standard cooling condition, corresponding to 9.4L/s per passenger, satisfying the recommendation of ASHRAE Standard 161-2007. The chamber and air supply temperature are the same, 19℃, under isothermal condition.

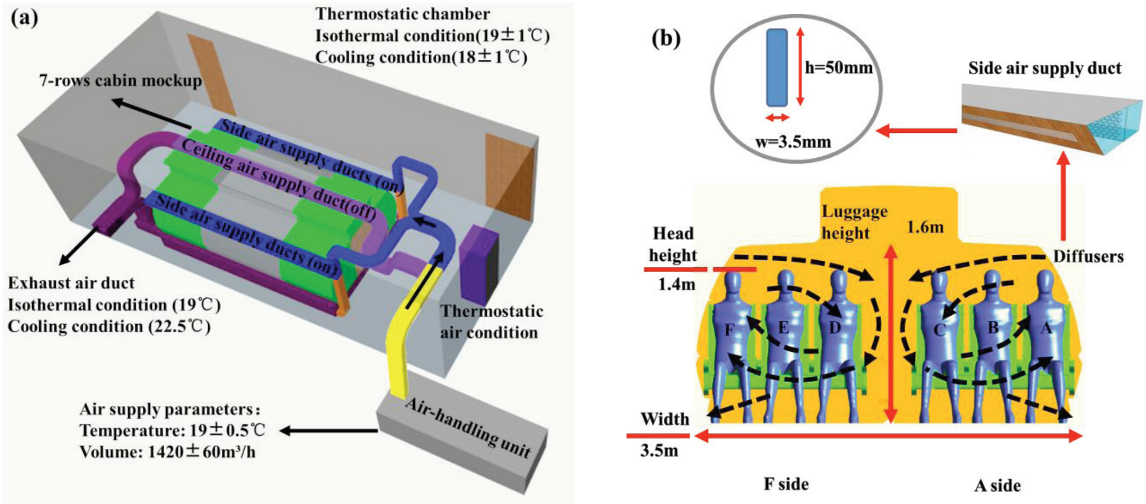


Fig. 1. (a) Schematic of 7-rows cabin mockup and climate chamber; (b) Schematic of cross-section geometry, diffusers, and ventilation pattern

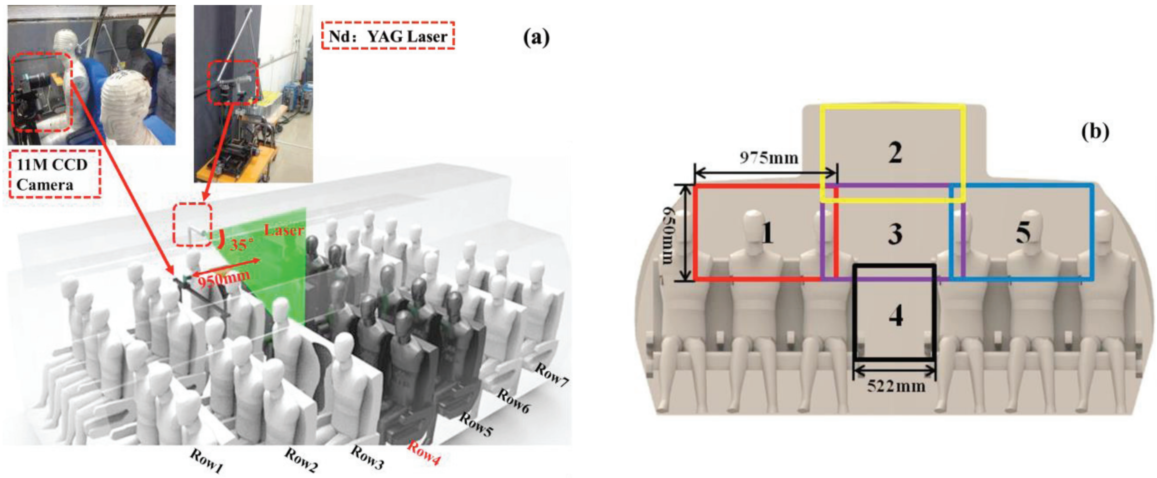


Fig. 2. (a) 2D-PIV cross-section flow field measurement system; (b) Composition of PIV measurement regions

2.2. Cross-section flow field measurement system

A high-power 2D-PIV testing system was used for the air jet measurement, consisting of Nd:YAG laser and 11M-pixels CCD camera. The camera was placed 950mm away from the cross section measured to achieve a film area of 975×650mm. Restricted by the film size, cross-section flow field were separated into five reasonable zones. And overlapping region of 100mm long (Fig. 2.(a)) was set between adjacent zones to reduce the joint errors. But only the A-side air jet was measured because of the symmetry of the cross section, which included part 3 and part 5 (Fig. 2.(b)). The measured cross-section was located at the middle on Row 4, which was about 10mm away from the manikin face. Liu et al. (2012) pointed out that the impact of the front and back ending wall can be neglected on the middle row. To remove errors of background noise in calculation, manikins on Row 4 and Row 5 were painted black.

The stage smoke oil was evaporated into 1.5μm diameter smog by PT-1000 evaporator-condensing smog generator. Cao et al. (2014) compared the response time and the degree of gravity induced of smog with that of 20μm diameter HFBS and 0.3mm diameter bubble to find out the best performance of the smog following with the air flow. 180 films were set as the statistical sample and calculated with high precision sub-pixel difference algorithm to work out the flow field results.

2.3. Dimensionless analysis of the impact of natural convection on the air jet

Archimedes number (*Ar*) is a dimensionless characteristics parameter describing the interaction between forced convection and natural convection. Hsin Yu (1996) proposed the Eq.(1) to evaluate the air jet character under side air supply method in different thermal environment controlled by air supply velocity and floor temperature.

$$Ar = \frac{g\beta\Delta Th}{u^2} \tag{1}$$

But ΔT in Eq.(1) can't reflect the complex heat transfer in cabins with a complex distribution of the heating interior surfaces. Wang and Ogilvie (1994) put forward Eq.(2) to describe the impact of room geometry, heat load, and air jet on the airflow pattern.

$$Ar_w = \frac{g\beta\Delta T_i HL_p}{(hu^2)} \tag{2}$$

But L_p can be obtained only through specific experiments and varies in different thermal environment. Cao et al. (2014) has worked L_p out, which is more than 2m, in the same cabin mockup under cooling condition proposed above. The air jet from the two sides crashed with each other at the aisle center, so L_p can be replaced with L, which means the half of the cross section width and just reflects the character of narrow space inside cabins. To sum up, Eq.(3) can be got which is fit to the dimensionless analysis of the impact of natural convection on the air jet.

$$Ar = \frac{g\beta\Delta T_i HL}{(hu^2)} \tag{3}$$

$$Re = \frac{uh}{v} \tag{4}$$

Ar is just a comparative parameter about the relative strength of forced convection and natural convection. For example, the air supply is very fast inside a cooling ventilated room with a very little temperature difference, so Ar is almost 0, which just means strong natural convection and weak forced convection based on the calculation result, but the truth is opposite. So, Reynold number (Re) should be added to make Ar result reasonable.

3. RESULTS AND DISCUSSION

The A-side air jet under standard isothermal and cooling conditions proposed in section 2.1 (Fig. 1.(a)) has been measured with the diffuser velocity of 1.82m/s. Six vertical plot lines were selected on the way the air jet developed (Fig. 3). Before location C, the vertical velocity distribution under the two conditions is almost the same, even at the height of 0.9 to 1.3m which belongs to the occupied zone, because of a higher velocity within a short distance away from diffusers; after location D, the isothermal air jet velocity decay rate is faster and the velocity on the occupied zone smaller (Fig. 3). Vorticity represented with ω is introduced to make an account for the second phenomenon, which can be calculated with Eq.(5).

$$\omega = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} \tag{5}$$

Where minus in the vorticity distribution (Fig. 4.(a)) means the vortex direction. Vorticity is meant for describing the vortex movement strength which can enhance the mixing of fluid and transportation of energy. As shown in Fig. 4.(a), vorticity becomes larger under cooling condition on both sides of air-jet centerline, especially the occupied zone, which means natural convection driven by temperature difference enhances air-jet entrainment of the air on the occupied zone. And the air-jet trajectory under isothermal condition becomes upward at location C because of the attaching effect and develops along the bottom of luggage carrier after location C, which forces the air-jet velocity decay rate faster because of wall shear stress, while natural convection forces the air jet of lower temperature in the cabin to flow lower gradually after location C. So, compared with the air-jet entrainment, the attaching effect plays the most important role on the air-jet velocity decay rate, which natural convection can weaken.

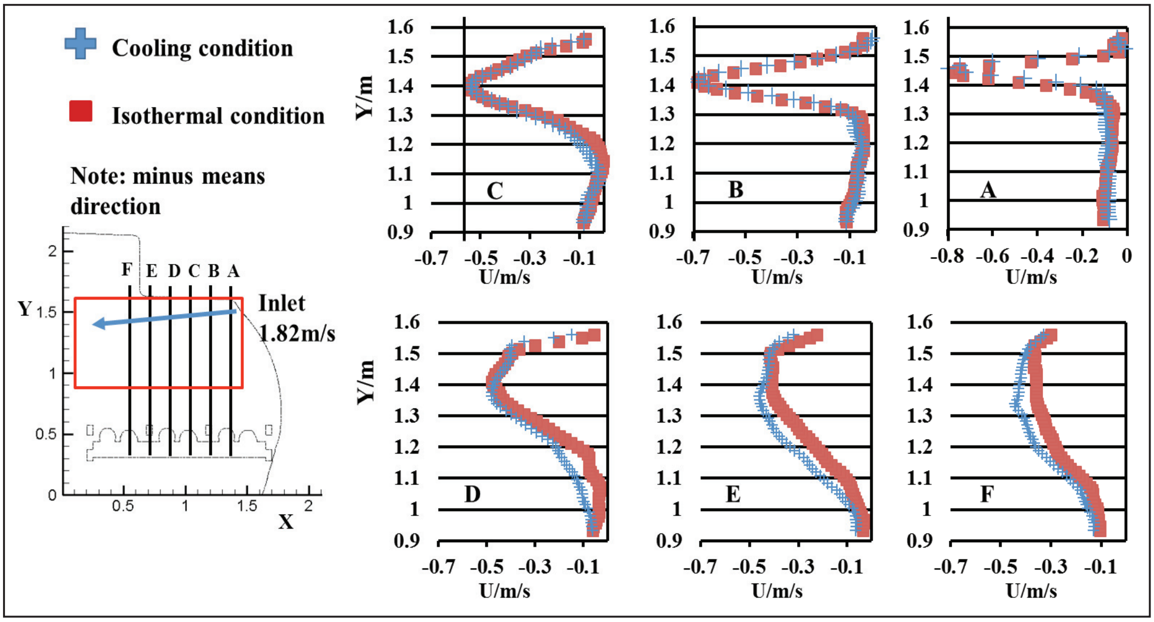


Fig. 3. The comparison of the A-side air jet attenuation process under isothermal and cooling conditions

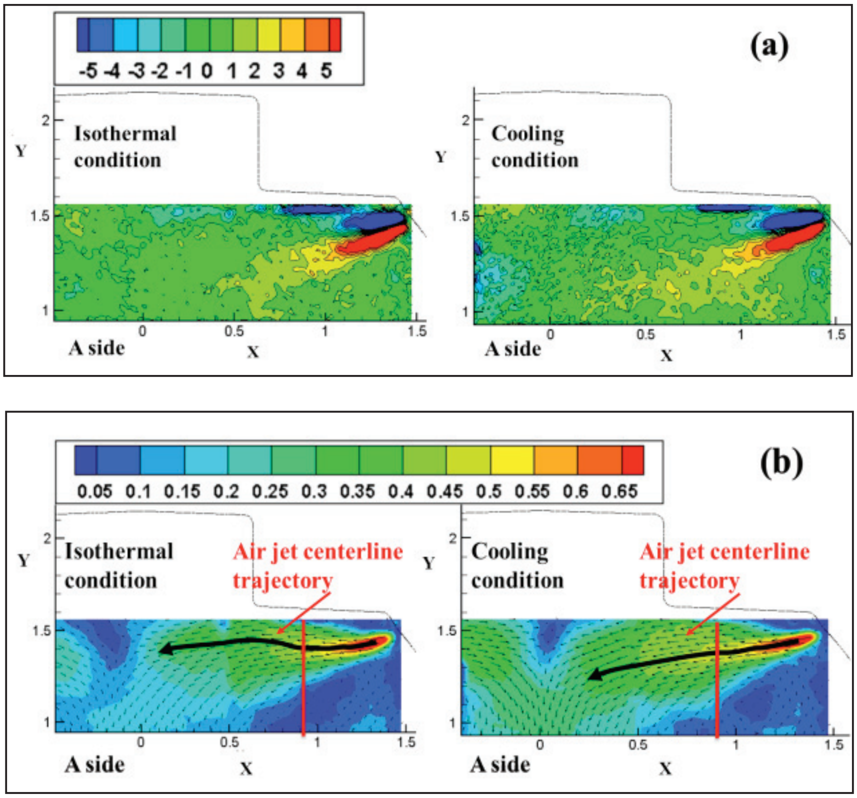


Fig. 4. The comparison of the A-side air jet contour under isothermal and cooling conditions: (a) Vorticity; (b) Flow filed.

To make further analysis of the air jet, more reasonable experiment conditions were set up based on the recommendation about air supply volume and temperature inside cabins of ASHRAE Standard 161-2007 and United Airlines (1994) (Table 1). And *Re* for the two conditions and *Ar* only for the cooling condition were calculated out based on Eq.(4) and Eq.(3) respectively listed in Table 1.

Table. 1.The parameters of experiment conditions under isothermal and cooling conditions

Experiment condition	Air supply velocity u/m/s	Air volume per passenger/ L/s	$T_d - T_e = \Delta T_i$	Diffuser air jet/ Re	Air jet/ Ar (cooling)	Cw/ (cooling)	Fitting Relevance/ (Cooing)
Isothermal/ Cooling	0.97	5.0	22-19=3	3031	10.86	1.081	0.873
------------/ Cooling	1.24	6.4	22.5-19=3.5	3875	5.91	0.976	0.864
Isothermal/ Cooling	1.33	6.9	22.9-19=3.9	4156	4.44	0.932	0.923
------------/ Cooling	1.45	7.5	23.3-19=4.3	4526	3.72	0.909	0.935
Isothermal/ Cooling	1.54	8.0	23.6-19=4.6	4806	2.99	0.876	0.911
------------/ Cooling	1.64	8.5	24.8-19=4.8	5125	2.36	0.856	0.942
Isothermal/ Cooling	1.82	9.4	23.7-18=5.7	5688	1.64	0.833	0.927

As shown in Fig. 6.(a), the isothermal air jet dimensionless centerline velocity decay characters under conditions of different air supply volume (Table 1) shows a very good self-similarity. A fitted equation can be got as below:

$$\frac{U_m}{U_d} = C_w \cdot \sqrt{\frac{h}{x}},\ C_w=0.79 \tag{6}$$

The dimensionless velocity vertical distribution on the same plot lines as shown in Figure 3 under different cooling conditions was shown in Fig. 5. It can be found out that the air jet dimensionless centerline velocity decay rate becomes slower with the decrease of air supply velocity and corresponding increase of ΔT_i. So, the stronger natural convection is, the slower the air jet decay rate is.

The fitted curves of the air jet dimensionless centerline velocity decay process under different cooling conditions can be got with the equation form of Eq.(6) and the fitted results of C_w were shown in Table 1, which is related to Ar closely. Fig. 6.(b) shows the relevance distribution of C_w and Ar, so a fitted curve can be got with Eq.(7) to set up a quantitative link between the air jet decay process and natural convection.

$$C_w = 0.028 \cdot Ar + 0.79 \tag{7}$$

As we can see in Eq.(7), 0.79, which is just the isothermal air-jet decay coefficient, is the foundation for cooling air-jet decay coefficient to increase with enhancement of natural convection.

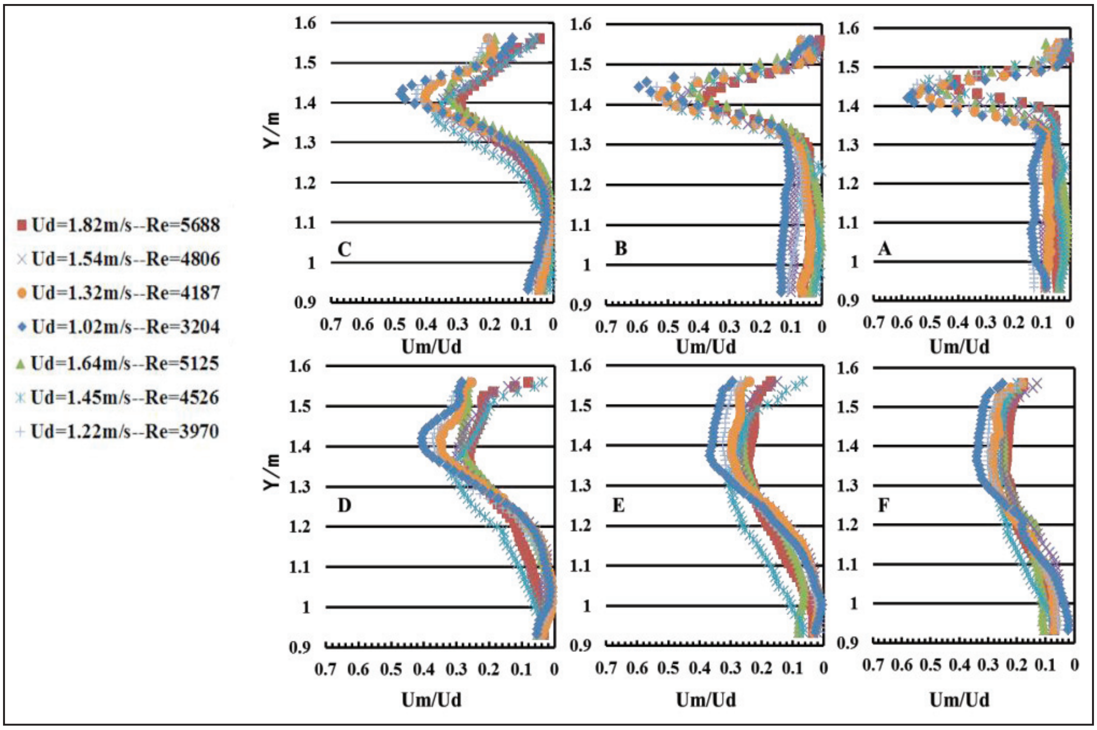
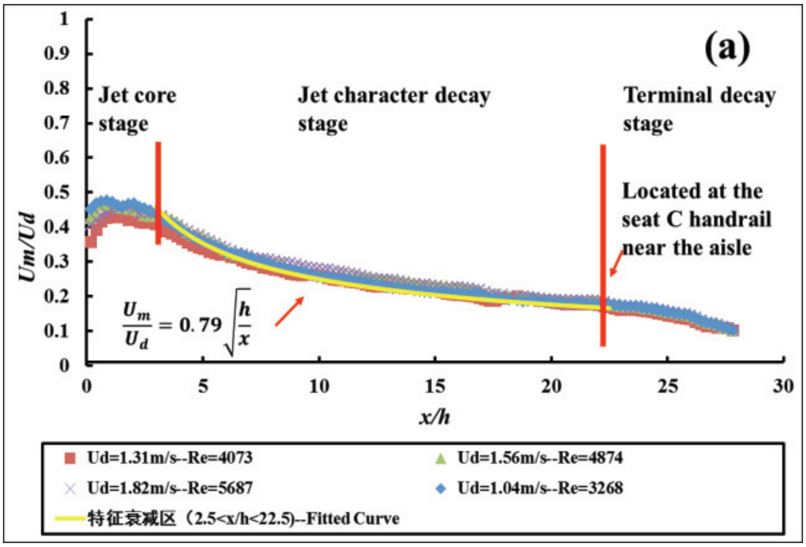


Fig. 5. The dimensionless velocity distribution of A-side flow field on the vertical plot lines



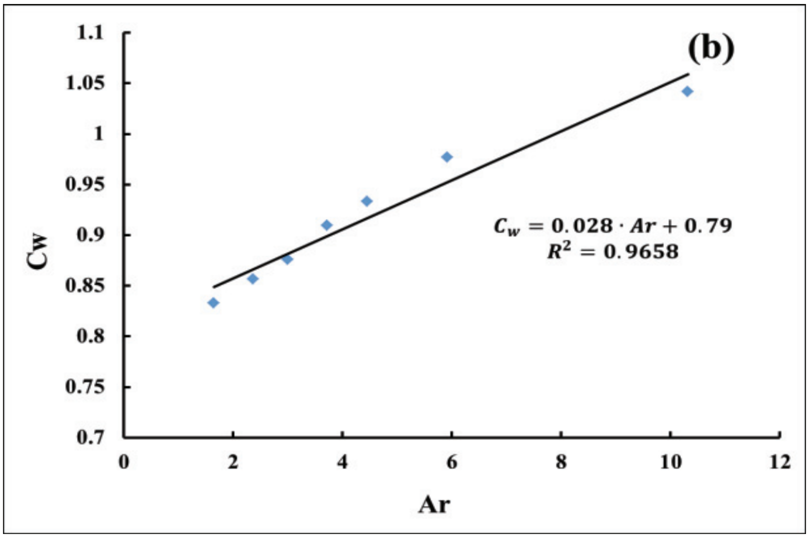


Fig. 6. (a) The isothermal A-side air jet dimensionless centerline velocity decay process; (b) The correlation of the cooling air jet center velocity decay and Ar number

4. CONCLUSION

The paper has researched the air jet in 7-rows cabin mockup with 2D-PIV air flow measurement system, and made comparison of the air jet under isothermal and cooling conditions to analyze qualitatively the impact of natural convection inside the cabin, which is to increase the air jet entrainment and weaken the attaching effect which can also enhance the velocity distribution uniformity. And set a variety of conditions within a reasonable range of design parameters based on the above qualitative analysis for further measurements, so as to quantify the effects of natural convection on the air jet. It can be concluded that the air jet decay rate becomes slower with the enhancement of natural convection.

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