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Chaotic behavior of human thermal plumes in an aircraft cabin mockup

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A B S T R A C T

The human thermal plume induced by body heat loss has a significantly impact on human thermal comfort, contaminant transport and indoor air quality. Few studies focused on the temporal unsteady characteristics of human thermal plume. In this study, the human thermal plume generated by a heated manikin was measured in a 7-row cabin mockup by mini particle image velocimetry (mini-PIV) system; and its unsteady and chaotic behavior was determined out of statistical and chaotic method. Probability density distributions of velocity time series of human thermal plumes presented Gaussian mixture models with two peaks, which substantiated the oscillating characteristics of human thermal plumes. The energy region of the human thermal plume was concentrated between 0.1 Hz and 10 Hz determined out of the power spectrum analysis, and the power spectrum exponent of the human thermal plume above the head ranged from 0.9 to 1.2. Evolution of phase space reconstruction of velocity time series from single-spindle to double-spindle revealed the human thermal plume presents obvious autocorrelation and oscillating behavior qualitatively. In addition, the fractal dimension of human thermal plumes overhead ranged from 6 and 12 without integers and Kolmogorov entropies of analyzed points were all larger than zero indicating the human thermal plume was kind chaotic airflow quantitatively.

1. Introduction

The human thermal plume induced by body heat loss has a significantly impact on human thermal comfort, contaminant transport and indoor air quality in enclosed environments. A large amount of studies have been conducted to investigate the airflow and temperature distributions of the human thermal plume and its influence on propagation of gaseous and particle. Melikov 2015 demonstrated thermal plumes above the head and the convective boundary layer near human body have impacts on the human thermal comfort and air quality in breathing zone [1]. To quantify the airflow characteristic of human thermal plumes, computational fluid dynamics (CFD) and experimental measurements were used extensively. Murakami et al. [2,3] studied the wind environment around heated human body and concluded the velocity of thermal plume can be up to 0.23 m/s. Their numerical simulation results were verified merely by the smoke tracer method qualitatively. Dan et al. [4] used numerical simulation to expose the thermal plume airflow and heat transfer of a seated human body and recommended low-Re turbulence model to determine the human thermal plume airflow and temperature. Liu et al. [5] analyzed the human thermal plume by large eddy simulation (LES) and found unsteady and intermittent characteristics of the thermal plume. Unfortunately, Liu's numerical results lacked of experimental verification.

For experimental studies, Graven et al. [6] determined the airflow field of human thermal plume qualitatively and quantitatively by shlieren image and particle image velocimetry (PIV), respectively. However, the human model in Graven's study was too simple to reflect real human surface temperature. Zukowska's [7] results showed that the airflow distribution of the thermal plume is closely related to the geometry, the surface temperature and area of the human body. For different clothing, breathing and body posture of the heated manikin, its convective boundary layer was investigated by PIV and pseudo color visualization (PCV) in a chamber without ventilation [8]. They found personal factors such as clothing and breathing can affect the volume flux of thermal plume and cause the asymmetric velocity distribution [13,14]. Koelblen et al. [9] investigated the airflow and temperature pattern of the thermal plume and found the velocity field varies with body postures. Voelker et al. [10] measured an ascending plume above the head and found the human thermal plume expanded growing up from the lower part of the torso. Particularly, human thermal plumes play a more significant role in forming the indoor environment of aircraft cabin and have impact on airflow distributions and

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pollutant transport because of large heat density from passengers and narrow space of aircraft cabin [11–13]. While, the characteristics of pure thermal plume generated by passengers are not clearly. Study of the characteristics of human thermal plumes can provide theoretical support for the design of better airflow distribution to rapidly eliminate body heat dissipation and keep passengers thermal comfort.

The schlieren video of human thermal plume recorded by Gary [6] and PCV measured results [8] qualitatively revealed that human thermal plumes present unsteady and oscillating behavior. From our literature review, the average velocity field of human thermal plumes was studied emphatically, while few studies focused on unsteady and turbulent characteristics. A number of researchers have studied the periodicity and oscillating characteristics of pure thermal plumes from heated flat and analyzed those airflows by nonlinearity and chaotic theory [14–18]. These chaotic method can explain the correlation between the turbulent characteristics of airflow and the human body draft sensation.

The main purpose of this paper is to study the unsteady and chaotic behavior of the human thermal plume. A mini-PIV system was utilized to measure the human thermal plume in a 7-row cabin mockup. In order to further understand the airflow mechanism of human thermal plumes and provide experimental data support for human comfort analysis, indoor air quality and numerical simulation, statistical method, spectrum method and chaotic method are used to study the airflow mechanism of the human thermal plume and analyze the experimental data. The statistical analysis, spectrum analysis and phase space reconstruction methods are used to substantiate the unsteady characteristics of human thermal plume qualitatively. To further analyze the unsteady characteristics of thermal plume quantitatively, the chaos theory including fractal dimension denoting to the relation between phase space structure feature and embedding dimension and Kolmogorov entropy representing quantification of chaos of transformed velocity time series based on phase space reconstruction based on are employed.

2. Experiment setup

A heated manikin with a thermal power of 75w sitting in a full-scale 7-row single-aisle aircraft cabin mockup was served as passenger generating thermal plume. The prototype of the aircraft cabin mockup is a section of Boeing 737–200. The geometry sizes of the aircraft cabin mockup are 5.85 m in length, 3.25 m in width and 2.15 m in height. Particularly, the luggage rack height is about 1.6 m. In order to facilitate the adoption of laser, the walls of the middle three rows were constructed by transparent acrylic. In order to guarantee the controllability of temperature boundary condition, the aircraft cabin mockup was set up in a thermostatic chamber. To meet the objectives of this investigation, the manikin was wrapped with electrical resistance, a total heat of 75 W. The manikin's sitting height is 1.4 m with a total volume 0.055 m^3. The surface area of each manikin is 1.3 m^2. The geometry of the manikin is similar to a real person, according to Chinese adult body size and seating space [19].

A mini-PIV system was utilized to determine the human thermal plume composing of a continuous wave laser and a CCD camera with a Canon 35 mm lens. Tracing particles were generated by diethylhexyl sebacate (DEHS) through a spray generator. As shown in Fig. 1, three cross sections were measured above the shoulders and head with each field area is about 0.32 m × 0.16 m. Due to the obstruction of the luggage rack, there is a certain deviation between the center of the human head and the center of measured cross section, i.e., CS2.

In the measurement process, there was no ventilation in the aircraft cabin mockup and temperatures were controlled by the thermostatic chamber with closed circulatory air condition system. Thermocouples were used to monitor temperature distributions of the manikin, aircraft cabin wall and ambient air. When the monitoring temperatures were stable, the experiment was started [20]. The constant temperature distributions in measurement process are listed in Table 1 with manikin divided into five parts. The temperatures of aircraft cabin wall and air surrounding manikin are 19.5 °C similarly. In order to accurately sample the turbulent characteristics of the human thermal plume, the sampling frequency of mini-PIV was set as 400 Hz and recording time was 100 s.

3. Result

3.1. Velocity and vorticity

Fig. 2 shows the average velocity distributions of the human thermal plume with sampling time 100 s. In the figures, vectors and contour represent velocity directions and velocity magnitude, respectively. Human thermal plumes rise from two side shoulders and collide with each other above the head. Maximum velocity appearing at CS2 located above the head is up to 0.24 m/s. The overall thermal plume flows upward in the CS2 section while moving toward the manikin body in CS1 and CS3. More close to the manikin body, the velocity is larger in CS1 and CS3. Evidently, the thermal plume expands growing up upward via entrain ambient air in CS1 and CS3 driven by buoyancy. The airflow fields above the left and right shoulders are not completely symmetrical because of obstruction of luggage rack and asymmetrical heated manikin surface.

In order to demonstrate the unsteady characteristics of human thermal plumes, instantaneous velocity distributions of CS2 section measured at 5th, 10th, 15th and 20th seconds are presented in Fig. 3. The airflow patterns of the four moments are basically different to each other and inconsistent with the average velocity distributions. The maximum velocity at 5th and 15th seconds is about 0.25 m/s while that is up to 0.3 m/s at 10th and 20th seconds. The velocity near the head is lower because of heat loss at that part is less simulating human with hair. Moreover, two strands thermal plumes rising from shoulders appear above head alternately. Summarily, the instantaneous velocity distributions of CS2 substantiate the asymmetrical and oscillating behavior of the human thermal plume.

Vorticity is introduced to demonstrate the unsteady turbulent characteristic of human thermal plume which can be calculated as follows [21]:

$$w = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad (1)$$

where v and u represent velocity components at x and y direction, respectively. Fig. 4 shows the instantaneous vorticity distribution of CS2 at 5th, 10th, 15th and 20th seconds. Irregular shape and random distribution of vorticity contours appear on the four moments inconsistently. The maximum vorticity can be up to 12 s^{-1}. At the center part of CS2, the sizes of vorticity are more obvious because of the collision of two thermal plumes rising from shoulders. The vorticity appearing on edge position of cross sections may cause by air entrainment. The obvious vorticity distributions also reveal high fluctuation and turbulent kinetic energy of thermal plume. The random and irregular vorticity contours reveal unsteady behavior of the human thermal plume.

For the convenience of the researches on temporal unsteady and chaotic behavior of the human thermal plume, several points are selected on CS1, CS2 and CS3 as shown in Fig. 5. In order to focus on the study of the thermal plume over the head in detail, more points are selected.