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The effect of building spacing on near-field temporal evolution of triple building plumes

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ABSTRACT

Building plume is important for ventilation and pollutants dispersion along and above buildings in an urban canopy layer. This study fundamentally explores the merging process and temporal penetration of triple uniformly distributed starting building plumes, with a focus of the spacing effect on near-field flow dynamics. Instantaneous velocity and vorticity distributions, penetrating velocities, and stream-wise penetrated heights are quantitatively examined using 2-D particle image velocimetry (PIV) measurements at spacing ratios S/W (building spacing/building width) of 0.2, 0.5, and 1.0.

We identified a four-stage merging progress and captured three main spacing-induced merging features. A compact layout at $S/W = 0.2$ introduces a strong upward channel flow. The wall flows beside the channel tend to draw together first and the unstable channel flow determines the flow pattern transition. In contrast, wider layouts at $S/W = 0.5$ and 1.0 exhibit intensive downward flow. The wall flows tend to exhibit self-merging initially and the downstream natural swaying motion dominates the merged pattern variations.

Merging effect and buoyancy force jointly determine the temporal penetrating velocities. Temporal series of maximum axial velocities above the middle source fits into a power law profile at $S/W = 0.2$ but a linear function of time at $S/W = 0.5$ and 1.0. The normalized penetrated heights at $S/W = 1.0$ are notably faster than in the other two cases before the normalized time is at 3.00 probably because the weaker entrainment and interaction with neighbors lead to less energy and momentum dissipation, quicker self-merging, and faster penetration.

1. Introduction

As summarized by Fernando [1], urban airflow dynamics are crucial for urban thermal environment design, energy consumption, and pollutant dispersion. Studies have mainly focused on the situation when the background synoptic wind is moderate or strong, and investigated the resistance or turbulence generated by buildings and building impact on the local environment, such as those by Refs. [2–4]. Another category of studies resolved the flow structure in street canyons jointly determined by both prevailing wind and buoyancy using methods of full-scale field measurement [5], scaled field models [6,7], scaled wind tunnel models [8], and numerical simulation [9]. However, with the rapid urbanization the background synoptic wind becomes more difficult to penetrate into the urban area, particularly in high-rise compact cities [10]. In contrast, buoyancy driven flows becomes more important. Yang and Li [11] showed that the thermal plumes produced by warm building surfaces can be very significant in high-rise compact cities due to the heights of the buildings, the large vertical wall areas and the potential large temperature differences. Fan et al. [12] conducted field measurement of wall flows along a 16-storey 60 m-height building and found the buoyancy-induced vertical velocity about 1.0–2.0 m/s along the building walls. These significant building plumes are essential to local thermal environments around and above buildings as well as in street canyons [12]. A deeper understanding of the merging and evolution of multiple building plumes is essential to further study the large-scale urban plume dynamics, especially in calm environments where most urban heat wave and severe air pollution episodes occur. According to Refs. [13,14], calm environment can be approximately true and

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buoyancy becomes dominated with an approaching wind speed less than 2.5 m/s, which occurs for about 18% of the year and more at low latitudes cities.

The buoyancy-induced flows have been well discussed by Ref. [15]. The first theoretical study of plumes can be traced back to 1937 [16]. The most classical plume theory is the well-known MTT model [17], which introduced three important assumptions: the entrainment assumption, the self-similarity profile, and the Boussinesq approximation. The MTT model has been used very successfully to analyze plume characteristics in various situations, as reviewed by Refs. [18–21]. Kaye and Hunt [22] studied the effect of area heat source geometry on ventilation and thermal stratification for a naturally ventilated room. Gladstone and Woods [23] studied the flows driven by buoyancy source distributed over a surface and indicated a multiple-solution regime in ventilation. However, most related studies on plumes/jets dynamics have focused on plumes from point or two-dimensional sources. In realistic urban environments, near-field 3-D building plumes differ from those generated by ideal point/2-D sources because the vertical wall boundary layers develop along the building walls below the roof level and have a complex interaction with convective flows on horizontal roof surfaces [12].

Furthermore, buildings are usually grouped together to form building clusters. Consequently, building plumes can interact when they are sufficiently close to each other. The flow becomes more complex, as each plume is subjected to multiple shear layers from surrounding plumes. The characteristics of the twin-plume have been well documented using theoretical studies and experimental modeling [24–29]. The flow structure of the twin-plume in a calm environment has been identified to comprise a merging region followed by a combined region [30,31]. Cao et al. [32] classified the flow of triple forced plumes into three regions: an entrance region, a convective mixing region and a post-mixing region. Yin [33] reviewed the studies on the interaction of twin plumes/jets and multiple plumes/jets where the number of plumes/jets is larger than two, such as Refs. [34,35]. As one of the most important factors in building layouts, building spacing S plays a key role on both dynamic building-plume merging progress and quasi-steady multi-plume structure. Fundamentally, when spacing changes, plumes' merged and combined levels, as the function of the spacing, correspondingly change [36–38]. When the building spacing is small enough, the natural convective flow between two adjacent building walls can be regarded as a channel flow [39]. In contrast, a large building spacing may lead to the relatively isolated development of two neighboring building plumes. Consequently, building spacing affects the local ventilation efficiency and thermal environment, the merging mode, and even the way to establish the larger scale flows, e.g., urban plumes.

However, nearly all related studies have focused on twin forced plumes/buoyant jets with source buoyancy and momentum simultaneously. Multiple pure plumes, such as building plumes, are considered less often. The pure plumes are flows solely generated by the source buoyancy, which introduce some distinct features comparing with jets, e.g., more effective entrainment, enhanced turbulence, and intensive flow instability. Furthermore, the investigated spacing S is usually very large at several times the source diameter/width D, such as $9 < S/D < 18.25$ in Ref. [40], $S/D = 10{-}23$ in Ref. [41], and $S/D = 30{-}40$ in Ref. [37]. This leads to less interaction in the near-field region and is not applicable for most developed compact cities, such as Beijing [42] and Hong Kong [43]. In terms of real scenarios, Mfula et al. [44] and Ng and Chau [45] studied the influence of building spacing on air quality in street canyon. However, they did not consider the buoyancy effect.

In view of these research gaps, there is a need to systematically and fundamentally understand the near-field dynamic merging and evolution of multiple pure plumes, and particularly the spacing effect on plumes development. As the background wind becomes more difficult to penetrate into the urban area, we considered the most serious situation that there is no background wind (clam environment) in this paper. Triple pure plumes, as the first step in multi-plume configuration, are the main target of this study, and they are expected to help future studies on thermal-induced larger scale urban plumes that are comprised of hundreds or thousands of building plumes. The experimental set-up and measurement are described in section 2. Main results, i.e., the basic merging process, the distinct merging features at different building spacings, the penetrating velocities, and the penetrated heights, are discussed in section 3.1–3.4 successively. Limitations are presented and briefly discussed in section 4. This study not only pushes the fundamental investigation on multiple plumes one step further, but also provides possible guidance to urban design aimed at establishing a more comfortable and healthier urban environment. To the best of our knowledge, this is also the first time that the near-field transient dynamics of triple pure plumes are explored in detail.

2. Methodology

2.1. Experimental set-up

Experiments were performed in a glass tank with internal dimensions of 300 × 150 × 120 cm^3, as shown in Fig. 1 a. A 40-cm-thick polyvinyl chloride (PVC) mound covered by an 8-mm-thick acrylic plate was placed on the tank bottom to establish a horizontal floor. The thermal conductivity of both the PVC mound and acrylic plate is about 0.2 W/(m·K). This low thermal conductivity also acts as insulation to reduce the heat loss through the bottom plate. The lost heat at temperature difference, e.g., 25 °C, can be limited to 0.1 W, which is very small and negligible.

We used electrically heating method to generate pure plumes from volumetric sources. Comparing with common salt-bath experiments, this method is relatively easy to exclude the effect from source momentum flux and establish the pure plumes. Three electrically heated rectangular aluminum blocks with dimensions of $5 \times 5 \times 18\ \text{cm}^3$ ($W \times H \times L$) were placed on the bottom with their longer edges in parallel. The building density was characterized by the block spacing ratio (S/W), defined as the ratio of the building spacing (S) to the building width (W) along the X direction. As shown in Fig. 1b-d, we studied three configurations (Case I, II, and III) with S/W of 0.2 (Case I), 0.5 (Case I), and 1.0 (Case I), respectively, equivalent to three height-spacing (H/S) ratios of 5, 2, and 1, which are practical in urban areas. A cartridge heater was installed inside each block to provide a constant heat strength of $Q = 180$ W. Source specific buoyancy flux $F_0 = g\beta Q/(\rho_0 C_p)$, was $6.84 \times 10^{-8}\ \text{m}^4/\text{s}^3$, where β (in K^{-1}), ρ_0 (in kg/m^3) and C_p (in J/(kg·K)) are the water thermal expansion coefficient, density and heat capacity determined at a reference water temperature T_r of 16 °C.

We followed the concept from Ref. [46] to use an equivalent hydraulic diameter l^* as the length scale. The l^* is considered for the whole source group, and defined as four times the top area A divided by the wetted perimeter P as following: $l^* = 4A/P$, where A contains the channel top surface, i.e., $A = (3W{+}2S)L$, and P correspondingly includes the building spacing, i.e., $P = 2(L{+}3W{+}2S)$. Velocity scale is defined as $v^* = F_0^{1/3}/l^{*1/3}$ and time scale is defined as $t^* = l^*/v^*$ [46]. Finally, the length scales l^* are 17.5, 18.9, and 20.9 cm, the velocity scales v^* are 0.73, 0.71, and 0.69 cm/s and the time scales t^* are 23.9, 26.6, and 30.4 s in Cases I ($S/W = 0.2$), II ($S/W = 0.5$), and III ($S/W = 1.0$), respectively. When analyzing the