Energy & Buildings 177 (2018) 64–76

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

2D-PIV measurement of range hood-driven flow in a domestic kitchen

Wenhua Chen, Jiayu Li, Congcong Wang, Xilei Dai, Junjie Liu*

Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin, China

ARTICLE INFO

Article history:
Received 7 January 2018
Revised 16 July 2018
Accepted 24 July 2018
Available online 9 August 2018

Keywords:
PIV
Range hood
Domestic kitchen
Air distribution
Spill length
Vortex identification

ABSTRACT

High-performance range hoods can quickly exhaust cooking smoke and fumes outdoors. Quantifying the detailed information that range hood-driven flow provides can be an essential prerequisite to optimize the hood's performance. Direct measuring instruments cannot easily determine the velocity due to large velocity gradients and high temperatures. Particle image velocimetry (PIV) is a non-intrusive velocimeter-based method with high spatial resolution and in a global domain. Thus, we applied large-scale 2D-PIV and measured the range hood-driven flow in three sections under isothermal and heating conditions. This study systematically investigated the influence of the exhaust flow rate and mounting height on the range hood-driven flow. The measurement results under isothermal conditions show the actual airflow driven by a range hood cannot be characterized as a simple exhaust and have self-similarity for different exhaust airflow rates. The results also indicate that the mounting height only slightly impacts the velocity boundary conditions of the range hood exhaust surface. The results under the heating conditions clearly reveal that the time-averaged spill length is larger than the average value of the dynamic spill length. This phenomenon indicates that the relationship between time-averaged velocity fields and spill length is not a simple linear scaling relationship. The unsteady flow in the kitchen should be considered to determine the true capture efficiency. Moreover, uncertainty analysis ensures that the benchmark flow data for the follow-up kitchen environment and range hood design simulations.

1. Introduction

Cooking is the most common daily activity in a traditional family. This activity has been reported as the major indoor source of air pollution in a residential building [1,2]. Many studies have found adverse health effects induced by the exposure to cooking emission, such as lung cancer [3] and respiration disease [4]. Therefore, high-performance ventilation systems are required to remove gaseous and particulate contaminants. Certain kitchen fume extractors must be considered to reduce exposure to such pollutants and maintain good indoor air quality inside the kitchen [5–7]. Especially in modern domestic kitchens, people commonly use range hoods.

A high-performance range hood can channel cooking smoke and fumes outdoors very quickly. Nevertheless, range hood performance is related to many parameters, including exhaust airflow rate [8,9], hood type [10–12], aerodynamic design [13–15] and the mounting height between stove and hood [16–18].

Exhaust airflow rate has a noticeable impact on the global flow field and contaminant capture efficiency in kitchen environments. Many studies [6,8,11,19,20] have considered the influence of exhaust airflow rate on the capture efficiency, but most of these studies [6,11,19,20] just characterized the range hood as a simple exhaust.

The exhaust flow is often driven by as centrifugal fan or axial fan installed in the domestic range hood [10,14]. Abanto and Reggio[14] simulated and characterized the range hood-driven flow as turbulent flow in three-dimensions (3D). The vector velocity distribution was found to be different from the simple exhaust. However, Abanto and Reggio[14] were focused on the predicted flow inside the range hood and less concerned about the airflow distribution above the kitchen stove, simulation results did not get validated because of lack of experimental data, so the turbulent model for the airflow is not warranted. Poon [20,21] developed an Eulerian turbulence computational fluid dynamics (CFD) model and fit well with the experimental data without hood operation, but Poon [20] found that the particle capture efficiency, calculated by the renormalization group (RNG) k–ε turbulence model combined with this Eulerian model, was overestimated compared with the measured results with hood operation. Poon [20] explained that this may be attributed to the oversimplification of the range hood as an exhaust surface. Based on several issues that are identified as the influence mechanisms of exhaust airflow rate on the range hood-driven flow still needs further description.

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* Corresponding author.
E-mail address: jjliu@tju.edu.cn (J. Liu).

https://doi.org/10.1016/j.enbuild.2018.07.051
0378-7788/

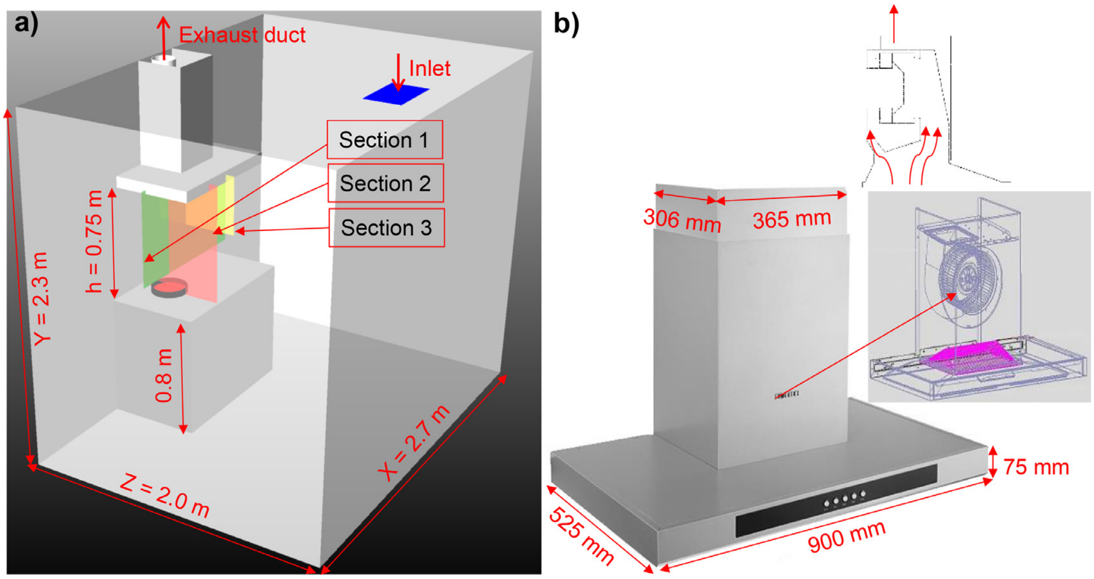

Fig. 1. (a) Schematics of the experimental setup; (b) range hood model.

The mounting height between the stove (or cooking oil surface) and hood was modeled, and its effect on the capture efficiency was determined [16,18]. Chiang et al. [16] investigated the efficiency of fume extractors with three mounting heights above the oil surface (500, 600 and 700 mm). They found the exposure to fumes was reduced by reducing the mounting height. This result agreed with Yik and Au [17]. Yik and Au [17] reported that the capture efficiency was 81% and 73% at mounting heights of 700 and 850 mm, respectively. However, Sjaastad and Svendsen [18] presented a contradicting result. The concentration of the respiratory area, as an indirect indicator of capture efficiency, associated with the mounting height of 500 mm was found to be larger than 600 mm. Because these studies [16–18] did not provide range hood-driven flow with the various mounting heights, this phenomenon is not characterized consistently. Furthermore, the manufacturer recommends a mounting height within the range of 600 to 750 mm in a domestic kitchen. However, the International Electrotechnical Commission (IEC) [22] tested the odor-reduction factor in 2011 at the mounting height of 600 mm. Hence, the actual performance that needs to be determined, when the kitchen hood is installed in a home, is the manufacturer-recommended mounting height.

Quantifying the detailed effect of exhaust airflow rate and mounting height on the range hood-driven flow should be an essential prerequisite to optimal performance. Currently, air distributions in kitchens are typically studied using CFD simulations [5,11,19,23,24] but are often not validated by experimental data. When the experimental measurements [25,26] are not used, some specific measuring instruments cannot be used to measure the thermal plumes of kitchen appliances. Resulting from the cooking fumes released at high temperatures, ultrasonic probes have a suction velocity in presence of large velocity gradients, which are also affected by large uncertainties and suffers from a higher vector rejection rate [27]. We use a point-wise method to get a more accurate air velocity model, because of the tiny space under the hood and the low spatial resolution. Particle image velocimetry (PIV) is a non-intrusive velocimetry high spatial resolution method that is preferable to determine an airflow distribution above the kitchen stove in a global domain.

High quality flow data obtained by PIV not only merely provides benchmark flow data for CFD simulations but can also directly indicate characteristic features of complex flows [28–30]. Furthermore, PIV techniques as well as the Schlieren visualization system [31,32] used in the ASTM F1704-12 [33], can observe cooking effluent of a hood, which can also provide information about spillage of hot air at the sides of the hood is a minor constraint given the air dynamics of exhaust hood systems. The spill characteristic, in a time scale, can help estimate the recommended flow rates.

Therefore, the primary purpose of this study is to acquire the high quality driven flow models for a range hood in a real-size kitchen cabin. We employed a high power 2D PIV to obtain the range hood-driven flow under isothermal and heating conditions, both with the following two varying factors: exhaust flow rate and mounting height. Based on the measurement data, the spill characteristic of cooking plumes was analyzed. This paper also provides a detail impact of the exhaust airflow rate and mounting height on the global flow field in domestic kitchen environment. Moreover, uncertainty analysis was conducted to ensure that benchmark flow data for follow-up kitchen environment and range hood design simulations.

2. Method

2.1. Experimental platform

The experiment was conducted in a kitchen cabinet with dimensions of 2.7 m (X) × 2.0 m (Z) × 2.3 (Y) m, as shown in Fig. 1a. The kitchen cabinet was placed in a thermostatic chamber with an air temperature of 22 ± 0.5 °C. The kitchen consisted of transparent acrylic resin and an airtight door to help the PIV measurements. A Chinese range hood was installed above the stove surface with two different mounting heights: 600 mm and 750 mm. The diameter (D) of a nonstick pan and the effective heating area of an electric stove are both 240 mm. The nonstick pan was placed on a Table 0.22 m from the pan center to the wall. The thickness of the nonstick pan was 5 mm, and a thermocoupler was mounted in the pan to measure the heating temperature. Considered the range hood should meet the worst cooking condition, The heating temperature of the pan was determined by referred the ASHRAE 1151-RP (2003) [34], IEC 2011 [35] and GB/T 17,713 (2011) [36], maintained at 260 ± 1 °C (measured by a thermostat). The supply air was provided by a variable speed fan, and the supply flow rate was set to be the same as the exhaust flow rate. Fig. 1b is a diagram of the range hood used in the experiment. A two-inlet centrifugal fan was installed in the range hood. We tested the range hoods at