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ORIGINAL PAPER

Experimental and computational study of particulate matter of secondhand smoke in indoor environment

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Abstract Tobacco smoking has become one of the greatest sources of indoor inhalable particles. Tobacco smoke changes chemically and physically after it is released into indoor air; these changes can increase secondhand smoke (SHS) toxicity. The SHS as assessed by indoor particulate matter with an aerodynamic diameter of less than 2.5 mm ($PM_{2.5}$) was investigated experimentally and computationally. Test house experiment was performed to study the $PM_{2.5}$ concentration under controlled conditions coupled with mathematical model of continuity equation. $PM_{2.5}$ was measured using a DustTrak personal sampler. Two-dimensional flow and dispersion of cigarette smoke were modeled using computational fluids dynamics model which were solved using Reynolds-averaged Navier–Stokes equations. The effect of air purifier in reducing SHS and thirdhand smoke (THS) was analyzed and evaluated. The results demonstrated that the air purifier cannot control the indoor $PM_{2.5}$ levels. Furthermore, amount of smoke from main stream of SHS is more compared to side stream and THS can be evaluated by calculating the adsorption term of continuity equation.

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Introduction

Over last years, greatest public attention was paid to the indoor air quality (IAQ) side due to its impact on human health and productivity. IAQ refers to the air quality within buildings that can be affected by polluted gases, particulates, or other contaminants that can induce adverse human health effects. Particulate matter $PM_{2.5}$ is a major indicator for smoking levels among the nicotine and heavy metals. Tobacco smoke contains over 4,000 chemical compounds which cause death from lung cancer and heart diseases, respiratory infections, and asthma. Secondhand smoke (SHS) is a global public health problem that considers emissions from cigarettes. SHS is a mixture of two forms of smoke: side stream smoke, which is smoke from the end of a lighted cigarette, and main stream smoke, smoke that is exhaled by a smoker. The residuals of tobacco smoke that are left on a variety of indoor surfaces are generally considered as "thirdhand smoke (THS)." These residuals are reacting with indoor pollutants to create a toxic mixture which cause adverse health effects.

A number of relevant studies have been performed to investigate tobacco smoke in indoor environment (e.g., Repace 1987; Leaderer 1990; Ott et al. 1992; Barnoya and Glantz 2002). Branis et al. (2002) measured fine particles in four different indoor environments, a lecture room, a restaurant, and two types of offices, and determined that the highest concentration was recorded in the restaurant. Another study in Perth, Western Australia, involved air quality measurements in 20 social venues that permitted smoking and found elevated particulate matter concentrations (Dingle et al. 2002). A study of Klepeis et al. (2002) derived analytical solution to solve the mass balance equations for predicting the air pollutant concentration from cigarette in home. As a result, indoor pollutant concentration from smoking activity in a home can be high because of small venue volumes and low air exchange rates of most of the homes. Furthermore, previous studies conducted in public venues had shown that occupants are exposed to harmful levels of SHS when smoking occurs (Farrelly et al. 2005; Repace 2004; Travers et al. 2004). Ning et al. (2006) investigated experimentally the variation of the ETS particle concentration and size distribution under an actual indoor environment, in a room of 30 m^3, using human smokers. The results indicated little difference in the environment tobacco smoke particles from those in background air. Waring and Siegel (2007) assessed the differences in the indoor air quality and occupancy levels in seventeen bars due to a city-wide smoking ban that took effect in Austin, Texas, USA.

Recently, Deshpande et al. (2009) estimated the indoor $PM_{2.5}$ concentrations based on a steady-state mass balance model and uniform mixing assumption. The $PM_{2.5}$ concentrations are affected by the exposure of smoking emission source. Air exchange rate, deposition factor, and indoor volume are factors affecting the model. The study found that the $PM_{2.5}$ concentrations are varied inversely and nonlinearly with respect to air exchange rate and deposition rate. Gerharz et al. (2009) estimated the indoor $PM_{2.5}$ levels using simple mass balance model to minimize the risk of personnel exposure. Milner et al. (2010) found that Particulate Matter from cigarettes has emission factor 8–20 mg per cigarette, and 0.07 mg per minute of $PM_{2.5}$ is re-suspended while cleaning. Nafees et al. (2011) observed the significant increase in indoor exposure level of particulate matter $PM_{2.5}$ when number of smokers increased inside the indoor areas and demonstrated the unacceptably high levels of indoor air pollution $PM_{2.5}$ exposure associated with SHS at various entertainment venues. The most widely used methods and applications for SHS environmental monitoring to implement tobacco control policies are summarized by Apelberg et al. (2012). Monitoring SHS exposure in indoor environments provides behavioral of SHS and evaluates tobacco control programmers; hence, respirable particulate matter is the most important indicator of SHS. In indoor environments, the most influential building characteristics are generally room size and ventilation rate. Matt et al. (2010) found THS accumulates in smokers' homes and persists when smokers move out even after homes remain vacant, cleaned, and prepared for new resident where they will be exposed to THS in dust and on surfaces.

On the other hand, indoor air quality modeling plays a key role in the building design and operation in order to maintain acceptable indoor air quality which can be used to evaluate a variety of parameters and simulate the pollutant source emission rates and ventilation rates. Currently, computational fluid dynamics (CFD) technique has become a very powerful and popular tool in indoor pollution simulation. Many studies in indoor environments have greatly advanced our standing of the characteristic of the smoke movement (e.g., Moschandreas et al. 2002; Zhao et al. 2003; Chang et al. 2006). CFD assessed the areas range from building site planning to individual room layout design, from active HVAC system design into passive ventilation study and from regular indoor air quality assessment to critical smoke and contaminant control (Zhai 2005). Yan et al. (2006) analyzed the indoor air quality to estimate $PM_{2.5}$ exposure which can be done with the help of CFD model and multiple parameters such as building parameters, ventilation, and air-cleaning devices in building. Employing CFD model to predict air pollutant $PM_{2.5}$ under smoking as emission scenario in UK homes was performed by Dimitroulopoulou et al. (2006). Villi et al. (2009) showed the evaluation of different simulation approaches to kitchen ventilation modeling using CFD. Milner et al. (2010) described the indoor exposure modeling in residential building using CFD for health impact assessment. In addition, Saha et al. (2011) investigated and analyzed the three-dimensional flow field and the distribution of temperature in large kitchens which are related with the architectural design, physical arrangement, and fluid flow field. The features from the experimental and computational results are used to improve indoor air quality in the future designs of large kitchens.

Also, few previous studies have been conducted to assess secondhand smoke and thirdhand smoke in indoor environments. However, better understanding in the movement of indoor tobacco smoke is awaited to be improved. Thus, the main objective of the present work is to assess experimentally and computationally the indoor air quality and personnel exposure to fine particles $PM_{2.5}$ from SHS using a background of engineering model with familiarity in basic numerical methods. Moreover, the study helps to evaluate the THS using mathematical model. Thus, test house experiment was used to study the indoor $PM_{2.5}$ concentration. Moreover, the k-ε turbulence model was used to simulate the flow of containment $PM_{2.5}$ from SHS that causes risk to secondhand smoking people. We tested the sensitivity and validity of the model to some parameters such as the volume of the venue and the design and flow of the Heating, Ventilation and Air Conditioning (HVAC) by comparing the predicted results with the experimental ones. In addition, we checked the effect of the stand-alone air purifying unit on secondhand smoke reduction. This research was conducted at the collage of graduate studies, Kuwait University, from September 2010 till December 2012.

Materials and methods

Experimental method

The objective of the experimental part is to model the indoor air flow of $PM_{2.5}$ from SHS. The experiments are performed under controlled conditions of air flow rates and other parameters to obtain $PM_{2.5}$ concentration. The experimental results from test house are analyzed and solved mathematically to obtain predicted results for the model. Also, THS is measured in the test house experiment which can be source emission of SHS.

Measurements and instrumentation

DustTrak Monitor is used to sample and record the levels of $PM_{2.5}$ in the air by displaying the real-time concentration of particles in milligrams per cubic meter every 30 s over 30 min. A DustTrak aerosol monitor (model 8520, TSI, USA) was employed to measure the concentration of particulate matter inside the house. This instrument employs light scattering technology to deliver real-time measurements. The detection range is from 0.001 to 100 mg m^{-3} with a resolution greater than 0.001 mg m^{-3} or 1 % of the reading. The particle size ranges from 0.1 to 10 mm; however, particle of size 2.5 μm is measured in this study. Air is continually drawn through the sample inlet into the internal chamber, forming a continuous stream of particulate matter. In the internal chamber, there is a source of laser light which is used to illuminate one section of the aerosol stream, and light is scattered from the illuminated aerosol stream. Some of the scattered light is collected and focused onto a photo-detector at 90° to both the aerosol stream and laser beam. The light is then converted into a voltage. The mass concentration of particulate matter is proportional to the amount of light scattered and the voltage generated. The mass concentration is calculated from the voltage and an internal calibration factor.

A standard operating procedure (SOP) was used for the analysis and samples as per indoor air monitoring protocol. A well-established protocol adapted by Harvard School of Public Health (HPSH) to monitor the indoor air quality in a venue would include the following:

a. Record time of entry/exist from venue.
b. A minimum of 30 min should be spent.
c. The monitoring device should be located in a central area.
d. The device can be placed on a table not on the floor to avoid damage to the device and to monitor air within people's normal breathing zone.
e. Spend at least 5 min as background concentration.

A "SHARP" air purifier is used in this study to remove contaminants from the air. It has coverage area of 26 m with humidification function. It has advantage of high-density plasma cluster ions and fan air purification that cleans the air using positive and negative ions. The ions are positive hydrogen and negative oxygen ions that are extracted from the water molecules in the air. These ions will be attached to unwanted components in the room air to restore the moisture state and breaking down unpleasant odors and particles in the air. At the same time, the air is also purified using the different filter system which provides a unique dual air-purification effect via ions and filters. High-density plasma cluster ion shower releases the balanced shower of negative and positive ions in the air to purify the entire volume of the air in the room. There is also pre-filter to protect fine high-efficiency particulate air filter from contamination by large particles and extends HEPA filter's lifetime. In addition, it contains HEPA filter which removes 99.97 % of particles that have a size of 0.3 μm including mold and dust, etc. HEPA filter is placed as the last one downstream the air flow to ensure that all particles that may be released by other components of the air filtration system are trapped and do not pass to the clean air outlet. Moreover, carbon filter is used in this air purifier, which removes chemicals from the air including cigarette smoke, odors, etc. Also, allergy filter exists in this air purifier to help kill bacteria and microbes.

Test house experiment

The facility was a single space room in test house with floor area of 7.2 × 4.2 m^2 and a ceiling height 3 m. The test house was a furnished, two-story villa type building with a central air conditioning system. The volume of the living room in ground floor of the house was estimated to be 90 m^3. The air flow rate was calculated by measuring the air velocity coming from the air conditioning ducts. Air velocity from the two ducts of central air conditioning in the room was assumed to be 3.25 m/s since the typical air velocity value from central air conditioning in building is between 2 and 4.5 m/s (Engineering and Design of technical Application). Two sets of smoking were conducted in test house, once when the cigarette smoke was considered as direct smoke, from the burning end tobacco products as side stream smoke, and indirect smoke when the smoke was exhaled by smoker which is main stream smoke. $PM_{2.5}$ samples were measured using DustTrak over 30 min. Total sample runs that measured the $PM_{2.5}$ in test house were 13 experiments including direct smoke in 6 sample locations and indirect smoke in one sample location 3. During the direct smoke experiments, the ability of air purifiers in reducing the effect of SHS was checked by measuring the $PM_{2.5}$ in 6 sampling locations while using the air purifier

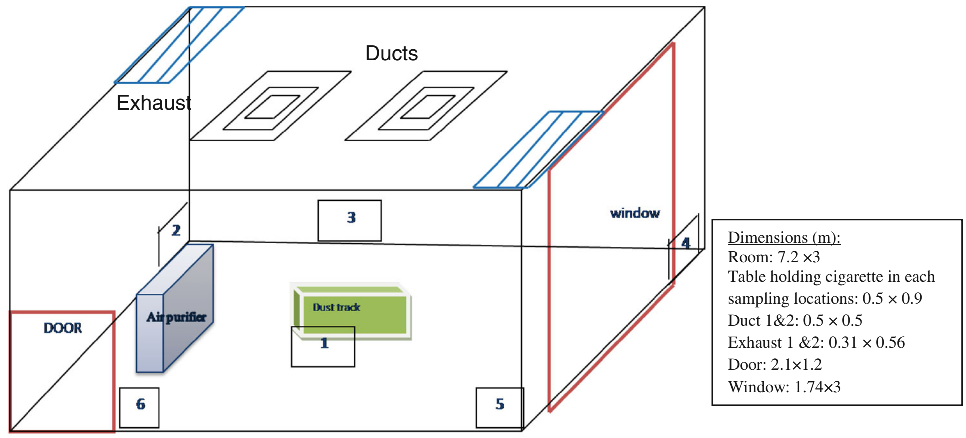


Fig. 1 Room geometry with different sampling locations

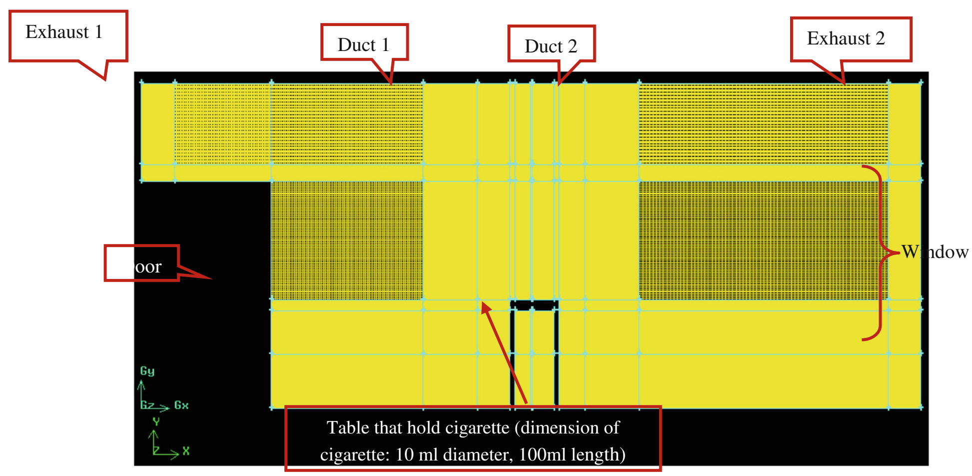


Fig. 2 Schematic layout of the computational domain of the test house

and by measuring the $PM_{2.5}$ in the same 6 sampling locations without using the air purifier. One run measured the $PM_{2.5}$ levels in sample location 3 as indirect smoke. For both experiments in test house, the concentration of $PM_{2.5}$ was measured with same fixed parameters such as size of room, number of cigarettes, usage of air purifier, sample locations, and air conditioning mode. The room geometry and sample locations are shown in Fig. 1. This schematic model was used for numerical simulation. During all measuring experiments, six sample locations were considered in measurements where the DustTrak was located in the middle of the room on table at breathable level, whereas air purifier was located in fixed place in this study as shown in Fig. 2. Air conditioning is on "ON" mode for all experiments inside the room.

Model formulation of test house

A mathematical model adapted from Elkilani (1999) was used in this study. The model expressed the time-dependent accumulation of pollutants in terms of pollutant concentration, source, and sink terms. Since SHS is a global public health problem, therefore, $PM_{2.5}$ pollutant from SHS is extensively studied. By mass balance model of a $PM_{2.5}$, the change with time of $PM_{2.5}$ concentration must be equal to the difference between sources and sinks:

$$\frac{\text{Indoor pollutant accumulation}}{\mathrm{d}t} = \sum \text{sources} - \sum \text{sinks}$$

The "sources" are the inlet pollutants and generations sources, whereas the "sinks" are the outlet pollutant and consumption sources. Conceptually, indoor concentration of $PM_{2.5}$ is described as follows:

Indoor $PM_{2.5}$ accumulation = $PM_{2.5}$ mass in−$PM_{2.5}$ mass out + generation (emission rate)−consumption (adsorption rate)

The input and output $PM_{2.5}$ pollutant rates were expressed in terms of the $PM_{2.5}$ concentrations. The generation rate was expressed in terms of the source emission rate per space volume. The consumption rate was expressed in terms of the indoor pollutant concentration and the adsorption rate constant. THS can be evaluated using the adsorption rate that refers to residual of tobacco smoke that left on a variety of indoor surfaces and trapped into hair, skin, fabric, carpet, furniture, and other surfaces that built up over time. As a result, a mathematical mass balance model equation was used for analyzing the test house data and is written as follows:

$$\frac{dC_i}{dt} = N\,C_o(t) - N\,C_i(t) - R_a(t) + R_s(t) \tag{1}$$

where C_i is indoor $PM_{2.5}$ concentration (µg/m^3), C_o is background $PM_{2.5}$ concentration (µg/m^3), R_s(t) is first-order emission rate (µg/m^3.min) which equals to $R_0\,\exp(-ks\,t)$, K_s is decay rate constant (1/min), R_o is initial emission rates (µg/m^3.min) [for more details of emission rate, refer to Al-sararf (2013), t is time (min), V is indoor venue volume (m^3), N is air exchange rate (min^{-1}) which equals to $Q_{\text{air flow rate}}/V_{\text{chamber volume}}$ and $Q_{\text{air flow rate}}$ equals to $u_{\text{air velocity}} \times A_{\text{cross-sectional area}}$, $R_a(t)$ is consumption rate (adsorption) which equals to $k_a A_{\text{sink}}/V\,C_i(t)$, k_a is adsorption rate constant (m/min), and A_{sink} is sink surface area (m^2).

The $PM_{2.5}$ levels from test house experiments were considered as "experimental concentration"; however, the concentrations obtained from solving differential equation were called "model concentration." The adsorption rate on the indoor surfaces such as furniture, carpets were considered as THS. The adsorption term in mass balance equation is defined as the transfer of indoor $PM_{2.5}$ to accumulate on the surface of another phase (building materials). THS can be later a source emission when the driving force changes (i.e. equilibrium: adsorption rate = desorption rate). Deposition of air particulate depends on particle size, surface material, whereas re-suspension and re-emission of deposited material is influenced by human activities such as cleaning. Application of the Eulerian approach, which is shown in Eq. 2, is used to obtain approximate solutions of the differential continuity equation. The model concentrations were validated using normalized mean square error (NMSE) when compared with the experimental concentrations to obtain the adsorption rate as shown in Eq. 3. Fitting curves between experimental concentration and model concentration are checked by obtaining lowest NMSE to get adsorption rate of highest $PM_{2.5}$ levels in the test house sample locations.

Euler's method is described as follows:

$$C_{i+1} = C_i + (h \times f(t, C)) \tag{2}$$

where C_{i+1}, C_i are $PM_{2.5}$ concentration at step time i and $i + 1$ respectively, $f(t, C)$ equals to dC_i/dt and h is time interval (min)

The expression for the NMSE is given by:

$$\frac{\sum (C_{\exp} - C_{\text{model}})^2}{C_{\exp}^2} / n \tag{3}$$

where n is number of data points, and C_{model}, $C_{\exp}$ are average $PM_{2.5}$ concentrations (µg/m^3) obtained from experiment, and approximate solution of continuity equation is obtained as follows:

$$\overline{C_{\text{model}}} = \frac{\sum C_{\text{model}}}{n} \quad \text{and} \quad \overline{C_{\exp}} = \frac{\sum C_{\exp}}{n}$$

Computational methods

Computational fluid dynamics methods have been applied to determine the velocity field within the room and to predict the distribution of pollutant concentration inside the room. The present study analyzes the characteristics of the flow field, velocity field, and diffusion field in the computational domain and tries to correlate all three fields to understand the indoor air quality of the computational domain.

Modeling description

The commercial CFD package ANSYS FLUENT Version 6.3.26 (ANSYS Inc., 2010) was used to simulate the wind flow and pollutant dispersion within the street canyon. The CFD modeling was configured to solve the pseudo-steady-state incompressible Reynolds average Navier–Stokes (RANS) equations equipped with $\kappa-\varepsilon$ turbulence models (κ is turbulent kinetic energy and ε is dissipation rate of kinetic energy) for the mean flow within test house. The standard $\kappa-\varepsilon$ turbulence model (Launder and Spalding, 1974) was used. The conservation equation for the species concentration of pollutants must also be solved together with the above-mentioned equations that describe the flow characteristics. In modeling indoor flow and dispersion, fine grid is desirable around cigarette model for better flow and dispersion fields solutions, whereas a coarse grid is preferred in the rest of the room except cigarette model. The above set of governing equations was numerically solved on a staggered grid using the finite volume following the semi-implicit method for pressure-linked equation (SIMPLE) algorithm described by Patankar (1980).

Model domain

Two-dimensional computational domain was used for test house experiment which is shown in Fig. 2. CFD methods have been applied within a room in test house of 7.2 m (x-direction) × 3 m (z-direction) for 2-dimensional CFD simulation with an window opening of 1.75 m (x-direction) × 3 m (z-direction) on the side wall and two inlet air ducts opening of 0.5 m × 0.5 m on the ceiling in addition to two exhausts opening of 0.31 m × 0.56 m. The door is 2.1 m long and 1.2 m width. The table dimension which holds the cigarette is 0.5 m (x-direction) × 0.9 m (z-direction) with two legs of 0.05 m (x-direction). The present investigation involved steady-state analysis. This study focuses on the numerical predictions of the $PM_{2.5}$ from cigarette smoke distribution within a ventilated room. The air velocity from the duct for air conditioning inside the room was assumed to be 3.25 m/s. The room under investigation was split into a number of smaller volumes using two-dimensional cells. Each cell was then assumed to be perfectly mixed with uniform temperature distribution in indoor mass balance model. Since fine meshes given better results, the interval count for each face is 98 (i.e. 70 % of the length of face). The number of cells and nodes in the computational domain is 34,732 and 346,346, respectively. The model boundaries were a distance 4*H* from the inlet domain, 4*H* from the outlet domain, and 3*H* from the upper domain (*H* is height of the table holding the cigarette). Extensive tests on the effect of the cell intervals were carried out by increasing the cell interval until the benefit of further refinement became insignificant. The fine grid was chosen closer to the table holding the cigarette and the ground. The expansion ratio for the non-uniform grid was 1.1. The configuration was meshed using GAMBIT software version 2.4.6.

Boundary conditions

Velocity inlet boundary layer conditions were used for the main inlet wind flow and the cigarette smoke emission. The initial wind speed was uniform (3.25 m/s), which was as the same of test house experiment, and the wind turbulence was weak. The initial condition for wind velocities, turbulent kinetic energy (TKE), and its dissipation rate (ε) are specified as (ANSYS FLUENT 2010):

$$T_{\mathrm{KE}} = \frac{u_\tau^2}{\sqrt{c_\mu}} \tag{3}$$

$$\varepsilon = \frac{c_\mu^{3/4}\left(T_{\mathrm{Ke}}^{3/2}\right)}{l} \tag{4}$$

where u_τ is the friction velocity and l is the turbulence length scale. The ground and building surfaces are defined as walls with no-slip boundary condition. The wall boundary conditions for momentum are applied to all solid surface and rough walls. Zero gradient boundary conditions are applied at the outflow and upper boundaries.

Results and discussion

Test house experiment

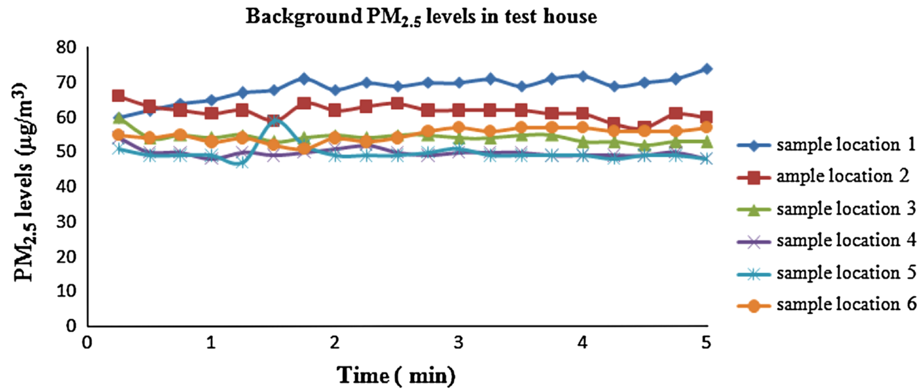
A room in test house was used in this study to analyze the particulate matter $PM_{2.5}$ from SHS by predicting the flow of SHS testing and the potential of HVAC rate and air purifier in reducing SHS. Since the emission rate of SHS is difficult to be measured in continuity equation, the emission rate from test smoking chamber was used in test house calculation to able to get the adsorption term of $PM_{2.5}$ on building material such as the furniture and carpets. The optimum emission rate was the average value of three brands of cigarettes which are used in test house calculation (Al-sararf 2013).

The aim of this experiment is to obtain the adsorption term of continuity equation that represents the term of thirdhand smoke. THS, which is deposited on the surfaces such as carpets and furniture for extended periods of time, causes harmful health effects. The effect of air purifier in reducing the effect of SHS on nonsmoking people was checked in this study when one cigarette was lightened up in different sampling locations in room. One additional sample run of direct smoke (exhaled by smoker) was measured in this study. In the beginning of test house experiment, the average background concentration of $PM_{2.5}$ was measured for 5 min in six locations inside the room which is shown in Fig. 3. The background $PM_{2.5}$ level is around 57 $\mu g/m^3$ for the six sampling locations.

In the test house calculation, only one cigarette was used as direct smoke (burning end tobacco) for six sampling locations and one sample run was measured when cigarette smoke was exhaled by a smoker (main stream of SHS) in sampling location 3 of the test house. The average smoking duration for the cigarette was 10 min for all experiments. Several factors affect the real-time $PM_{2.5}$ concentration of cigarette, which are cigarette durations, smoking styles, and ventilation rates. Since SHS is only the indoor source of $PM_{2.5}$ levels considered in this study, the direct cigarette smoke is from SHS; side stream smoke is from burning tobacco ends; it is the major contributor to environmental tobacco smoke. Dangers of SHS exposure are highest among indoor venues especially in private places such as houses that have low levels of protection provided by smoking regulations.

The $PM_{2.5}$ concentration was plotted versus time showed a line decay pattern for different sample locations in test house that is illustrated in Fig. 4. The average concentration of $PM_{2.5}$ levels of one cigarette in sample location 1 of the test house without using the air purifier is 146 $\mu g/m^3$. Compared to Alberta hourly standard of 80 $\mu g/m^3$ (Alberta Ministry of Environment), the average concentration of $PM_{2.5}$ levels in sample location 1 is approximately twice higher than the standard. The average concentration of $PM_{2.5}$ levels of one cigarette in sample location 2 of the test house without using the air purifier is 55 $\mu g/m^3$. The average concentration of $PM_{2.5}$ levels in sample location 3 of the test house without using the air purifier is 77.5 $\mu g/m^3$. The average concentration of $PM_{2.5}$ levels in sample location 4 of the test house without using

Fig. 3 Background $PM_{2.5}$ levels in the test house in sex sampling locations



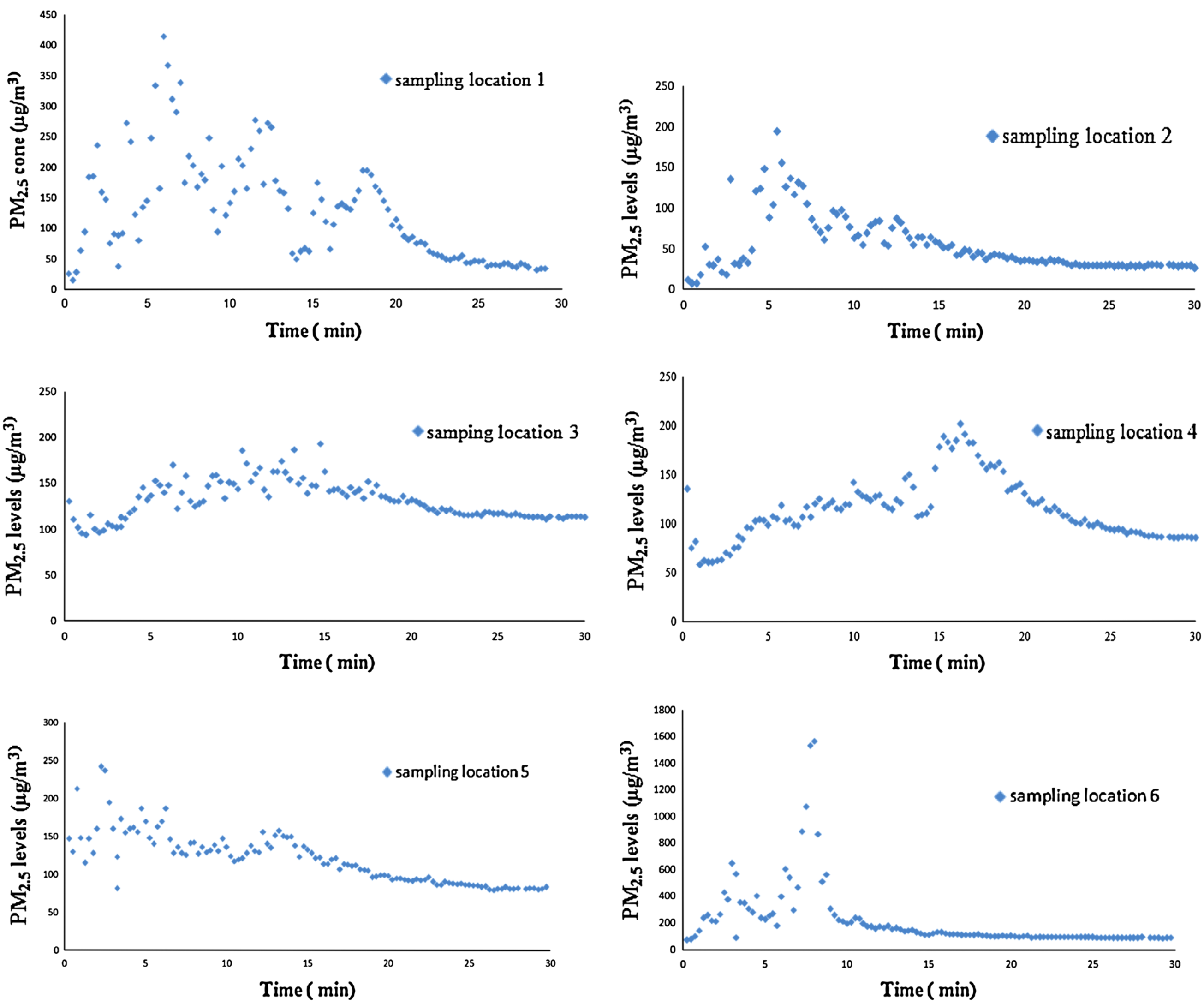


Fig. 4 $PM_{2.5}$ levels in different sampling locations of the test house

the air purifier is 114 μg/m^3. Compared to Alberta hourly standard of 80 μg/m^3, the average concentration of sample location 4 is approximately 1.5 times higher than the standard. The average concentration of $PM_{2.5}$ levels in sample location 5 of the test house without using the air purifier is 124 μg/m^3. Compared to Alberta hourly standard of 80 μg/m^3, the average concentration of sample location 5 is approximately 1.5 times higher than the standard. The average concentration of $PM_{2.5}$ levels in sample location 6 of the test house without using the air purifier is 218 μg/m^3. Compared to Alberta hourly standard of 80 μg/m^3, the average concentration of sample location 6 is approximately 3 times higher than the standard. The average concentrations of $PM_{2.5}$ for different sample locations are illustrated in Fig. 4.

Moving to indirect smoke, when the cigarette smoke was exhaled by a smoker, the average concentration of $PM_{2.5}$ levels of smoker in sample location 3 (center of venue) of test house without using the air purifier is 182 μg/m^3 which is illustrated in Fig. 6. Compared to Alberta hourly standard of 80 μg/m^3, the average concentration of sample location 3 is approximately twice higher than the standard. Also, this figure shows that the average concentration is higher when including human puff rather than burning tobacco ends (77.5 μg/m^3) with 57 % increasing which means the amount of such smoke inhaled by a non-smoker is more than lightning the cigarette. The SHS people in the test house (average $PM_{2.5}$ = 182 μg/m^3) would be exposed to $PM_{2.5}$ in excess of the Alberta standard of 1-h limit of 80 μg/m^3 within 27 min. It would take only 58 min for a non-smoking people to reach exposure levels that are "very unhealthy" of average 175.5 μg/m^3 according to air quality index (US EPA).

Since this study tested the sensitivity of air purifier, two sets of experiments were conducted in the test house while using the air purifier and without using the air purifier for direct smoke (burning tobacco ends) of same six sample locations. It was found that the air purifier and ventilation system are not the solutions to reduce secondhand smoke which is shown in Table 1 and Fig. 4. As a result, air purifier partially removes the cigarette odor since SHS can linger for hours in the room. However, locations 1 and 6 in the test house, which is shown in Fig. 5, presented that air purifier has approximately 30 % reduction of $PM_{2.5}$ but actually there may be outdoor air near door and this may have effect on these locations. The air circulation would be increased if air fan was used or opening the window in the room of the test house which may lead to reduction in the concentration of indoor particles. In addition to that, air purifier has no effect in cigarettes $PM_{2.5}$ according to Harvard School of Public Health (HPSH). Comparing $PM_{2.5}$ level with air purifier to ones without air purifier, it is found that the average values of $PM_{2.5}$ without air purifier are less than the values with air purifier due to natural ventilation from opening window (before and after experiment) which maintain good indoor air quality that dilute the indoor air containments. These results are consistent with those found in indoor air quality document of EPA that stated "There is no scientific evidence shows air-cleaning devices to be consistently and highly effective in reducing adverse health effects from indoor air pollutants (US Environmental Protection Agency 2009)."

The residuals of tobacco smoke are suspended on furniture, walls, carpets, and other surfaces that build up over time are considered as THS which can be a source emission when the driving force changes that cause adverse health effects. THS resists normal cleaning. THS cannot be eliminated by opening windows or using fans or air conditioners. Therefore, the adsorption rate was calculated

Table 1 Comparison of $PM_{2.5}$ level in the test house with/without air purifier

Sampling locations in the test house	$PM_{2.5}$ average concentration without air purifier	$PM_{2.5}$ average concentration with air purifier
Location 1	146.4	103.6
Location 2	55.0	93.6
Location 3	77.5	172.6
Location 4	114.0	227.7
Location 5	123.7	146.3
Location 6	217.8	151.6

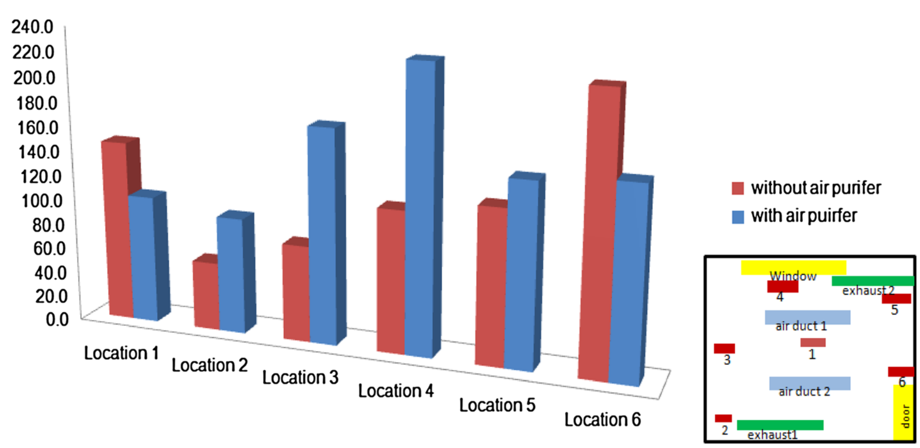


Fig. 5 Comparison between $PM_{2.5}$ levels in the test house with using air purifier and without using air purifier

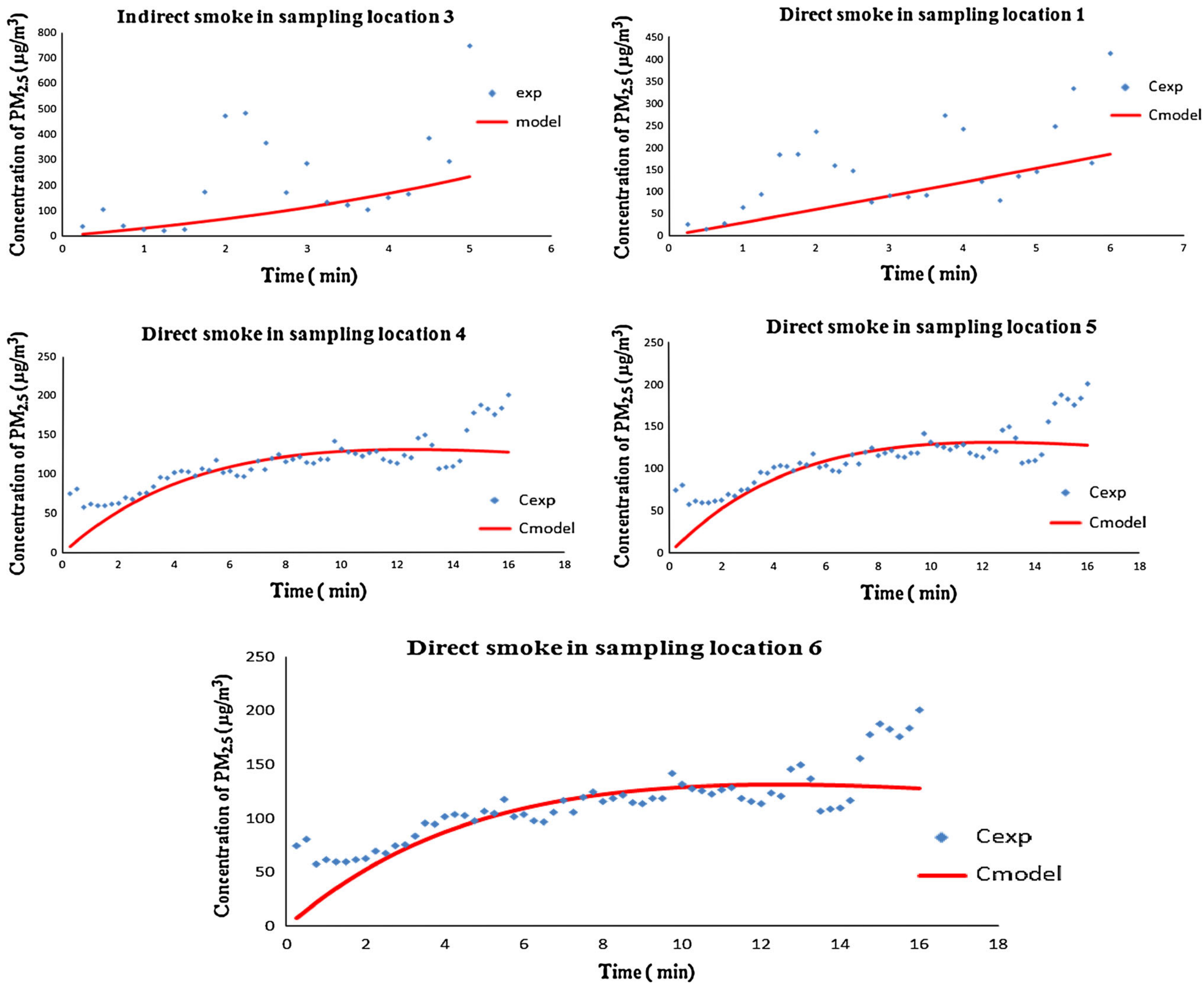


Fig. 6 Fitting curve of adsorption term for indirect and direct smoke in different locations of the test house

from mathematical model in continuity equation to evaluate the THS in this study. The deposition of air particulate depends on particle size, surface material, whereas re-suspension and re-emission of deposited material are influenced by human activities such as cleaning.

The air duct velocity inside the room was 3.25 m/s and the volume of the room was 90.72 m^3, and the air exchange rate is estimated to be 0.54 min^{-1}. In general, the small volume and low flow air exchange rate of the venue in test house help in increasing the $PM_{2.5}$ concentrations from smoking activity which can persist for many hours. The model concentrations were compared with experimental concentration of SHS $PM_{2.5}$ in fitting curves. As a result, the adsorption rate that is obtained from the fitting curve of indirect smoke (i.e., smoke exhaled by a smoker), which is shown in Fig. 6, is 5.47 m/min with NMSE of 0.338. The adsorption rate that is obtained from fitting curve of direct smoke without air purifier in sample location 1 is 4.14 m/min with NMSE of 0.219. The adsorption rate which is obtained from fitting curve of direct smoke without air purifier in sample location 4 is 2.72 m/min with NMSE of 0.056. The adsorption rate which is obtained from fitting curve of direct smoke without air purifier in sample location 5 is 4.183 m/min with NMSE of 0.267. The adsorption rate which is obtained from fitting curve of direct smoke without air purifier in sample location 6 is 5.83 m/min with NMSE of 0.352. The adsorption term was obtained from the test house by taking the average value of adsorption terms of indirect smoke (exhaled by a smoker) and direct smoke (lightning the cigarette) for sample locations 1, 4, 5, and 6. As a result, adsorption term in test house was calculated by using the average emission rate from test chamber ($R_o = 29.85$ μg/m^3 min and $k_s = 0.031$ min^{-1}) for high $PM_{2.5}$ concentration in locations 1, 4, 5, and 6 that is shown in Table 2. It is found that 4.47 m/min of cigarette smoke dust was adsorbed in furniture and carpets that

Table 2 Adsorption term in the test house

Sampling locations	K_a value (m/min)	NSME
Indirect smoke—sample location 3	5.47	0.338
Direct smoke—sample location 1	4.14	0.219
Direct smoke—sample location 4	2.72	0.056
Direct smoke—sample location 5	4.183	0.267
Direct smoke—sample location 6	5.83	0.353
Average value	4.47	–

later can be a source emission when the driving forces changes which demonstrate the THS phenomenon. $PM_{2.5}$ is transported via convection and molecular diffusion processes from the bulk air phase to locations of building materials such as carpets and furniture with the rate of HVAC system.

Computational model

The numerical solutions of the flow field and the distribution of concentration of smoke are analyzed in this section. The present study analyzed the characteristic of SHS emission source flow field in computational domain during isothermal condition to understand the indoor air quality of test house which helps better understanding of the effect of HVAC system on SHS. Two-dimensional simulation of $PM_{2.5}$ flow which is emitted from a cigarette located in sample location 3 without using air purifier in a room of the test house was modeled using $K - \varepsilon$ turbulence model. There are several factors that affect the overall intensity of pollutant diffusion through the room such as inlet air flow from ducts, room geometry, number of ducts and their locations, number and location of exhausts in the room, containment source $PM_{2.5}$ location, building objects like furniture and wall and ceiling surface condition, and temperature.

Flow field

The mean velocity contour of the cigarette emission in test house that consists of the two components velocity is shown in Fig. 7a. According to flow characteristics, duct 1 and 2 show the maximum velocity flow in the room which is obvious in the green boundary layer in the middle area of the room near the two ducts. Furthermore, a thick boundary layer can be seen near window and floor due to increase in turbulence velocity. On the other hand, the low mean velocity is shown near the two exhausts due to its low momentum which helps in picking up partial of the air flow with its containment of SHS.

Figure 7b represents the mean velocity vectors profile showing the eddy vortex in different parts of the room. The converged solution evolves the correct direction of velocity vectors as achieved in test house experiment. A large circulation of eddy vortex is produced near the window area due to the slight increase in flow velocity. From the plotted figure, the air enters the room through inlet air ducts with high velocity. The high velocity is achieved also near/under the table due to high velocity turbulence that trapped the flow in the mentioned area. A small vortex is achieved near the corners because the air exits through the two exhausts upward with lower velocity and the flow is hitting the obstacle such as walls. Figure 7c shows the air path line for the ventilation system in the room. The flow is entered from ducts (point 1) hitting the wall (point 2) then the table (point 3). After that, the velocity is reduced when hitting the floor (point 4) and then sucked up to the exhaust (point 5). Figure 8a illustrates the proportional relation between the turbulent intensity and velocity. If the flow velocity is more, more turbulent intensity occurs, which is shown near the two air ducts. However, when the velocity hits the obstacles such as wall, the velocity is reduced, which causes reduction in turbulent intensity. The turbulent kinetic energy is related to the mean velocity, which means that the increase in the mean velocity causes increase in turbulent kinetic energy which is shown in Fig. 8b.

Smoke diffusion

The simulation predicts the concentration diffusion when using the emission source of the cigarette that is obtained from the experimental part of the test chamber. According to the diffusion characteristics, Fig. 8c illustrates the higher concentration values in middle of the room toward the door and duct 1 due to increase in source emission velocity. This higher concentration occurs because it is close to source and because of the bouncy force which has effect on the mean velocity. Lower concentrations are observed at two ducts and exhaust 1 due to existence of obstacles which is the inlet air that comes from ducts and the far distance from the emission source to the ducts. However, the two exhausts are taking partial smoke flow which proves the experimental work of the test house.

The previous results of numerical simulation were consistently in line with the test house experiment. This study demonstrates unacceptably high levels of $PM_{2.5}$ exposure associated with SHS in the test house. $PM_{2.5}$ contaminate produced in a ventilated room from smoking activity can quickly spread over the whole zone. The ventilation system is not the solution to reduce secondhand smoke which is concluded from the experimental work and the simulation. These results are consistent with those found in the previous studies (Repace and Johnson 2006; ASHRAE 2005; WHO 2007). Furthermore, SHS can seep under doors thru ventilation ducts through electrical wall

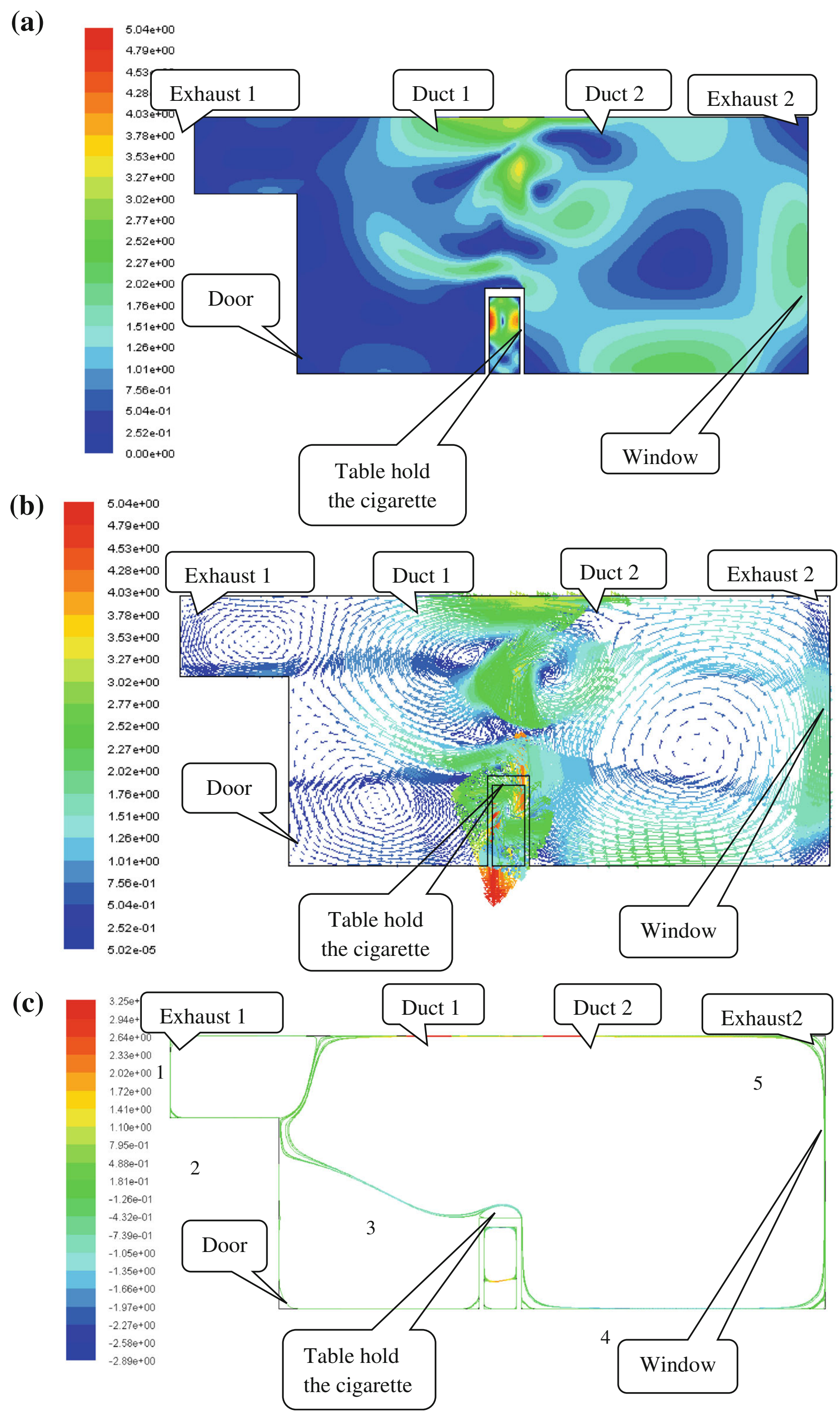
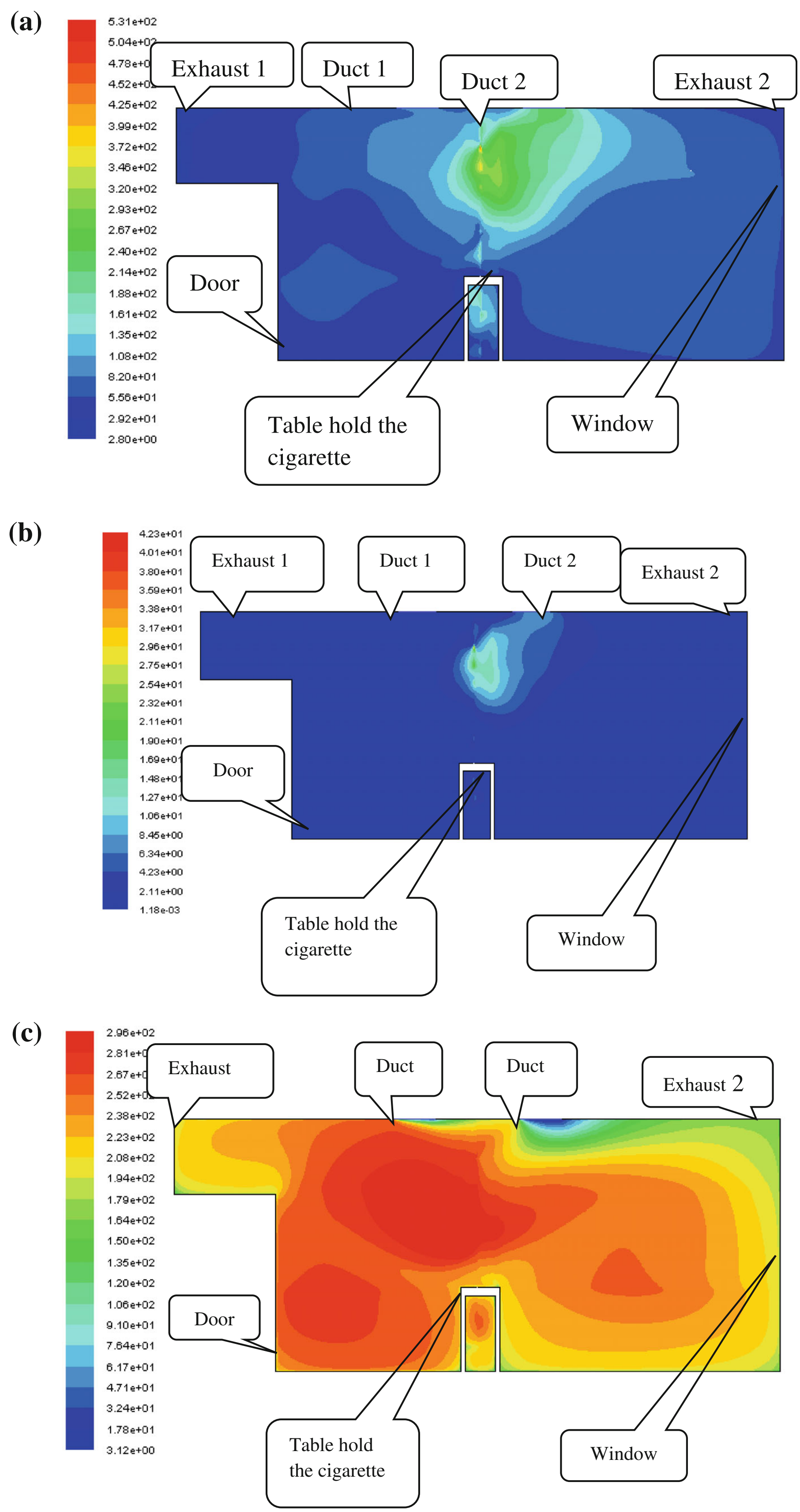


Fig. 7 **a** Contours, **b** vectors, and **c** path lines of mean velocity of cigarette emission

sockets and light fixtures which can stay in air for hours. The American Society for heating refrigerating and air conditioning engineers is not recommending a ventilation standard or air purifier for removing secondhand smoke since they have studied drifting secondhand smoke for years (ASHARE 2005). Ventilation cannot remove smoke from air. It may remove smell of smoke but not the dangers of SHS.

Fig. 8 Contours of **a** turbulent intensity, **b** kinetic energy *K*, **c** cigarette smoke in the test house



Conclusion

Since indoor air quality is important worldwide, SHS has been the most extensively studied pollutant among previous years. SHS is a major source of exposure to indoor air pollution that is based on the average particulate matter $PM_{2.5}$ concentrations. This paper studies SHS levels of $PM_{2.5}$ in test house experiment in order to construct a mass balance model which evaluates and models pollutant levels using CFD. The simulated results are consistently in line with experimental part. The general conclusions from this study are as follows:

a. Test house experiment

Ventilation system and air purifiers are not effective solutions to Secondhand smoke seepage through building or venue. Average $PM_{2.5}$ concentration is higher when including human puffs rather than burning the cigarette. The amount of $PM_{2.5}$ adsorbed on carpets and furniture is 4.47 m/min which later can be source emission of cigarette smoke.

b. Computational model

This study investigated two-dimensional characteristics of $PM_{2.5}$ smoke distribution in computational domain of the test house which demonstrated the unacceptably high levels of $PM_{2.5}$ exposure associated with SHS in the test house. The CFD model successfully predicted the experimental data. Maximum velocity flow is shown in the middle area of the room near the two ducts. A thick boundary layer can be seen near the window and floor; however, low mean velocity is shown near the two exhausts. The mean velocity vectors profile that shows eddy vortex is analyzed in different parts of the room. A large circulation of eddy vortex is produced near the window area. The high velocity is achieved near/under the table and near the two ducts; however, a small vortex is shown near the corners. The high turbulent intensity along with high flow velocity occurs near the two air ducts. The higher concentration values are shown in the middle of the room toward the door and duct 1; however, lower concentrations are observed at two ducts and exhaust 1. The ventilation system is not the solution to reduce secondhand smoke which is concluded from the experimental work and the simulation.

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Nomenclature

CFD	Computational fluid dynamics
HVAC	Heating, ventilation and air conditioning
HPSH	Harvard School of Public Health
IAQ	Indoor air quality
$\mu g/m^3$	Micrograms per cubic meter
mg/m^3	Milligrams per cubic meter
NMSE	Normalized mean square error
$PM_{2.5}$	Particulate matter of diameter of 2.5 micro meters or less in size
RANS	Reynolds averaged Navier–Stokes equations
SHS	Secondhand smoking
SOP	Standard operating procedure
THS	Thirdhand smoke
TKE	Turbulent kinetic energy
ε	Dispassition of turbulent kinetic energy

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