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Indoor air quality and ventilation requirement in residential buildings: A case study of Tehran, Iran

Abtin Ataei [*1,2], Ali Nowrouzi [1] and Jun-Ki Choi [2]

[1] *Department of Energy Engineering, Graduate School of the Environment and Energy, Science and Research Branch, Islamic Azad University, Tehran, Iran*
[2] *Department of Mechanical and Aerospace Engineering, University of Dayton, Dayton, Ohio, USA*

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Abstract. The ventilation system is a key device to ensure both healthful indoor air quality (IAQ) and thermal comfort in buildings. The ventilation system should make the IAQ meet the standards such as ASHRAE 62. This study deals with a new approach to modeling the ventilation and IAQ requirement in residential buildings. In that approach, Elite software is used to calculate the air supply volume, and CONTAM model as a multi-zone and contaminant dispersal model is employed to estimate the contaminants' concentrations. Amongst various contaminants existing in the residential buildings, two main contaminates of carbon dioxide (CO_2) and carbon monoxide (CO) were considered. CO and CO_2 are generated mainly from combustion sources such as gas cooking and heating oven. In addition to the mentioned sources, CO_2 is generated from occupants' respirations. To show how that approach works, a sample house with the area of 80 m^2 located in Tehran was considered as an illustrative case study. The results showed that CO_2 concentration in the winter was higher than the acceptable level. Therefore, the air change rate (ACH) of 4.2 was required to lower the CO_2 concentration below the air quality threshold in the living room, and in the bedrooms, the rate of ventilation volume should be 11.2 ACH.

Keywords: indoor air quality; ventilation; contaminants; modeling; ASHRAE 62

1. Introduction

There has been increasing concerns about indoor air quality (IAQ) in residential buildings mainly because of its influence on occupant's health. This has led to several conducting researches to address the problems arising from poor indoor air quality (Langer and Beko 2013, St-Jean *et al*. 2012). This would be noticeable where residential building hasn't equipped with ventilation system or with poorly designed one. IAQ relates indoor pollutant concentrations to various influencing factors, i.e., building geometry, ventilation system, sources and sinks of contaminants, air flow characteristics including wind air pressure coefficient, leakage of envelope elements, and schedules for openings of building elements (doors and windows) (Frontczak *et al*. 2011, Pepper and Carrington 2009, Trading Standards Institute 2013). Contaminants dispersal analyses require

*Corresponding author, Professor, E-mail: abtinataei@gmail.com

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contaminant source information, filter efficiencies, reaction and deposition rates, and schedules for elements such as sources, and indoor-outdoor air exchange rate (Kim *et al*. 2011, Joo *et al*. 2012, Zheng *et al*. 2011). There are variety of pollutants sources in residential buildings dispersing VOC, CO_2 to particle and even water vapor (Bortoli and Colombo 1992, Colome *et al*. 1994, Xiong *et al*. 2015). Beside the pollutants emitted from burning sources such as cooking and heating oven which is the main source of contaminants, activity of occupants which disperse CO_2, vapors from cooking activities, and product such as carpet are also the sources of pollutants (Xiong *et al*. 2015).

Ventilation system as part of air handling system is designed to achieve thermal comfort in building's space and to provide occupants with outdoor air fresh (Rackes and Waring 2014). Previously, HVAC systems have designed to provide outdoor air for ventilation to maintain thermal comfort in proportion to heating and cooling load. However, today's IAQ has become a key parameter to design ventilation (Frontczak *et al*. 2011). In fact, in addition to thermal comfort, ventilation is also required to control indoor contaminants (Chithra and Shiva Nagendra 2012). In addition to active ventilation in which the amount of outdoor provided the space with fresh air is controlled mechanically, natural ventilation should be considered to evaluate IAQ. This also would be useful in terms of low-energy consumption (Dutton *et al*. 2015). Therefore, ventilation needs may not coincide with thermal loads especially in the case of variation of pollutants sources (Hekmat *et al*. 1986). The volume of outdoor air flow is considered during ventilation designee in quantity that satisfies ASHRAE 62 (2001). On the other hand, when comes to energy consumption, low-energy consumption is a key factor showing high performance of a building. Energy consumption due to ventilation needs is increasingly becoming a high percentage of total space conditioning energy consumption. Achieving better performing ventilation systems requires steps in the effort to reduce energy consumption without compromising indoor air quality. Therefore, a deliberate ventilation design would be supposed in order to achieve both efficient energy consumption and proper indoor air quality.

There is considerable research worldwide on the importance of good quality ventilation, the impact of poor IAQ and designing the ventilation systems to keep IAQ below the maximum levels suggested by several standards such as ASHREA 62 (2001) (Kim *et al*. 2011, Zheng *et al*. 2011, Joo *et al*. 2012, Langer and Beko 2013, St-Jean *et al*. 2012, Frontczak *et al*. 2011, Chithra and Shiva Nagendra 2012). Most of those studies were based on experimental approaches and on-site measurements for existing buildings. However, a systematic approach based on well established models is required to estimate the ventilation and IAQ requirement for new residential building plans.

In this paper, a new method to calculate the ventilation and IAQ requirement in residential buildings was suggested based on Elite software and CONTAM model. In that method, Elite software is used to calculate the air supply volume and CONTAM model is used to estimate contaminants' concentration. The suggested approach was applied for a 80 m^2 home located in Tehran, Iran as an illustrative example. According to Iranian fuel conservation company (IFCO) (2008), In Iran, there are variety types of buildings in terms of building geometry, ventilation system and especially sources of pollutants which have a bearing on IAQ. Therefore to consider the majority of buildings, this paper assumes a specific HVAC system and a building layout which are more prevalent in the residential buildings. Amongst various contaminants existing in the residential buildings, two main contaminates of carbon dioxide (CO_2) and carbon monoxide (CO) were considered as the main indoor pollutants in the residential sector of Iran for the illustrative example.

2. Materials and methods

To date, researches and studies carried out to model IAQ have been employed variety approaches utilizing various models. Though, CFD as a comprehensive models technique that provides a more detailed figure of the airflow, temperature, and contaminants using many nodes per zone, there are models and approaches generally called “multi-zone modeling” which treated each zone as a node (Gilham *et al*. 2000). CFD analysis tools solve the system of mass, energy, and momentum conservation equations known as the Navier-Stokes equations to determine the air velocity, temperature and contaminant concentration at each of these nodes. While, multi-zone technique solves mass balance equations in each zone. Thus, in contrary with CFD model, multi-zone technique become more favor in terms of economical and flexibility when geography of a building become more complex or various system are designed in the building such as passive or active ventilation system (Emmerich 1997, Walton 1989). To simulate IAQ this study employs a multi-zone and contaminant dispersal model CONTAM version 3.1. CONTAM 3.1 is the latest version which is also used a ventilation analysis computer program developed by the Building and Fire Research Laboratory of the National Institute of Standards and Technology (NIST) - U.S. Department of Commerce. This model provide the user with a graphical user interface to create details of a building’s plan such as air handling system, windows, doors as air flow paths and geometry such as walls and floors implementing a Sketchpad by user to draw the mentioned features (Walton 1989). Each building’s room represents single zone having uniform temperature, humidity and concentration. Rooms are connected to one another and outdoor via air flow path such as doors and windows. Then the user can design air handling system and can determine the characteristics of contaminates. The mass flow is the function of pressure difference between zones ($\Delta P_{j,i} = P_j - P_i$). Using Bernolli equation, pressure difference is computed according the static pressure of each side of air flow path, pressure created due to density and height difference and pressure differences because of wind pressure bearing on building’s sides. In addition to pressure difference equations, mass conservation is used for all zones then the model solved the nonlinear equations by Newton-Raphson method for all zones.

Pressure differences created by wind on the envelope of a building, CONTAM uses pressure coefficient (C_p) which is relate to wind pressure on the wall (P_w) according to Eq. (1);

$$P_w = C_P \times \rho \times V^2/2 \tag{1}$$

Where V is wind velocity, and ρ is the air density.

When entering data for exterior air flow path, CONTAM 3.1 requests for pressure coefficient. Most reliable way to determine C_p is trough on-site measurement or wind tunnel studies. However, the ASHRAE handbook (1997) offers a specific correlation for low-rise, rectangular buildings that was developed by Swami and Chandra (1988). This correlation achieved based on a numerical study, relates C_p to the direction of wind normal to the exterior wall as Eq. (2)

$$\begin{aligned} C_p = C_{P_O} \ln(1.248 - 0.703\sin\left(\frac{\alpha}{2}\right) - 1.175\sin^2(\alpha) - 0.131\sin^3(2\alpha G) \\ +0.769\cos\left(\frac{\alpha}{2}\right) + 0.07G^2\sin^2\left(\frac{\alpha}{2}\right) + 0.717\cos^2\left(\frac{\alpha}{2}\right)) \end{aligned} \tag{2}$$

Where α is the wind direction degree normal to the wall, C_{p0} is the pressure coefficient with (α = 0) which is obtained from ASHRAE handbook (1997) and equated to 0.6, and G is the natural log of the ratio of the length of the wall to the length of the adjacent wall.

To calculate the air flow mass due to pressure difference through an opening element or such as door or window as well as leakage, CONTAM 3.1 uses effective leakage area (ELA) parameter defined as Eq. (3)

$$Q(\Delta P) = C_D \times A \times \Delta P\sqrt{2}/\rho \tag{3}$$

Where Q is the airflow rate through the orifice, C_D is discharge coefficient, A is the cross-sectional area of opening element, and Δp is the pressure difference. Assuming $\Delta p = 4$ and $C_D = 1$, as well as parameter n which is used to calculate actual air flow rate and equated to 0.65 according to ASHRAE (1997), the air flow rate is calculate by the software.

After solving all equations leading to mass flow rate of each zone, the amount of contaminants are evaluated based on Eqs. (4)-(5)

$$m_i^\alpha = m_i \times C_i^\alpha \tag{4}$$

Where m_i^α is contaminant mass, m_i is mass flow rate of zone i, and C_i^α is pollutants concentration of contaminant α.

$$\frac{dm_i^\propto}{dt} = -R_i^\alpha \times C_i^\alpha - F_{ij} \times C_i^\alpha + F_{ij}\left(1 - \eta_{ij}^\alpha\right) \times C_i^\alpha + m_i \times \kappa^{\alpha,\beta} \times C_i^\beta + G_i^\alpha \tag{5}$$

Where R_i^α is the removal rate of contaminant α, $F_{i,j}$ the rate of air follow from zone i to zone j, η_{ij}^α is the filter efficiency which removes contaminant α via filter placing within path of zone i to zone j, $\kappa^{\alpha,\beta}$ is the kinetic reaction coefficient in zone i between species α and β, and G_i^α is the rate of pollutant α generated by the source located in zone i (Axley 1988).

3. Case study and simulation

To perform current study, a sample house with the area of around 80 m^2 located in Tehran is chosen. We neglect the city with humid and hot weather conditions firstly due to avoid the complexity in the study and secondly indoor air quality during the cold season have become crucial problem in Iran due to lack of suitable ventilation system and traditional heating system as sources of contaminants.

To cover various HVAC system used in residential building, this paper considers two main systems employed in the mentioned cities including; in-house heater and ducted natural vapor cooling, and central heat-water boiler and ducted cooling system.

The house involved in this study is intended to be representative of residential construction in Iran. According to floor plan of the house depicted in Fig. 1, the living area consists of two bedrooms, a kitchen, living room, and two bathrooms. To perform modeling, six zones are identified, as represented within CONTAM 3.1.

3.1. Air flow and leakage model

After drawing rooms through SketchPad, next step is to identify the air flow characteristics by defining the air flow path. While putting building air path elements such as doors, windows, air vent, and so on, the user is considered to enter air flow characteristics to let the software to calculate air flow mass. As described above, the air path should consider the effective leakage area (ELA). ELA is the area of an orifice with a discharge coefficient of 1.0 would result in the same flow rate across an opening at the difference pressure of 4 Pa (Uhde and Salthammer 2007).

To estimate infiltration and ex-filtration, this paper considers the leakage from exterior walls described as ELA at 4 Pa with which is expressed as ELA per unit of wall area or per unit interference length. To identify the value of ELA, the paper uses data based on the ASHRAE Fundamental Handbooks (1997), Table 3 of chapter 25. Unless, the air flow paths are described in terms of ELA at 4 Pa employing an exponent of 0.65. Table1 lists the values of ELA for corresponding air flow paths modeled in CONTAM 3.1.

In addition to air flow elements, vents are paced at an elevation of 2 m in kitchen and bathrooms and modeled with an effective area of 4 cm^2 at 4 Pa.

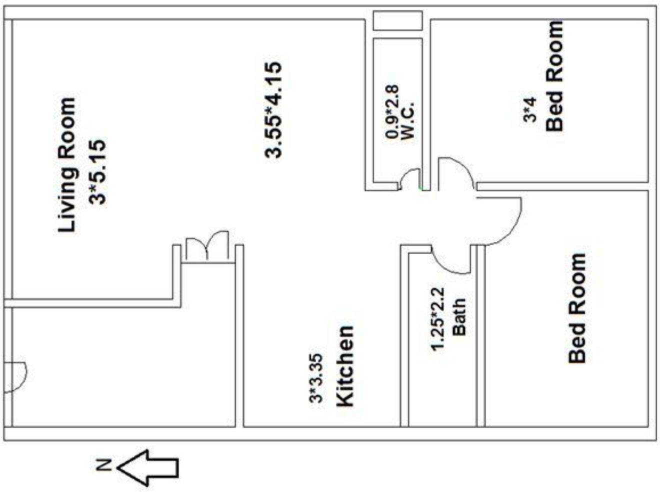

Fig. 1 Floor plan of house

Table 1 The leakage values of the air flow paths in term of ELA in the model

Interior air flow path	**ELA**
Opening elements(doors and windows)	Orifice with a discharge coefficient of 1.0 at 4 Pa.
Envelope leakage	**ELA**
Door frame	1.7 cm^2 per m^2
Exterior wall	1.4 cm^2 per m^2
Window frame	1.1 cm^2 per m^2
Window (Living room)	2.7 cm^2
Window (Bedrooms)	2.1 cm^2
Exterior Door	4.0 cm^2
Fire place	6.0 cm^2
Electrical and Switches	0.5 per item
Vents (Kitchen and bathrooms)	6 cm^2 at 4 Pa
Duct penetration in rooms	6.0 cm^2 per item

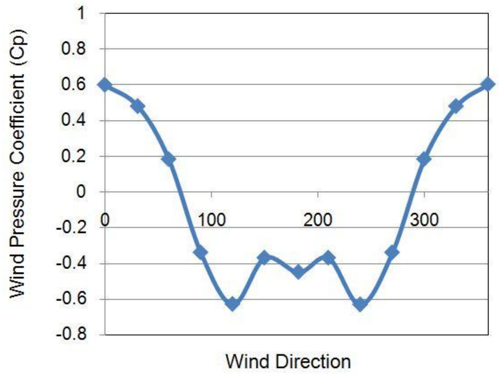

Fig. 2 Profile of wind pressure coefficient

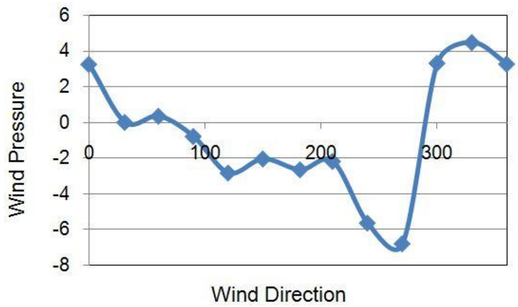

Fig. 3 Wind pressure due to wind on the building's envelope in Tehran

The model uses C_P parameter to correlate the air flow rate to take the wind pressure into consideration. To do so, firstly the weather data of two cities was converted to appropriate format to employ in the software. Then, according to different wind direction and the corresponding wind speed, C_p coefficient and wind pressure (P_w) was calculated and depicted in Figs. 2 and 3 for the mentioned cities

3.2. Ventilation system

The building has a forced cooling system in each scenarios and local exhaust system in the kitchen area and bathrooms. The ductwork supplies the building with fresh air and modeled by the software using air handling module. This modeling requires the user to input the length of ductwork, junctions, and terminals with each considering the friction losses and leakages.

To consider the cooling and heating load, we employ Elite model in evaluating the air flow volume required to satisfy the comfort conditions. Rhvac version 8.01 is software of Elite software family which calculates cooling and heating load for residential buildings accenting for building geometry, HVAC system and weather conditions based on the 8th edition of Manual J. Rhavc software has the capability to calculate the volume of air flow using ductwork module to model air ventilation system. In fact, by employing Elite software we would consider cooling and heating load into indoor air quality studies. Table 2 shows heating and cooling load as well as air supply calculated by Rhvac for each room in the building.

Table 2 Heating and cooling load and air supply design for each room modeled by Elite

Room name	Heating load (Btu/h)	Cooling load (Btu/h)	Air supply (CFM)
Bedroom1	7690	7511	366
Bedroom2	8343	8112	397
Living room	19380	22282	988
Kitchen	2777	4479	207
Bath1	614	707	35
Barth2	909	1050	52

Table 3 The rates of contaminants emitted from sources

Contaminants	Sources	Rate (mg/s)
CO	Gas cooking	0.11
	Each heating oven	0.07
CO_2	Gas cooking	780
	Each heating oven	520
	Occupants' respiration	8.5 for awake time 5.6 for asleep time

Once the air ventilation volume is calculated, data is entered to perform the air handling molding of CONTAM3.1software to consider the ventilation in IAQ assessments.

4. Contaminants' characteristics

Amongst various contaminants existing in the residential buildings, two contaminates were considered including; carbon dioxide (CO_2) and carbon monoxide (CO). CO, and CO_2 are generated mainly from burning sources such as gas cooking and heating oven. In addition to the mentioned sources, CO_2 is generated from occupants' respirations (Muller 1989). According to recent studies, the rates of contaminants emitted from sources are described as Table 3.

At first scenario, to consider the rate of contaminants' generation, we suppose 3 people accommodated in the building and the building is supposed to be equipped with three heating ovens located in bedrooms and the living room. Also, a cooking oven serving three occupants is located in the kitchen area having the rate of gas consumption of 1.5 m^3 per hour, according to IFCO (2008).

5. Results

After entering wind data and leakage characteristics of building envelope, the software calculate the infiltration rate of the building. The average infiltration of the building determined to be 21 cfm equal's 0.16 ACH. Infiltration, as mentioned before, is influenced by wind pressure and temperature differences. Fig. 4 shows the leakage flow rate of living room window as an example.

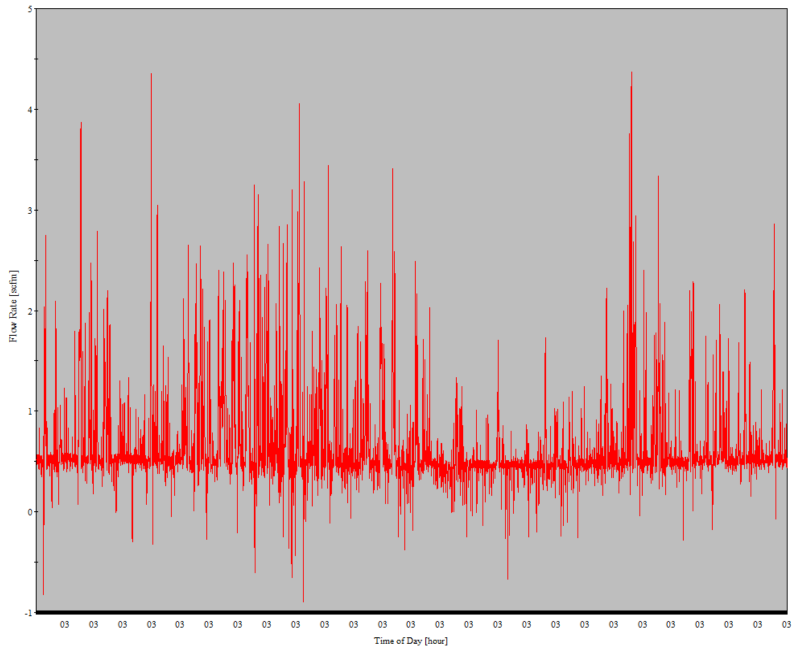

Fig. 4 Variation of infiltration flow rate caused by the living room's window leakage

Fig. 5 CO_2 concentration during day in the living room and bedrooms in winter season

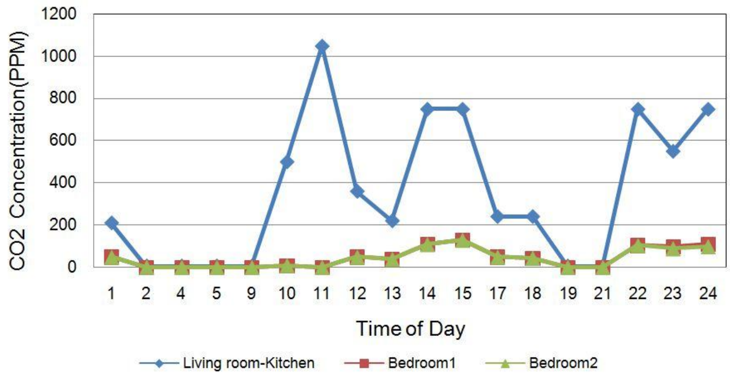

Fig. 6 CO_2 concentration during day in the living room and bedrooms at summer and spring

In accordance with ASHRAE 62 (2001), the volume of air ventilation rate should satisfy the criteria of ASHRAE 62 (2001) which is equated with 119 cfm. Therefore, in designing the ventilation system we employ this standard as input data. After entering ventilation and contaminant data, CONTAM software results show the concentration of CO_2 in each zone as Fig. 3.

The results show that CO_2 concentration in winter except during the day time when the rate of heating load declines, is higher than the threshold level (1000 ppm), suggested by NIOSH (1987) though, according to Fig. 6 during the spring and summer CO_2 concentration would satisfy the thershold. So, during the cold seasons the criteria of ASRAE 62 cannot meet the air quality requirement. To consider the threshold, we changed the outdoor ventilation so that the amount of CO_2 concentration declines below the threshold level. After adjusting the volume of ventilation, the result shows that the rate of 4.2 ACH is required to lower CO_2 concentrations below the air quality threshold in the living room. While, contaminant concentration is still higher in the bedrooms. Indeed, to meet the air quality standard in the bedrooms, the rate of ventilation volume should be around 11.2 ACH.

This rate of ventilation will increase energy consumption due to heat loss. The efficient way to reach the air quality standard is employing air handling systems using appropriate filters to remove CO_2.

On the other hand, CO concentration will satisfy the air quality standards at any time. Maximum CO concentration is under 1.2 ppm, below the value of 35 ppm suggested by NIOSH.

6. Conclusions

The IAQ relates indoor pollutant concentrations to various influencing factors, i.e. building geometry, ventilation system, sources and sinks of contaminants, air flow characteristics including wind air pressure coefficient, leakage of envelope elements, and schedules for openings of building elements. The ventilation and IAQ are closely linked. An inadequate ventilation might be a common problem in the residential buildings in Iran.

There is considerable research worldwide on the importance of good quality ventilation, the impact of poor IAQ and designing the ventilation systems to keep IAQ below the maximum levels suggested by several standards such as ASHREA 62.

In this paper, a new method to calculate the ventilation and IAQ requirement in residential buildings was suggested based on Elite software and CONTAM model. In that method, Elite software is used to calculate the air supply volume and CONTAM model is used to estimate contaminants' concentration. The suggested approach was applied in a 80 m^2 residential building located in Tehran, Iran as an illustrative example considering carbon dioxide and carbon monoxide as the main indoor pollutants. CO and CO_2 are generated mainly from combustion sources such as gas cooking and heating oven. In addition to the mentioned sources, CO_2 is generated from occupants' respirations.

The results showed that the CO_2 concentration in the winter is higher than the threshold level. We would suggest that the rate of 4.2 ACH is required to keep the CO_2 concentrations below the air quality threshold in the living room, and in the bedrooms, the rate of ventilation volume should be around 11.2 ACH.

If the quality of indoor air is compromised by pollutants, ventilation may alleviate the situation but may not cure it. Elimination of pollutants at their source is the most effective way to improve the IAQ in residential buildings.

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References

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (1997), ASHRAE Handbook, Atlanta, GA. USA.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (2001), ANSI/ASHRAE Standard 62-2001, Ventilation for Acceptable Indoor Air Quality.

Axley, J. (1988), *Progress Toward A General Analytical Method for Predicting Indoor Air Pollution in Buildings*, Indoor Air Quality Modeling Phase III Report, NBSIR 88-3814; National Institute of Standards and Technology.

Bortoli, M.D. and Colombo, A. (1992), Characterization of Organic Emissions from Indoor Sources.(1992), pp 49-58.

Chithra, V.S. and Shiva Nagendra, S.M. (2012), "Indoor air quality investigations in a naturally ventilated school building located close to an urban roadway in Chennai, India", *Building Environ*., **54**, 159-167.

Colome, S., Wilson, A.L. and Tian, Y. (1994), *Carbon Monoxide and Air Exchange Rate*: *A Univariate & Multivariate Analysis*, California Residential Indoor Air Quality Study; Volume 2, CA, USA.

Dutton, S.M., Mendell, M.J., Chan, W.R., Barrios, M., Sidheswaran, M.A., Sullivan, D.P., Eliseeva, E.A. and Fisk, W.J. (2015), "Evaluation of the indoor air quality minimum ventilation rate procedure for use in California retail buildings", *Indoor Air*, **25**(1), 93-104.

Energy Saving and Environmental Study in Household Sector, Iranian fuel conservation company (IFCO) (2008), Tehran, Iran.

Emmerich, S.J. (1997), Use of Computational Fluid Dynamics to Analyze Indoor Air Quality Issues, NISTIR 5997; National Institute of Standards and Technology.

Frontczak, M., Schiavon, S., Goins, J., Arens, E., Zhang, H. and Wargocki, P. (2011), "Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design", *Indoor Air*, **22**(2), 119-131.

Gilham, S., Deaves, D.M. and Woodburn, P. (2000), "Mitigation of dense gas releases within buildings: validation of CFD modelling", *J. Hazard. Mater*., **71**, 193-218.

Hekmat D., Feustel, H.E. and Modera, M.P. (1986), "Impact of ventilation strategies on energy consumption and indoor air quality in single-family residences", *Eng. Buildings*, **9**(3), 239-251.

Joo, J., Zheng, Q., Lee, G., Kim, J.T. and Kim, S. (2012), "Optimum energy use to satisfy indoor air quality needs", *Eng. Buildings*, **46**, 62-67.

Kim, M.J., Kim, Y.S., Ataei, A., Kim, J.T., Lim, J.J. and Yoo, C.K. (2011), "Statistical evaluation of indoor air quality changes after installation of the PSD system in Seoul's metro", *Indoor Built. Environ*., **20**(1), 187-197.

Langer, S. and Beko, G. (2013), "Indoor air quality in the Swedish housing stock and its dependence on building characteristics", *Building Environ*., **69**, 44-54.

Mueller, E.A. (1989), *Indoor Air Quality Environmental Information Handbook*, Combustion Sources; U.S. Department of Energy Washington D.C., USA.

National Institute for Occupational Safety and Health (NIOSH), (1987), Guidance for Indoor Air Quality Investigations; Cincinnati, OH, USA.

Pepper, D.W. and Carrington, D. (2009), *Modeling Indoor Air Pollution*, Imperial College Press, UK.

Rackes, A. and Waring, M.S. (2014), "Using multiobjective optimizations to discover dynamic building ventilation strategies that can improve indoor air quality and reduce energy use", *Eng. Buildings*, **75**, 272-280.

St-Jean, M., St-Amand, A., Gilbert, N.L., Soto, J.C., Guay, M., Davis, K. and Gyorkos, T.W. (2012), "Indoor air quality in Montréal area day-care centres, Canada", *Environ. Res.*, **118**, 1-7.

Swami, M.V. and Chandra, S. (1988), "Correlations for pressure distributions on buildings and calculation of natural-ventilation airflow", *ASHRAE Trans.*, **94**(1), 243-266.

Trading Standards Institute (TSI) (2013), Indoor Air Quality Handbook: A Practical Guide to Indoor Air Quality Investigations; TSI Incorporated, USA.

Uhde, E. and Salthammer, T. (2007), "Impact of reaction products from building materials and furnishings on indoor air quality—A review of recent advances in indoor chemistry", *Atmos. Environ.*, **41**(15), 3111-3128.

Walton, G.N. (1989), *AIRNET - A Computer Program for Building Airflow Network Modeling*, NISTIR 89-4072; National Institute of Standards and Technology.

Xiong, Y., Krogmann, U., Mainelis, G., Rodenburg, L.A. and Andrews, C.J. (2015), "Indoor air quality in green buildings: A case-study in a residential high-rise building in the northeastern United States", *J. Environ. Sci. Health. Tox. Hazard. Subst. Environ. Eng.*, **50**(3), 225-242.

Zheng, Q., Lee, D., Lee, S., Kim, J.T. and Kim, S. (2011), "A health performance evaluation model of apartment building indoor air quality", *Indoor Built. Environ.*, **20**(1), 26-35.

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