Implications of natural and mechanical ventilation on exposure to dust at the housing scale: a case study in Tucson, Arizona, US

Implicaciones de la ventilación natural y mecánica en la exposición al polvo en vivienda: caso de estudio en Tucson, Arizona, EE.UU.

DOI: https://doi.org/10.32870/rvcs.v0i7.136

SANDRA BERNAL
https://orcid.org/0000-0002-3235-2014 / sbernal@email.arizona.edu

ALTAF ENGINEER
https://orcid.org/0000-0001-7257-188X / aengineer@email.arizona.edu

NADER CHALFOUN
chalfoun@email.arizona.edu

University of Arizona, Estados Unidos

RESUMEN

De entre las alternativas para proporcionar una adecuada calidad ambiental interior en las viviendas del noroeste de México y suroeste de los Estados Unidos, los sistemas de ventilación mecánica son la fuente más utilizada para proveer aire fresco y control de temperatura. La innovación tecnológica en los sistemas de ventilación a menudo nos conduce a la disminución en el uso de la ventilación natural, aunque, durante selectos días del año, la libre circulación del flujo de aire puede contribuir a la salud humana y la conservación de la energía. Para este estudio se realizó una evaluación de riesgos sanitarios a un estudio de caso donde se comparan los tres sistemas regulación de temperatura por su función como suministro de aire: ventilación natural, refrigeración evaporativa y aire acondicionado, para con ello observar y medir acumulaciones de polvo y variación de temperatura en una vivienda unifamiliar ubicada en Tucson, Arizona.

Este estudio tiene como objetivo entender si la cantidad y la ubicación de las acumulaciones de polvo en una casa están correlacionadas con el tipo de ventilación. En segundo término, este estudio prueba cómo la exposición al polvo es diferente en dependencia de la ubicación de la acumulación dentro de la casa. Por último, se reflexiona acerca de las lecturas de temperatura y su relación con la eficacia de los tipos de sistemas de ventilación para mitigar la acumulación de polvo.

Palabras clave: ventilación natural, ventilación mecánica, polvo, exposición, vivienda.

ABSTRACT

From all the alternatives to provide a better indoor environmental quality in the residential sector in Northwest Mexico and Southwest U.S.; mechanical ventilation systems are the most commonly used source of air exchange and temperature control. Innovation in the technology of ventilation systems often leads to declining use of natural ventilation, although, during selected days of the year, the free movement of airflow can contribute to human health and energy conservation. This study applies a hazard assessment process to a case study, and compares the three most common systems of temperature control and air supply: natural ventilation, evaporative cooling, and air conditioning; to observe and measure accumulations of dust and temperature variation in a single-family household in Midtown Tucson, Arizona.

Firstly, this study aims to understand whether the amount and location of dust accumulations throughout a house is correlated to the type of natural ventilation and mechanical systems in operation at that time. Secondly, this study tests how human exposure to dust is different depending on the location of the accumulation within the house. Finally, temperature measurements are discussed to reflect upon the effectiveness of different types of ventilation systems in operation, to mitigate dust accumulation.

Keywords: natural-ventilation, mechanical-ventilation, dust, exposure, housing.

INTRODUCTION

Excessive and long-lasting exposure to high temperatures can result in dehydration and other health effects (Popkin *et al.*, 2010). It is important to consider that houses that do not have adequate cooling systems can accumulate heat and become hotter than outdoors, having severe and even deadly consequences in vulnerable people (ASHRAE, 2007). Under extreme temperature, health and comfort concerns, humans have historically adapted residential buildings. One of the most populated and heat-stressed regions, the Sonoran Desert's unique characteristics include dust, allergens, and wildfires along with water scarcity and heat (Peter, 2018). Technological advances in indoor comfort, among other demands of modern life, make possible for people spend up to 90% of their time indoors (UA EPA 2015). EPA,[1] however, reports that the levels of pollutants indoors may be now 2-5 times greater than outdoors. We now face the consequences of our reliance on conditioned spaces which contradict the main goals of a home, that include providing shelter, comfort, and keeping us healthy.

This topic has recently created awareness in government and social agencies such as EPA and SERI[2] since low income households in the U.S. have a history of experiencing the impacts of crowded spaces, mold, lack of ventilation, heavy use of cleaning products, paint with lead and isolation based on asbestos (Atkinson *et al.*, 2009; Escobedo *et al.*, 2014; US EPA, 2015.). Ventilation systems, therefore, are, or should be, a central part of the decision-making process of architectural design, especially since mechanical ventilation systems have now become the norm. The more the systems are seen only as accessories to the overall design, the more the negative effects, including higher energy consumption, human discomfort, and illnesses, could potentially arise. One of the many undesirable consequences of the lack of healthy air and temperature is the Sick Building Syndrome, which can be experienced across different income levels, building sizes, and types of spaces (Joshi, 2008). Exposure to toxicity in sick buildings is an important concern. Mold, dust, soot, smoke, fumes, impact human health as well as increase medical and living expenses of household members (Escobedo *et al.*, 2014).

Although public policy and guidelines in the United States such as the Clean Air Act and its section for National Ambient Air Standard, the International Residential Code, the Polluter Pays Policy and the ASHRAE[3] acknowledge the roll of indoor environments and ventilation systems in human health, and the EPA's Indoor Air Plus

1. U.S. Environmental Protection Agency.
2. Sonoran Environmental Research Institute.
3. American Society of Heating, Refrigerating and Air-conditioning Engineers.

program and the Green Building Codes are especially concerned about the interior sources of pollutants, the use of these guidelines mostly happens in cases where the user, the owner or the architect is aware of potential risks (Bernal, 2018). Therefore, indoor air quality should be a mandatory requirement in renovations of existing housing stock or design of new homes. The solutions should take a multidisciplinary approach that understands key issues faced by indoor air quality research: low degree of awareness of design, construction, occupancy and post-occupancy processes of a building, a poor understanding of human behavior and not accounting for its unpredictability, proposing solutions *before* the damage is done, and failing to address the need to adapt to future climate change scenarios. This research assumes the point of view of an average user to observe a typical ventilation system in an average household. The objective is to provide a set of evidence-based recommendations that bring awareness to decision-makers, technology developers, innovators, and users. The study also investigates how to effectively account for social, cultural, and economic implications of different design processes in the residential sector, in heat stressed regions.

VENTILATION SYSTEMS

ASHRAE standards for a healthy average residential building, indicate that the volume of indoor air has to be replaced with fresh air at a rate that ensures enough oxygen for the occupants. The whole-house ventilation rate recommended by ASHRAE's *Handbook of HVAC applications (2007)* is between 45 to 50 cfm for a 3-bedroom house with 2,000 ft^2 meaning that an effective ventilation system should replace 45 to 50 cubic feet of air per minute (cfm), i.e. 24 L/s. In some regions, this exchange rate is possible with natural ventilation because the local weather conditions and air quality provide adequate airflow, temperature, and low or non-risky exposure to polluted air. Under extreme heat and in the presence of dust, however, the most commonly used ventilation type is mechanical.

Natural ventilation, in regions exposed to high temperature, is generally known to challenge existing indoor environmental health and comfort standards. Natural ventilation systems rely on the movement of air through buildings (Bjorn, 2002). This movement is forced by outdoor air intensity, its direction, pressure differences, and humidity in the environment (Atkinson *et al.*, 2009; Faggianelli *et al.*, 2014). Airflow is provided in rooms via openings and vents, with special attention to areas such as kitchens and bathrooms. For the arid region of the Southwest US, it is possible to have up to 24 hours of natural ventilation from the months of November to March, and from 10:00 pm to 7:00 a.m. in the months of April to October (Chalfoun, 2015).

The case study selected for this research has openings in all the facades that allow adequate natural ventilation; it also has a 14 SEER self-contained packaged air conditioner (HVAC), and a downdraft evaporative swamp cooler of1/3hp.

The air conditioner or HVAC system control indoor air conditions by providing fresh air via a combination of recycled air from the same room and outdoor make-up air passed through filters. The systems can serve three purposes: heating, cooling, and exchanging polluted air with clean, filtered air. Malfunctions, lack of maintenance, leakages, fractures in the building envelope, and the lack of effective zoning challenge the operation of mechanical ventilation systems which are effective for removing airborne pollutants mostly when the systems are used according to the manufacturer's recommendations. Failing to change filters as recommended by manufacturer guidelines, leads to insufficient intake of air and reduced or non-particle removal.

An evaporative swamp cooler forces hot outdoor air through water-soaked pads after which it is blown into the house. In dry environments, this system is effective because it adds moisture to indoor air, cooling it in the process. Unlike HVAC, this system always uses outdoor air, and it needs openings in the farthest point of the house for the air to find a route to leave the space. Without adequate outlets for the air, the system creates a buildup of positive pressure with excessive moisture which can lead to sick building syndrome (Pavelchak *et al.* 2002).

METHODOLOGY

The methodology is based on a hazard assessment process that is used to estimate the nature and provability of adverse consequences in humans when exposed to contaminated environmental media (ECA, 2000; US EPA, 2015). This study adapted the process to help understand how temperature and dust may be related during September and October under average outdoor temperatures of 83°F (28°C). The Midtown Tucson house used as a case study has five household members: two adults that work office jobs, and three adolescents, two high school and one in middle school. The three children have outdoor sport practice four days a week. The family also has a medium-sized pet dog.

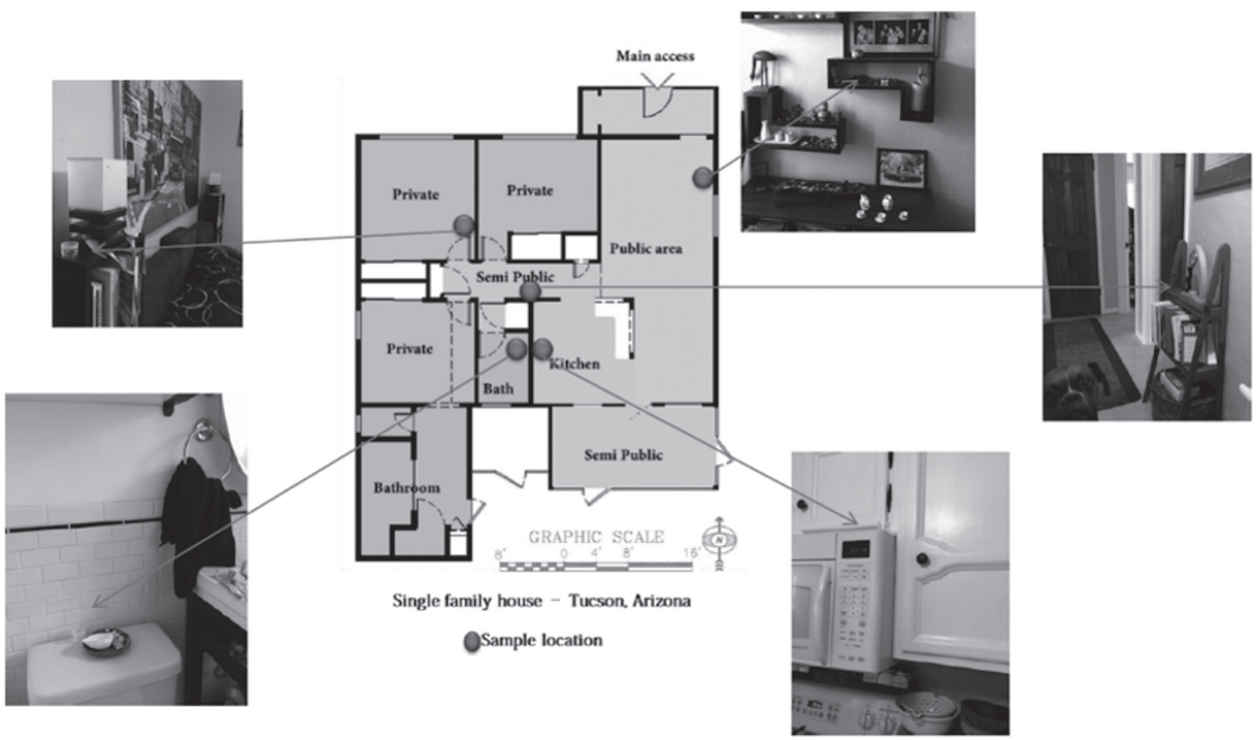
The map in figure 1 shows the setup for data collection of temperature and dust. The property was divided in areas as per their general use: Private (PR), Public (PA), Semi Public (SP), Kitchen (KT), and Bathroom (BA).

The collection of dust was done using 1.5-inch (38 mm) diameter plastic dishes labelled according to the following conventions:

- Ventilation system: NV for natural ventilation, HVAC for air conditioning and EV for evaporative cooling.
- Ventilation mode: CV for cross-ventilation, SV for single sided ventilation, NF for new filter and of for old filter.
- Area of the house: PR for private, PA for public, SP for semipublic, KT for kitchen, and BA for bathroom.

FIGURE 1

Floor plan and areas of the household



Source: Bernal, Engineer, Chalfoun, 2019.

The hazard assessment process includes three steps (UA EPA, 2015): 1) *Hazard identification*, which involved recording temperature readings to assess effectiveness of the systems to provide a healthy thermal comfort level, and observing whether or not there are evident accumulations of dust. 2) *Exposure assessment* that observes dust accumulations in weekly intervals in each selected area of the house, and its variations according to the ventilation system in use. 3) *Dose-response assessment* which analyses the amount and content in the dust samples and evaluates their health impacts in relationship to the location, including amount of time spent by residents and activities normally performed by them in these areas.

RESULTS

The hazard identification on day one showed that during a period of 10 minutes after enabling natural ventilation (figure 2), the bathroom was the hottest room in the house. The bathroom faces south (figure 1) and has no sun shading devices for solar exposure protection. The temperature, therefore, did not change even when the openings were closed. The temperature dropped by one degree only during the period of cross-ventilation. Similarly, in other public and private areas of the home, the temperatures dropped when cross-ventilation or totally open ventilation were enabled, while the semi-public area remained the same. The kitchen temperature rose by a degree during the totally open ventilation mode, perhaps as a result of heat migration either from the laundry room or from other parts of the house. After this exercise, the sample plates were placed in position for a week of dust collection.

After the dust samples from the natural ventilation period were collected, the HVAC system was put to work for 10 minutes with new filters. The original temperature in each room was 80 degrees Fahrenheit (26°C) in all areas except for the bathroom, which was at 82°F (27°C). At this point, we stopped tracking the bathroom temperatures since it was consistently giving different readings and the conditions were distinctly different from the rest of the house as well. The HVAC system reduced the temperature by 10°F. During that period, the time the public area took to reach 70°F (21°C) was 4 minutes; the semi-public area took 5 minutes, the private area, 3 minutes, and the kitchen, 7 minutes. The dust sample collection plates were then placed in the exact same locations used by the ones used during the natural ventilation period. These plates were also put there for a week. After the week using the HVAC system with the setback temperature of 70F, the plates were removed but the HVAC system was kept on and working for another whole month. With a one-month old filter, it was found that the temperatures took more time to decrease by 10°F degrees (5°C approx.). The public area took 9 minutes, the semiprivate area, 9 min, the private area, 11 min, and the kitchen took 8 minutes. The increase in time to reach the same reduction in temperature in these spaces could possibly be linked to other factors such as increase in outdoor air temperature, a failure in mechanical systems, a change on the behavior of the occupants, or other external factors. It was evident, however, that the old filters played a role in this increase of temperature.

FIGURE 2

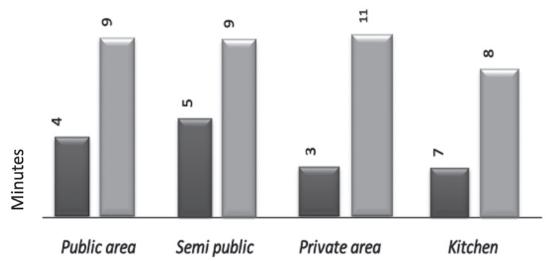
Temperature comparison under natural ventilation

	Closed openings	Cross- ventilation	Single sided vent	Totally open ventilation
Public area	80F (26C)	78F (25C)	80F (26C)	79F (26C)
Semi-public	80F (26C)	80F (26C)	80F (26C)	80F (26C)
Private	80F (26C)	79F (26C)	80F (26C)	79F (26C)
Bathroom	86F (30C)	85F (29C)	86F (30C)	86F (30C)
Kitchen	80F (26C)	80F (26C)	80F (26C)	880F (27C)

Source: author, 2019.

FIGURE 3

Time that the HVAC system took to reduce 10 degrees Fahrenheit (5 degrees Celsius) in each area



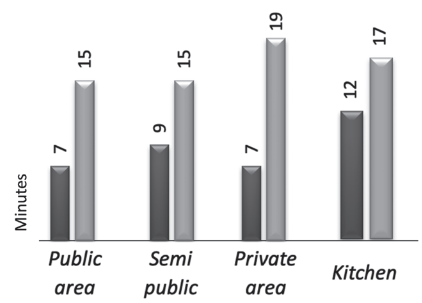
	Public area	Semi public	Private area	Kitchen
New filter	4	5	3	7
Old filter	9	9	11	8

Source: Author, 2019.

For the next step of this study, the evaporative cooling system was set up, cleaned, tuned up, and turned on. Windows of each area were left slightly open and the interior doors were closed for each room to have a single opening for the time period taken to reduce the room temperature by 10°F (5°C approx.) (figure 4).In the public area it took 7 min for this reduction to happen, the semipublic area, 9 min, the private area, 7 min, and the kitchen, 12 min. The sample dishes were placed in the same spots as those in the previous two collections for a week, while the evaporative cooling system kept running with one opening per room and with normal use by the household, including opening interior doors when required for passing through. After a week, the system was turned off overnight and the next day, the openings were closed with the exception of only one window in the living room and one in the master bathroom which were left open for supporting the work of the swamp cooler using the cross-ventilation principle. The experiment was then repeated. The time taken for the temperature to reduce by 10°F (5°C approx.) in each area was 15 min in the public area, 15 min in the semipublic area, 19 min in the private area, and 17 min in the kitchen. The sample plates were then put in place for a week of dust collection.

FIGURE 4

Time that the evaporative cooling system took to reduce 10° Fahrenheit (5 degrees Celsius) in each area



	Public area	Semi public	Private area	Kitchen
Cross ventilation	7	9	7	12
Single sided ventilation	15	15	19	17

Source: Author, 2019.

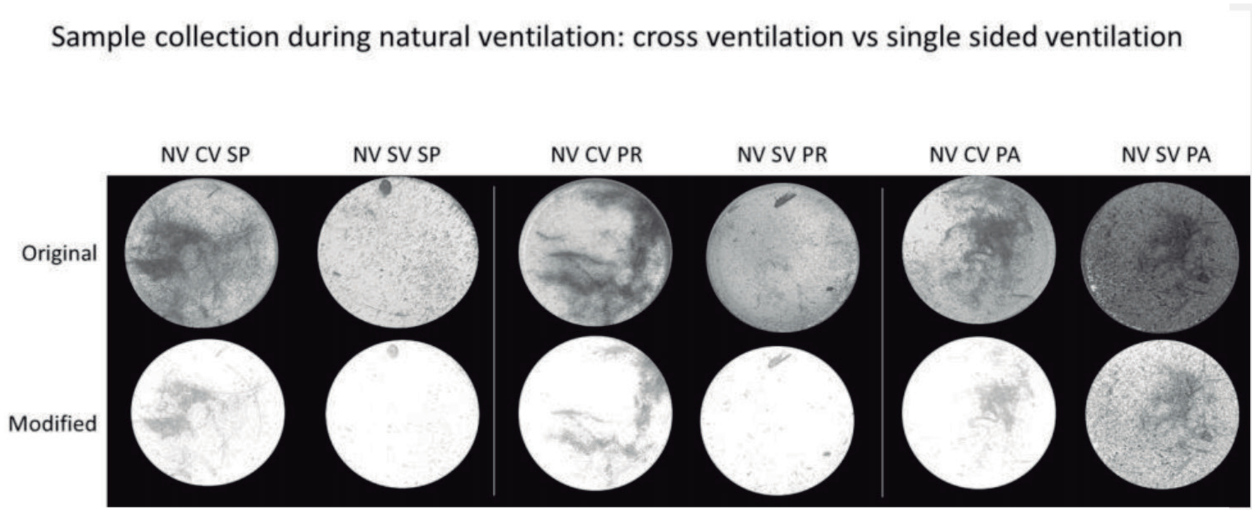
TABLE 1

Particle size comparison modified from Hyde *et al.*, 2018

particle size	*particle shape*	*particle origin*	*pathway*	*effect*	*house effect related*	*human activity related*
pm 0.1	spheres	chemical	inhalation	Asthma Emphysema a cancer	doors, windows, leakages, chimneys, attached garages	transportation
pm 2.5	flakes	chemical	inhalation , absorption ingestion	poisoning	doors, windows, leakages, chimneys	carrying on clothes, shoes, food, preparation, water storage
pm 5.0	varies	natural	inhalation, ingestion	allergies	bed rooms, living rooms	hygiene
pm 10	varies	natural	inhalation	allergies	doors, windows, leakages, chimneys	carrying on clothes, shoes, food, preparation, water storage

FIGURE 5

Visual comparison of sample collection under natural ventilation



Source: Bernal, Engineer, Chalfoun, 2019.

The hazard identification procedure showed that all the sample collection dishes had an accumulation of dust.

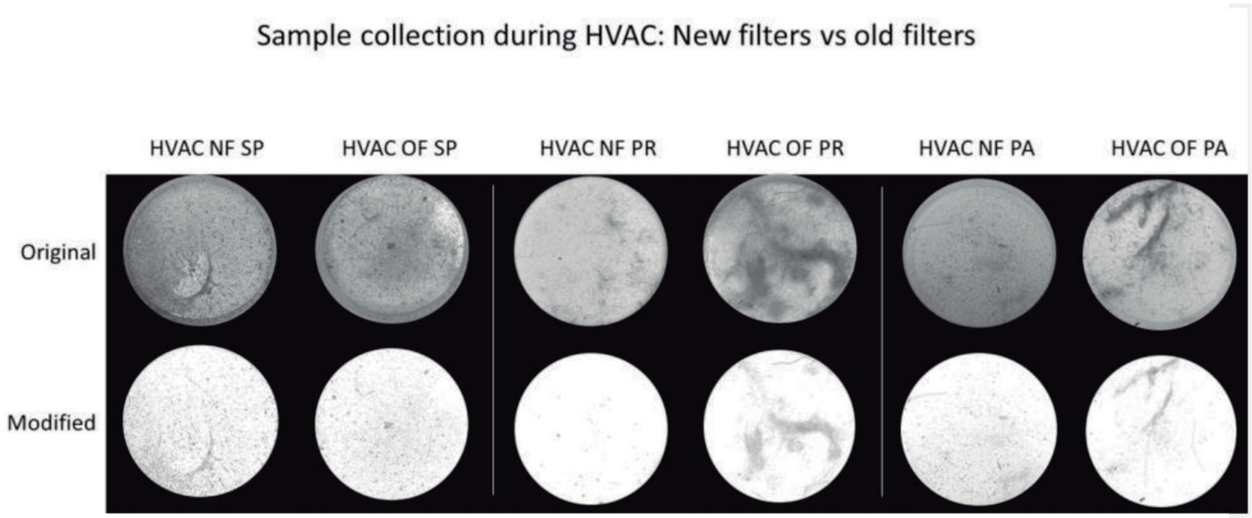
The results of the exposure assessment showed that each combination of location and system dust samples with different characteristics such as color and size of the particles as well as fibers, insects, and other unidentified content. Exposure implications in table 1, considers size as an important factor, because smaller particles, such as particulate matter (PM) 2.5 and PM 0.1 reach tracheobronchial and pulmonary areas in humans, resulting in short or long-term health problems. Meanwhile, larger particles such as PM 5 and PM 10 can be retained at the nasal level (Hyde *et al.* 2018). In all cases, the fact that the samples show particles regardless of the ventilation system, raises concerns.

In the visual assessment of the dust collection shown in figures 5, 6 and 7, each deposition is shown in the original state and then compared with a high-contrast version of the same sample. Each image was edited using Photoshop software, increasing the image exposure to 100%, reducing showdowns to 0%, and turning up the sharpness to 100%. This image editing process attempts to show larger particles. By contrasting the original and the modified image, we can assume that the particles which are not visible in the second image are likely to be inhaled into nasal or deeper respiratory track.

- Semipublic area: more particles and clusters when using cross-ventilation, less and loosen particles plus insects during single sided ventilation.
- Private area: more particles and clusters when using cross ventilation, less and loosen particles plus insects during single sided ventilation.
- Public area: Less particles when using cross-ventilation, clusters in both samples, more of the loosen particles during single sided ventilation.

FIGURE 6

Visual comparison of sample collection under HVAC

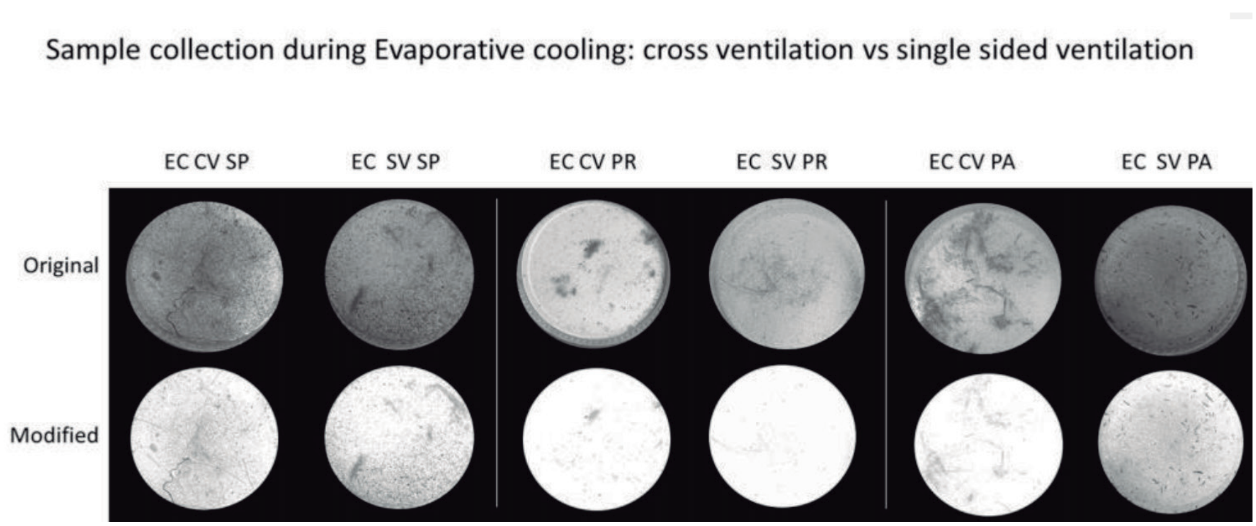


Source: Bernal, Engineer, Chalfoun, 2019.

- Semipublic area: both samples have loosened particles; there are apparently more particles when using a new filter.
- Private area: less and more loosened particles; apparently more particles when using an old filter and more clusters mostly with textile fibers.
- Public area: both samples show similar amount of particles, some hair and small incents are within booth samples as well; under the new filter period the sample show loosen particles while during the period of old filter the particles are clustered.

FIGURE 7

Visual comparison of sample collection under evaporative cooling



Source: Author, 2019.

- Semipublic area: both samples show similar amount of dust and other particles; the sample under cross-ventilation shows hairs, textile fibers, and insects; during single sided ventilation the sample has more clusters.
- Private area: during the period of cross-ventilation the samples show clusters and more particles; the single sided ventilation sample show less particles and hair but no clusters.
- Public area: both samples show clusters in difference sizes and color. The sample from when the system was using cross-ventilation has more particles and the clusters are bigger; the single sided ventilation sample has small black clusters.

Dose response assessment to the areas and systems that provide less possibility of intake of particles by humans (possible dose):

- Semipublic area during single sided natural ventilation, HVAC with old filters, however, the results from the evaporative cooling period is inconclusive since the amount of particles is similar in both tests, but the difference between the appearances of the clusters may have to be analyzed in a specialized laboratory to see what it is in those clusters besides moisture.
- Private area during single sided natural ventilation although there were insects, HVAC with new filter and during single sided ventilation evaporative cooling.
- Public area during cross-natural ventilation, HVAC during both samples and during single sided evaporative cooling ventilation.

Overall, the comparison between original and modified images of each sample reveal that there is an important amount of Ultrafine PM 0.1 and fine particles PM 2.5, both responsible for chronic diseases due to their tracheobronchial and pulmonary deposition, and are present in large quantities, in dry environments. Particles from combustion in kitchens maybe re-suspended and transferred into bedrooms and represent a major hazard for users, since people spend more time and breathe deeper in bedroom (Bjorn, 2002).

Natural ventilation created a deposition of dust particles in public areas, but this was not much of a concern to human health since the activities in this area are transitional; these spaces are not used for more than 2 to 3 hours a day in this particular case study, and humans would only be exposed to a greater degree of dust than the outdoors if the dust settled in food. Settled dust cannot be re-suspended with the movements of humans, air and objects, and this could be an increased risk factor in public areas. In this case, however, it was a lower degree of concern because of the little amount of time spent inside these spaces and minimal number of vehicles such as food, for human intake.

Dust in the private area, in this case – the master bedroom, appeared to have a higher content of textile fibers, and some particles not found in other areas of the house in a pale beige color scheme indicative of dead cells, dandruff and dust mites. The scale of human health exposure in this case, is of medium to high concern, because the bedroom is a space where occupants tend to spend more time inside the house. This time period is mostly spent in bed in which one breathes at a lower point from the floor level than during other activities. The area under 3 feet above the ground is more prone to dust exposure for humans because dust in the floor is easily re-suspended, airborne dust is pushed down by fans and air blown from windows and vents and, settled dust in upper surfaces can easily be re-suspended and then resettle over the bed. One more factor that increases human exposure to dust is the typical human breathing pattern during night. Humans may breathe deeper and from the mouth more often while sleeping, making the intake of dust easier.

The temperature reading did not show an important reduction using the different modes of ventilation which is indicative of a need to support the natural ventilation strategy with other physical and natural barriers to reduce heat while restricting dust accumulation to specific areas.

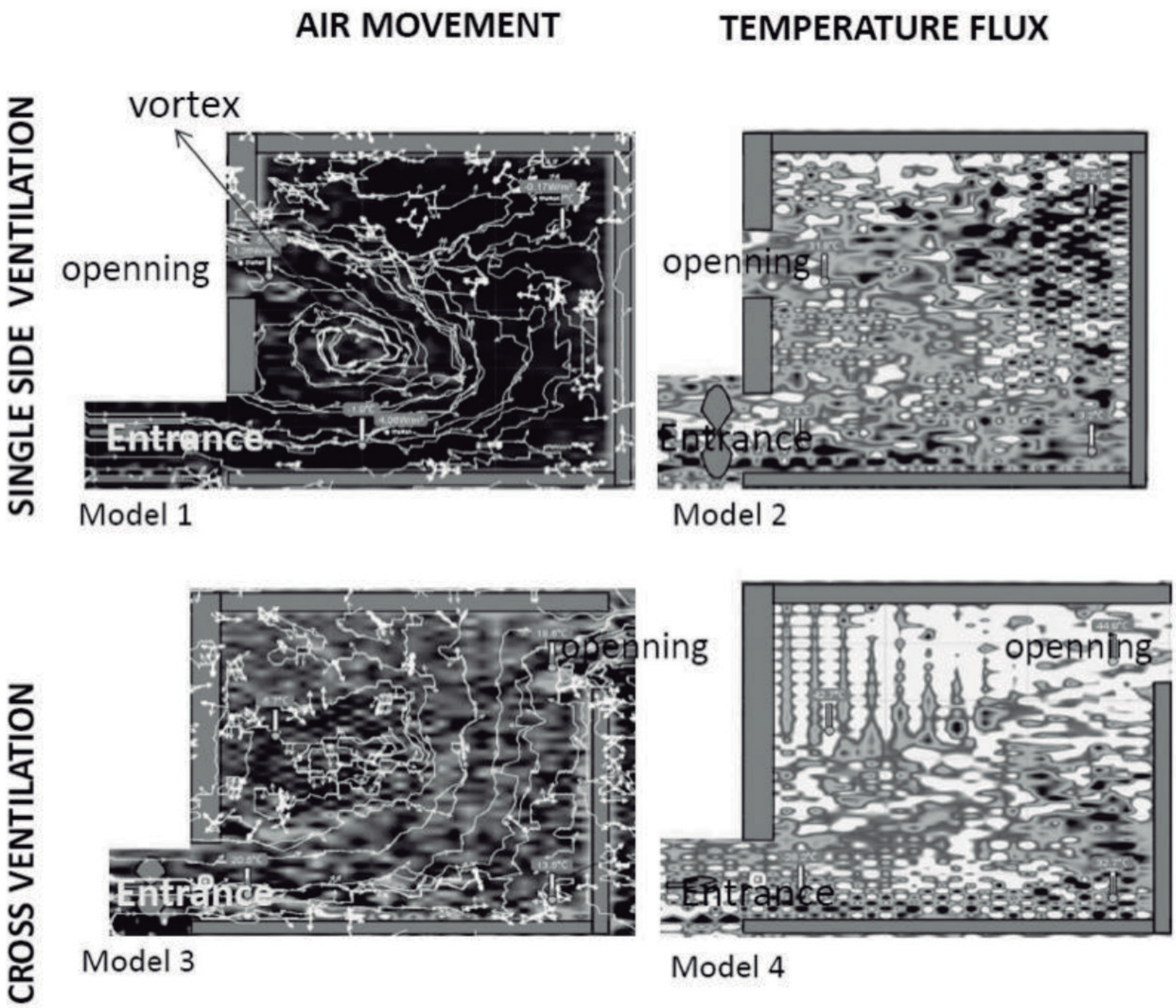
During the use of the HVAC system, the higher collection of loosen particles was in the semi-public. The location of particle deposition is near the location of the return air intake of the HVAC system from where the air is recirculated. The human health concern in this scenario is medium to high, since the semipublic area of this house connects a bathroom to the bedrooms and the probability of users walking barefoot or with open footwear in this area is high. It is also a place that is usually unfurnished, therefore the dust will settle on the floor. Additionally, the chances for re-suspension of dust by walking are high which in turn increases the risk for this dust to be brought to the private area and into the beds. A second examination of the samples showed that during the old filter period the amount of dust accumulation in spaces was different. More dust was found in public areas and less in the private area. The return-air-duct was clogged due to the accumulation of dust in the filter and this may have played a role in reducing the suction of the system due to which particles were not carried to the intake as effectively as with the new filter. This unexpected finding calls for future research regarding the efficiency of centralized HVAC systems. The HVAC showed good results for reaching thermal comfort easily and quickly, however, the presence of dust in semipublic areas was ambiguous and studies for the optimal performance of air filters for dust reduction deserves more attention.

Samples from the period when the evaporative cooler was running, revealed that moisture prompted the formation of dark dust clusters. Moisture was present in the system due to the outdoor air being forced to pass through pads soaked in water which also filtered the outdoor air. However, the presence of moisture elevates human health risk since more humidity increases the chances of mold and bacteria growth. Bacteria and viruses expelled by humans and pets may also live longer in this environment. The system was more effective when every room had an opening for natural air flow due to which the humidity levels dropped and there were fewer clusters in the samples. The efficiency of the system for thermal comfort was higher when there was a single opening per room rather than cross-ventilation across rooms.

DISCUSSION

Results from the hazard assessment show the behavior of the natural cross-ventilation system and the evaporative cooling system from the perspective of dust accumulation. Natural cross-ventilation has been established one of the most effective passive strategies for cooling in heat-stressed regions (Chalfoun, 2015 & Faggianelli, 1996). When a simulation of both, cross-ventilation and single sided ventilation using Energy 2d software was run, simulated air movement showed that the single side ventilation had a vortex right at the entrance, pushing the air towards the negative pressure side, and exiting without entering the opposite side of the room. The cross-ventilation simulation showed an almost even distribution of temperature and a better distribution of air while creating a slight vortex at the same time. This simulation exercise verified the effectiveness of cross-ventilation as compared to a single-sided one. It may be assumed that the effectivity relies on the position of the air supply in relationship to the opening, however, this need to be tested and verified in further studies. Another finding of this study was that the cross-ventilation was less effective during the evaporative cooling cycle. This may be due to the location of the air supply to each room from a top outlet which led to the airflow following the easiest pathway in the room, i.e. towards the negative pressure side. When the temperature is measured along this pathway, it was found to be lower than the other position in the same room at the same time, away from the pathway. This may also have influenced the dust collection pattern, as well as direction of the moisture. Another possibility is that cross-ventilation under evaporative cooling as it was set up – one opening in the living room and one in the master bedroom - may have forced the airflow to travel in a forced pathway against

FIGURE 9
Simulation of air movement and temperature flux



Source: Bernal, Engineer, Chalfoun, 2019.

the direction of its supply. The study also found that the creation of vortices which are related to the layout of the house may warm the air faster. These findings are shown graphically in figure 9 consisting of four simulation diagrams of air flow and temperature flux in single-sided and cross-ventilation systems.

While the dust samples and temperatures may not be useful parameters for an overall building performance assessment, the findings may be useful for the development of new inquiries. Technological advances in the field and knowledge about how humans inhabit indoor environments are developing rapidly. These advances may lead to standardizations while, on the other hand, humans tend to have unpredictable, erratic behaviors. Residential design as of today pays more attention to aesthetics than indoor environmental quality. An affordable and aesthetically pleasing house is a priority. However, this research reveals that there are unseen variables putting people at risk ones that are not commonly studied or considered in decision-making processes.

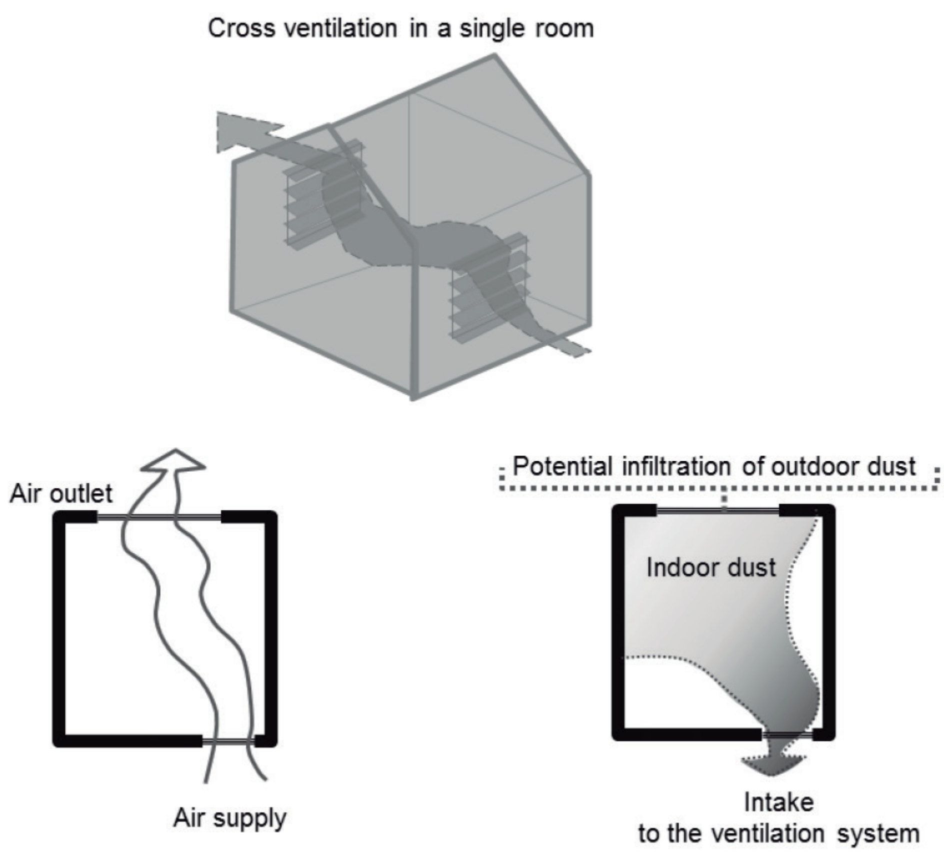
Recent concerns about energy consumption and its impact on climate change and air pollution have opened the conversation about more suitable buildings. We now have the opportunity to reassess our design priorities and develop new solutions, inspire new technologies and avoid human health risks. In hot arid regions, there is significantly more concern about managing high temperatures while reducing energy consumption at the same time, therefore, it is urgent that our understanding about indoor air quality is further developed and made easily available to all. Research and innovation should lead to better ventilation systems based on health impact and energy consumption together, from a user-perspective. Human behavior which includes changing air filters as instructed, breathing patterns during the day versus at night, and activities that occur in different parts of the house, schedules and location are some of the many factors that impact indoor air quality.

Effective mechanical ventilation could be the key for fighting pollutants that were either generated indoors or leaked from outdoors. Higher incidence of airborne dust is one of the many variables which may impact the performance of ventilation systems. If the ventilation system is not designed appropriately or working properly, infiltration and re-suspension of dust in the indoors represent higher risk for users and ultimately lead to more costly maintenance, tune-ups, upgrades and energy use.

One example of how to use this study for decision making is shortening the distance in between air supply and air intake based on the

FIGURE 10

Cross-ventilation in a single room



Source: Bernal, Engineer, Chalfoun, 2019.

observation of temperature dissipation and dust accumulation.

In Figure 10, the alternative is to treat each room in isolation managing the air supply and its outlet in a short-distance cross-ventilation pathway. Shorter distance between air supply and outlet may guarantee that the temperature in the case of evaporative cooling and natural ventilation does not easily dissipate. The same set up but now looking at the air intake of the HVAC system, may avoid resuspension and settlement of dust and lessen the risk to humans also take due to the short distance between the farthest point of the room and the air intake.

In contrast, cross-ventilation and centralized ventilation systems in multi-room settings were shown in the study to be less effective in maintaining temperature and they also contributed to reallocating dust in the center of the house.

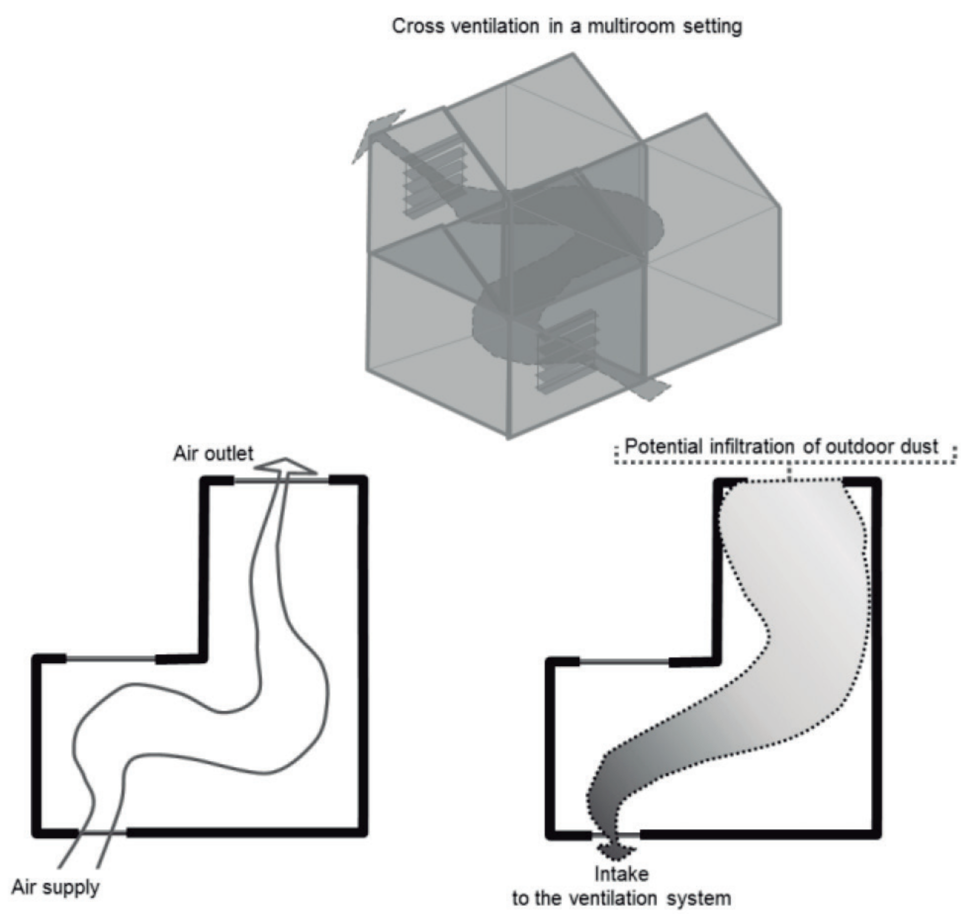
For architects, designers, technicians, and even social services and healthcare providers, a user-based decision-making process can significantly reduce risk.

CONCLUSIONS

This research proves that there is a correlation between amount and location of accumulation

FIGURE 11

Cross-ventilation in a multi-room setting



Source: Bernal, Engineer, Chalfoun, 2019.

of dust throughout the house and the type of natural ventilation and mechanical systems used. It highlights concerns about human exposure to dust, especially under high temperatures due to the dependency on mechanical ventilation for supplying enough air changes. Due to such dependency, we believe there are additional linkages between these concerns and energy consumption that need to be studied further. These findings require new research and innovation based on more case studies including but not limited to computer simulations, which include passive and mechanical ventilation techniques that mitigate human exposure to indoor pollutants. The presence of dust during the period when the HVAC and the Evaporative Cooler were active is an area that needs to be better further studied by the industry for better filtration solutions which can stop dust more effectively and accumulate less dust than during natural ventilation. The new paradigm should account for human error, unforeseen real-world conditions, and mismatched and uninformed design strategies. The architectural and engineering team which oversees design, site, building systems, structural design, code requirements, and aesthetics plays a crucial role in determining a new, human-centered approach in the residential sector. The relationship between indoor ventilation and airborne and settled dust must be included in building codes and guidelines for environmentally responsible designs.

BIBLIOGRAPHY

Atkinson, J.; Chartier, Y.; Pessoa-Silva, C. L.; Jensen, P.; Li, Y. y W.-H. Seto (2009). *Concepts and types of ventilation.* Disponible en: http://www.ncbi.nlm.nih.gov/books/NBK143277/.

ASHRAE (2000) Handbook of HVAC applications. (2007). USA *American Society of Heating Refrigerating and Air-Conditioning Engineers Inc.*

Bernal, S. (2018). *Socially Constructed Narratives for Exploring the Impacts of Air Pollutant infiltration in Built Environments. ProQuest Dissertations and Thesis Global. (212802811).*

Bjorn, H. (2002). "Impact of Open Windows on Room Air-flow and Thermal Comfort". *International Journal of Ventilation*, (2).

Chalfoun, N. (2015). *Active and passive; - TubacHawaii2010.pdf.* Disponible en: http://hed.arizona.edu/hed/docs/TubacHawaii2010.pdf. Consultado: 12 de octubre de 2015.

Escobedo, L. E.; Champion, W. M.; Li, N. y L. D. Montoya (2014). "Indoor Air Quality in Latino Homes in Boulder, Colorado". *Atmospheric Environment*, 92: 69–75. Disponible en: doi.org/10.1016/j.atmosenv.2014.03.043.

Etheridge, D. y M. Sanberg (1996). *Building Ventilation Theory and Measurement.* JWS.

European Collaborative Action (2000). *Risk Assessment in Relation to Indoor Air Quality.* (Environmental and Quality of Life núm. 22).

Faggianelli, G. A., Brun, A., Wurtz, E., & Muselli, M. (2014a). "Natural Cross Ventilation in Buildings on Mediterranean Coastal Zones". *Energy and Buildings*, 77: 206–218. Disponible en: doi.org/10.1016/j.enbuild.2014.03.042.

Halios, C. H.; Helmis, C. G.; Deligianni, K.; Vratolis, S. y K. Eleftheriadis (2014). "Determining the Ventilation and Aerosol Deposition Rates from Routine Indoor-air Measurements". *Environmental Monitoring and Assessment,* 186(1): 151–63. Disponible en: doi.org/http://dx.doi.org.ezproxy1.library.arizona.edu/10.1007/s10661-013-3362-5.

Hoddinott, K. B. y A. P. Lee (2000). "The Use of Environmental Risk Assessment Methodologies for an Indoor Air Quality Investigation. *Chemosphere*, 41(1–2): 77–84. Disponible en: http://doi.org/10.1016/S0045-6535(99)00392-6.

Hughes, B. R.; Chaudhry, H. N. y J. K. Calautit (2014). "Passive Energy Recovery from Natural Ventilation Air Streams". *Applied Energy*, 113: 127–140. Disponible en: http://doi.org/10.1016/j.apenergy.2013.07.019.

Hyde, P.; Mahalov, A. y J. Li (2018). "Simulating the Meteorology and PM10 Concentrations in Arizona Dust Storms using the Weather Research and Forecasting model with Chemistry (Wrf-Chem)", *Journal of the Air & Waste Management Association*, 68:3: 177-195, Disponible en: DOI: 10.1080/10962247.2017.1357662.

Joshi, S. M. (2008). "The Sick Building Syndrome". *Indian Journal of Occupational and Environmen-*

tal Medicine, 12(2): 61–64. Disponible en: http://doi.org/10.4103/0019-5278.43262.

Nielsen, P. (1974). *Flow in Air Conditioned Rooms — Model Experiments and Numerical Solutions of the Flow Equations*. Technical University of Denmark.

Niu, S.; Zhang, X.; Zhao, C. y Y. Niu (2012). "Variations in Energy Consumption and Survival Status between Rural and Urban Households: A Case Study of the Western Loess Plateau, China. *Energy Policy*, 49: 515–527. Disponible en: http://doi.org/10.1016/j.enpol.2012.06.046

Pavelchak, N1; De Persis. R. P.; London, M; Stricof, R.; Oxtoby, M.; Di Ferdinando, G. Jr. y E. Marshall (2002). "Identification of Factors that disrupt Negative Air Pressurization of Respiratory Isolation Rooms". *Infection Control and Hospital Epidemiology*, 21(3): 191–195.

Popkin, B. M.; D'Anci, K. E. e I. H. Rosenberg (2010). "Water, Hydration, and Health". *Nutrition Reviews*, 68(8): 439–458. Disponible en: doi:10.1111/j.1753-4887.2010.00304.x

Tan, C. C. L.; Finney, K. N.; Chen, Q.; Russell, N. V.; Sharifi, V. N. y J. Swithenbank (2013). "Experimental Investigation of Indoor Air Pollutants in Residential Buildings". *Indoor and Built Environment,* 22(3): 471–489. Disponible en: http://doi.org/10.1177/1420326X12441806-

US EPA (2015). *Risk Assessment for Toxic Air Pollutants: A Citizen's Guide Technology Transfer Network Air Toxics Web site* | *US EPA*. Disponible en: http://www3.epa.gov/airtoxics/3_90_024.html. Consultado: 23 de noviembre de 2015.

Yassin, M. F.; AlThaqeb, B. E. Y. y E. A. E. Al-Mutiri (2012). "Assessment of Indoor PM2.5 in Different Residential Environments". *Atmospheric Environment*, 56: 65–68. Disponible en: doi.org/10.1016/j.atmosenv.2012.03.051.