Design of a Ventilation System to Improve IAQ and Thermal Comfort in a Textile Factory

Djapermal Bernard Anders, MSc BEng(Hons) **Venkannah Santaram, PhD**
Member ASHRAE

ABSTRACT

Indoor environment quality has been researched extensively, with many countries adopting regulations to ensure that building occupants enjoy healthy working environments. In many small island developing states (SIDS), such as Mauritius, the population benefits from perfect weather conditions, but building design considerations often under-estimate the effects of outdoor weather conditions, heat and pollutant emission, illumination and noise, which worsen indoor environment. This study aims at determining the actual indoor environment inside a dyehouse of Mauritius and to propose engineering solutions for better IAQ and thermal comfort. Although Mauritians spend 90% of time indoors, a survey conducted among factory operators reveals 69% of employees having poor understanding of IEQ and 96% being unaware of laws and standards regulating IEQ. 85% of population express dissatisfaction for indoor temperature despite preventive measures already implemented. According to NIOSH heat matrix, 66% and 30% of zones are in "Extreme caution" and "Danger" categories respectively, where employees are likely to experience heat stress, heat exhaustion and muscle cramps. A building load assessment confirmed that manufacturing processes deteriorate IEQ, with internal heat gain between 40%-77% during day shift and reaching 93% during night shift, compared to heat gain from external sources. High concentrations of $PM_{2.5}$ and PM_{10} recorded in several zones, lead to alarming air quality index, due to manufacturing processes used and raw materials treated. A mechanical ventilation was therefore designed to enhance IAQ and thermal comfort. Design procedures followed guidelines from ASHRAE Standard 55-2017, ASHRAE Handbook Fundamentals (2001) and Equal-friction method. The ventilation system was split into 12 air supply systems and 11 air return systems, with main components consisted of fans, filters, air inlets, diffusers, ductings and fittings. The textile factory was modeled on ANSYS-Fluent-2020-R2 to evaluate the air distribution patterns, air temperature contours and air velocity contours. The proposed design, with capital investment of 1million USD, offers satisfactory air distribution, reducing rise in air temperature and pollutant level. However, an important decision-making factor for implementing ventilation systems implies balancing price competitiveness versus ethical and environmental compliance.

INTRODUCTION

Progress in building engineering has always accompanied the evolution of mankind. A time-study of Mauritians reveals that people spend 90% of time indoors (Statistics Mauritius 2013). Houses, offices, schools, banks, supermarkets, shopping malls and recreation centers are present in our everyday life to provide shelter and protection of assets. With more complex architectures and more demanding requirements from building occupants, the control of internal environmental

Djapermal Bernard Anders is a MSc student in the Department of Mechanical and Production Engineering, University of Mauritius, Reduit, Mauritius. **Venkannah Santaram** is an Associate Professor in the Department of Mechanical and Production Engineering, University of Mauritius, Reduit, Mauritius.

quality is more challenging. 1984 WHO Committee report estimated that 30% of all new and existing buildings received complaints for poor IAQ (EPA 1991). Inadequate IAQ and ventilation, not only affect the health and comfort of the occupants, but the building as well. 75% of problems related to building envelope are caused by high indoor humidity (Ronald 1994), while poor ventilation results in sick building syndromes (SBS), respiratory problems, lower performance of employees, allergies and asthma (Fisk and Seppanen 2004). In fact, ventilation systems gained importance after 1973 oil crisis. The market demand for ventilation systems is still rising nowadays, thanks to (1) increased awareness about IEQ v/s SBS and (2) higher energy-efficient buildings designed to reduce infiltration and exfiltration, but equipped with mechanical systems for air circulation (Komfovent 2018). Similar to other manufacturing sectors, textile factories are affected by IEQ problems. The main operations of a dyehouse is the conversion of undyed fabric into dyed form, using chemical, physical and mechanical processes in the dyeing and finishing units. Dyeing machines, continuous washers, dryers, stenters and fabric compactors release high amount of heat, moisture, dust and fluffs. These contribute to the deterioration of IEQ, which possibly affect the operators' performance. The study was conducted in a dyehouse situated in the north-western coastal region of Mauritius. The prevailing climatic condition is hot and humid, with average solar insolation of 7 kWh/m^2 per day during summer (Gaisma 2019); outdoor air conditions of 27°C with 81% RH during summer; and 23°C with 76% RH during winter (Statistics Mauritius 2018). The project scope covers the evaluation of dyehouse's IEQ and the design of a ventilation system to provide better IAQ and thermal comfort.

LITERATURE REVIEW

Toyinbo (2019) considers IEQ factors as biological, physical and chemical. Bluyssen (2009) splits IEQ into four main categories, which are thermal comfort, lighting comfort, indoor air quality (IAQ) and noise level. USGBC (2014) and Mujeebu (2019) further extend these factors to include ergonomics, odor and micro-organisms. Although, measurements of IEQ factors are generally benchmarked against standards or guidelines, the perceptions of occupants with regards to their comfort should also be accounted.

Indoor Air Quality (IAQ)

IAQ focuses on the air quality inside a building and its effects on the health and comfort of occupants. The extent that indoor pollutants affects the building's occupants varies according to the nature of pollutants, building conditions (e.g. air flowrate) and people behavior. Improving air quality can be achieved by either eliminating, reducing or controlling the level of contaminants, as recommended by the hierarchy of controls (NIOSH 2015). Kamaruzzaman et al. (2011) showed that maintaining poor IAQ frequently results in health problems such as dermatitis, respiratory problems, irritation, lung cancer caused by radon, Legionnaire's diseases and other SBS.

Thermal Comfort

Each person defines thermal comfort differently because it involves environmental factors and the person's perception of comfort (Mujeebu 2019). ASHRAE Standard 55 (2017) identifies air temperature, radiant temperature, air speed, humidity, metabolic rate and clothing insulation as main factors for good thermal comfort. NIOSH (2017) recommends the use of indices, such as wet bulb globe temperature (WBGT) and heat index (HI), Equation 1, to express level of comfort.

$$HI = -42.38 + 2.049T + 10.14(RH) - 0.2248T(RH) - 0.0068T^2 - 0.055(RH)^2 + 0.0012T^2(RH) + 0.0008T(RH)^2 - 0.0000019T^2(RH)^2 \quad (1)$$

Types of Ventilation Systems

An engineering control for IAQ and thermal comfort consists of installing a ventilation system in the building. This is achieved either by natural (e.g. windows, doors) or mechanical means (e.g. fans). ASHRAE Standard 62.1 and EN15251, mention two main methodologies for ventilation system design, namely prescriptive approach and analytical approach. However, air leakage also affects the ventilation system by infiltration and exfiltration. A proper design as per Standard 62.1 and Standard 55, ensures that IAQ and thermal comfort are acceptable to 80% of population (ASHRAE 2001). Mechanical ventilation can be categorized by the supply and exhaust systems (Foldbjerg et al. 2015).

The reliability and consistency of mechanical ventilation have facilitated the integration of ventilation system in industrial sectors. Commonly, textile mills are not equipped with sophisticated ventilation systems, especially in wet processing factories. In regions having a good average annual air velocity, wind turbines are installed on the roof (Hasanbeigi 2010). Otherwise, fans or extractors are used to generate an air movement inside the buildings.

Simulation Software

The design of ventilation systems involves so many parameters and mathematical formulae that it is tedious and most probably impossible to predict thermal comfort, air flow, air distribution patterns and level of pollutant in each area of complex buildings. ANSYS Fluent 2020 R2 was selected for simulating the indoor conditions and the ventilation systems. Several studies were successfully conducted using ANSYS Fluent for building and ventilation system evaluation (Popovici 2017, Adewumi et al. 2020, Gulten and Oztop 2020).

IEQ SATISFACTION SURVEY

Methodology

A survey was conducted to evaluate the building occupants' appreciation of the internal environment of production floor, with the aid of questionnaires. The sample size was based on Cochran formula, with confidence level of 95% (Jaakkola and Miettinen 1995, Daisey et al. 1996, European Commission 2003, Brightman et al. 2007) and margin of error of 10% (Sherman 1990, Gunay et al. 2016). Accordingly, 75 people were interviewed for the survey. Reference was made to ASHRAE Standard 55-2017 Section L2 and Thermal Comfort Checklist (HSE n.d.) to select questions.

Results, Analysis and Discussions

Employees' Awareness about IEQ. 69% of population have poor knowledge on IEQ, among which are mainly expatriates. The 'age group' factor shows negligible effect on IEQ awareness. Supervisors and managers are more conscious about IEQ and the related issues because they obtain introductory courses to IEQ during their studies. In fact, the application of IEQ control measures is closely linked to laws and international standards. The survey reveals that Mauritian managers made the only 4% who were aware of laws and standards (OSHA and ASHRAE standards). This can be associated with the low education level of expatriates who represents the population's majority and also, lack of awareness campaigns and talks on IEQ and its consequences at work.

IEQ Satisfaction. Thermal comfort and IAQ listed among the top factors affecting IEQ. 85% of respondents are dissatisfied with indoor temperature and all employees agree that temperature fluctuates during the day. The highest level of discomfort is encountered between 11:00 to 14:00 (41% of population) and between 14:00 to 17:00 (59% of population). 100% of population agrees to experience better thermal comfort at night. Mauritius goes through two seasons annually; summer and winter. All population express that temperature changes are noticeable and summer brings more discomfort.

61% of employees were dissatisfied with RH level while 73% of respondents reported to work near equipment producing heat and 21% working near machines operating with steam. People finding RH level acceptable were normally those working either in processes that are not "heat producers" or near openings such as doors/exits. Poor thermal comfort was accentuated by low air movement. 80% of population stated having little to no air movement at their place of work.

Poor IAQ is also a prominent concern in the dyehouse. 39% of population believes that level of air contaminants is acceptable. Employees in the wet processing show higher rate of satisfaction. 83% of dyeing department agrees to have good air quality. In contrast, workers in dry processing (preparation, finishing, special finishing and quality) are less satisfied with IAQ; only 48% were comfortable with actual air quality. This can be explained by the larger emissions of dust, fluffs and vapors of chemical products during dry processing. From the responses, it is obvious that major improvements are needed to provide a better and safer environment to workers.

IAQ AND THERMAL COMFORT

Methodology

The dyehouse has overall dimensions of 172 m by 163 m (perimeter of 897 m and surface area of 22346 m^2). Air samples were done as recommended in ISO 16000-1 (2004) and measurement plan devised as per ISO 19011 (2018). Measurement points were identified by dividing the building floor into zones by imaginary boundaries. Both IAQ and thermal comfort measurements were done, as far as possible, at the center of zones allocated and a minimum distance of 1m from openings, as per Section 7.3.2 from ASHRAE Standard 55 (2017). Thermal comfort was determined using dry- and wet-bulb temperatures from whirling thermometer. IAQ was measured based on particles concentration and volatile compounds using Temtop-LKC 1000S+ detector. Comparison was done against US-EPA (2006) guidelines for air quality.

Results, Analysis and Discussions

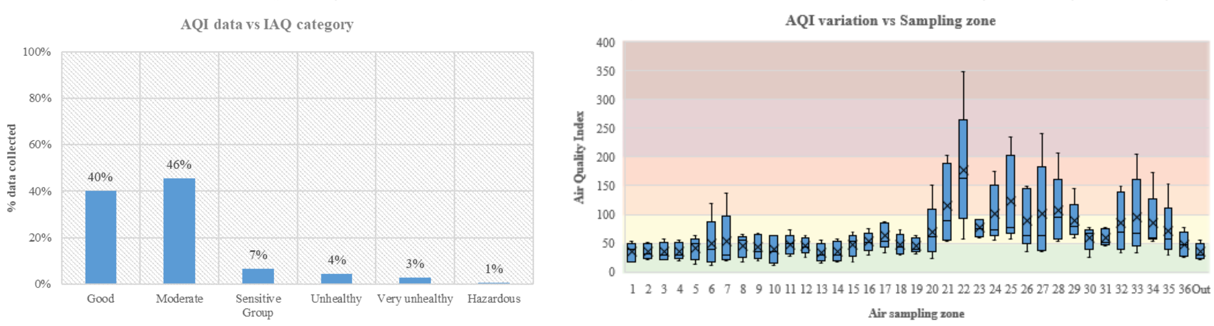
Particulate matters. The air audit reveals that only 41% of the total building zones benefit from air with low $PM_{2.5}$ that is suitable for work activities. 44% have moderate air quality while the remaining 15% have air quality classified as unhealthy for human. US-EPA (2006) health status and color coding system were used. Some readings even peaked in the hazardous zone. This severe condition indicates that exposure to such a high concentration of $PM_{2.5}$ represents very high risks for occupants to suffer from respiratory diseases. American Heart Association (2010) stated that breathing $PM_{2.5}$ for even some hours can lead to cardiac failure while long exposure at lower concentration can decrease the workers' life expectancy. PM_{10} also contributes to the deterioration of respiratory diseases, although PM_{10} is less dangerous than $PM_{2.5}$.

Formaldehyde and VOC. The concentration of formaldehydes and VOCs was categorized as healthy or unhealthy, with threshold of 0.1 mg/m^3 and 0.6 mg/m^3 respectively. In all 36 zones, the air quality in dyehouse was healthy with regards to level of formaldehydes and VOCs. Normally, these two compounds are emitted when processing polyester fibers, during chemical application on stenter padders and by decomposition of chemicals into formaldehydes or VOCs. The low levels of these two chemicals are explained by the need to comply with customers' requirements for formaldehyde-free and VOC-free processes, especially as textile industry is moving towards green manufacturing.

Air Quality Index (AQI). AQI serves finally to convert all measurements PM, particles, formaldehyde and VOC into a standard format, then categorizing the air quality same as the worst AQI factor. US-EPA (2006) calculates the AQI based on a linear interpolation formula, as per Equation (2). The room AQI is equal to the maximum index value of any pollutant.

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}\left(C_p - BP_{Lo}\right) + I_{Lo} \tag{2}$$

The factory has 40% of zones with good AQI, but Figure 1(a) also indicates 15% of zones as unhealthy. Figures 1(b) and 2(a) show zones 21-22, 24-28 and 33-34 as the worst areas. On average, a slight improvement was seen for night shift, whereby 50% of zones have good AQI, but still 16% having unhealthy AQI. The high level of $PM_{2.5}$ was noticed especially during the operations of certain processes, namely, (1) heatsetting of fabric with elastane, (2) thermofixing of polyester fabric and (3) curing of printed fabric on steamer and/or stenter. These processes liberate hazardous chemical vapors. The architecture and lack of openings cause a diffusion of these particles inside the factory affecting the neighbouring zones.



(a) (b)

Figure 1 (a) AQI data distribution during day shift vs IAQ category and (b) AQI variation during day vs sampling zone

Thermal comfort. The indoor environment shows great temperature variations inside the building. The mean dry-bulb temperatures per zone vary between 30.1ºC to 35.1ºC. There is always a minimum temperature difference of 2ºC between indoor and outdoor air, while temperature can even peak to 37ºC. The mean relative humidity shows also great fluctuations for each zone, varying between 55% and 68%. An effective way of expressing the temperature felt by building occupants consists of combining the effect of air temperature with RH and to produce a heat index. Heat index calculations were performed on NOAA (2018). The data obtained were classified as per NIOSH (2017) heat index matrix, see Figure 2(b).

An analysis of heat index values obtained shows that during the day, all zones are outside the "Safe" category. 4% of measurements are in "Caution", 66% in "Extreme caution" and 30% in "Danger". During the night, the mean heat index falls to 23ºC, that is 9ºC less that day temperature. The inside of the building is also much cooler as the indoor heat index ranges between 25ºC to 34.3ºC. 19% of zones are considered safe at night, compared to 0% during the day.

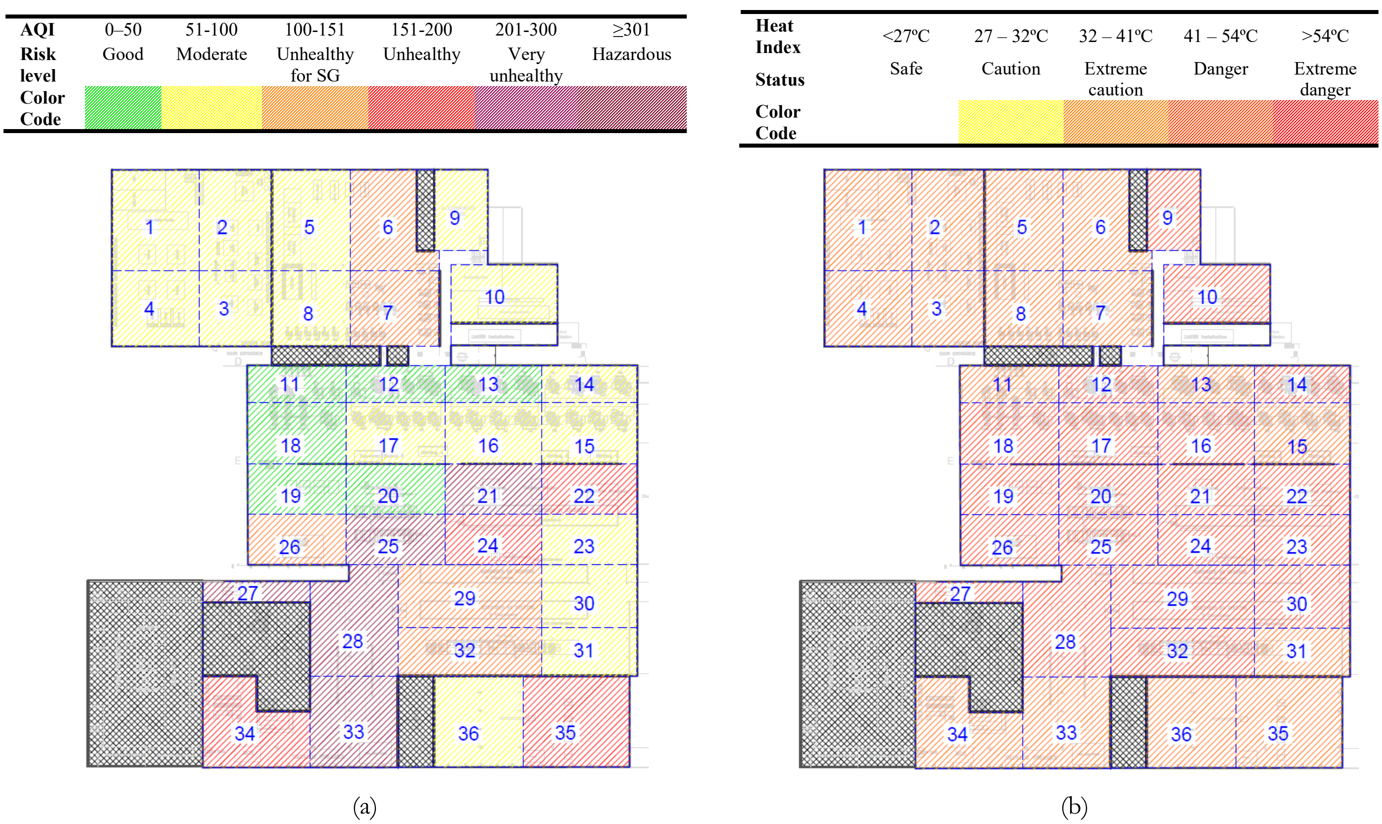


Figure 2 (a) AQI color coding of production floor and (b) Heat index of production floor

Natural ventilation was initially considered to improve thermal comfort. However, as per ASHRAE Standard-55 (2017), outdoor air conditions were not favorable for natural ventilation because outdoor air temperatures recorded fell outside the 80% of acceptability range. That is, the outdoor air only is not sufficient to regulate indoor air conditions.

BUILDING LOADS

CIBSE Guide A: Environmental Design (2018) lists five main categories for building heat gains as solar gain, building fabric, infiltration, occupants and internal gain from equipment. Actions to reduce building loads depend on the ratio of internal-to-external heat gains.

Methodology

A walk-through audit was done to identify the position of all machines and equipment. The processes used for each machine were obtained from the Production management team. Increase in energy content of indoor air during factory operations w.r.t. outdoor air was calculated by change in air enthalpy. The heat load is normally the sum of heat due to infiltration, building fabric, solar gain, occupants and equipment. The heat loads for each zone can as well be expressed as the difference in energy content between indoor air and outdoor air. The total building heat load is calculated as the sum of the individual heat load for each zone.

Results, Analysis and Discussions

The manufacturing lines of the dyehouse comprise of more than 100 machines in the Preparation, Dyeing, Finishing, Special Finishing, QC departments, which are energy consumers, thus releasing heat as waste. The textile factory employed 307 people to work in the manufacturing processes. The occupants' activities are comparable to a machine work of 2met units (ASHRAE 2017). Based on Dubois and Dubois formula, heat gain due to metabolism is approximated to 21.5 kW per shift. 196 metal halides headlamps, model Philips Master HPI-T Plus 400W/645, having heat dissipation of 75%, contribute to 58.8 kW of heat gain. 208 twin fluorescent tubes T8 36 W, having heat dissipation of 80%, produces 12.0 kW heat. This represents a total 70.8 kW from lighting system. Change in enthalpy is taken as heat energy required to increase enthalpy of outdoor air to indoor conditions. During shutdown period, the air gained 678.6 MJ of energy from the building (mainly from solar energy) during the day. When the production lines were running, there was an increase in enthalpy by 40% up to 77%. During the night, with a much cooler temperature, the air has lower enthalpy of 183.3 MJ on shutdown. On average, the internal energy gain represents 93% of energy content of the indoor air. With a large percentage of internal heat gain during high production periods, a mechanical ventilation was selected to regulate the thermal comfort as well as IAQ.

VENTILATION SYSTEM DESIGN

Air Duct Design Procedures

The ducting design procedures were adopted from ASHRAE Handbook Fundamentals (2001). Reference was also made to Wang (2001) and ASHRAE Handbook – HVAC Systems and Equipment (2016). Ducts were sized using the equal-friction method, with constant pressure loss of 4Pa/m for both air supply and air return to target a medium velocity system.

Results, Analysis and Discussions

In hot and humid climates, occupants can enjoy a thermal comfort at high temperature and high humidity if air velocity is increased (Arens et al. 2013, Srivajana 2003, Huh et al. 2019). The minimum volumetric flowrate for each zone is based on outdoor air rate 0.9 $l/s.m^2$ from ASHRAE (2013) and recommended air change per hour of 15-20 ACH for dyehouse (Leakair n.d., Oxycom 2017, Brumbaugh 2004). Dynamic losses in ducting are associated to fluid disturbance when air moves through fittings, equipment and openings. Equation (3) expresses dynamic losses as a factor of velocity pressure. ASHRAE Duct Fitting Database Version 6.0.4 was used to calculate K value for fitting losses in each ducting system.

$$\Delta P_d = KP_v = K\left(\frac{\rho v^2}{2}\right) \tag{3}$$

Fan for each system was designed to provide at least the pressure losses in the critical path. A balanced ventilation system was considered most appropriate for improving both thermal comfort and IAQ inside the building. The proposed ventilation system supplies fresh air to the workers first for better thermal comfort. Then, air flows around the machines carrying heat and particulate matters/volatile compounds away from the workers. This air is sucked by an air return system on top of the machines and extracted outside the dyehouse. A single ducting system for air circulation and air exchange requires very large ducts and leads to high pressure drop due to the various fittings necessary to cover the whole production floor. The ventilation system was split into 12 air supply systems (SS01 to SS12) and 11 air return systems (ES01 to ES11).

Air Supply System. The air supply system consists of a main duct and branches to distribute air to different regions of the dyehouse. The design shows a higher percentage of pressure losses due to dynamic losses, varying between 69%-92%. In all systems, the critical path was not the furthest point from the fan, but in a branch in the middle of the ventilation system.

The high losses were caused at the Tee-junction for the following reasons: (1) change in flow direction, (2) change in velocity from main to branch duct and (3) diameter ratio of main-to-branch. From ASHRAE Duct Fitting Database Version 6.0.4, it was observed that larger diameter of main duct helps to reduce the dynamic losses while the fluid flows to branches. When this ratio approaches 1:1, the fitting losses increases drastically.

Air Return System. In air return systems, the critical path was the furthest point from the fan. However, the total pressure losses consist of 64%-91% of fitting losses. Tees have less influence on the overall losses in the air return, compared to the air supply system. Branches do not exhibit the same loss in return system as for supply system. The momentum of air moving along the main duct sucks the air from the branches, resulting in very low fitting losses. In some systems, the air velocity is getting high enough when reaching the fan that it causes negative losses in the branches.

CFD SIMULATION

Methodology

ANSYS SpaceClaim was used to draw all geometries (building, openings, machines and ventilation systems) for analysis. ANSYS Meshing creates nodes on the system in order to calculate fluid motion and other parameters at different areas of the factory. The higher the number of nodes, the more accurate is the simulation results. IEQ inside the dyehouse was simulated for four different scenarios using ANSYS Fluent 2020 R2.

Results, Analysis and Discussions

Case 1 – Factory shutdown, No ventilation. Case 1 shows the IEQ during shutdown with the contribution of external gains as building loads. Slight rise in temperature was obtained in several regions based on building geometry and solar radiation, affected by the sun orientation to the building. ANSYS Fluent shows a high solar gain on the west side of the building, see Figure 3(a). The region of La Tour Koenig faces winds from the East with an average speed of 6 m/s. However, this does not benefit to the indoor environment due to lack of openings for natural ventilation. This confirms the need for a mechanical ventilation system to bring fresh air inside the factory in order to improve IEQ.

Case 2 – Factory operational, No ventilation. Case 2 represents the simulated conditions when the factory is running. Heat dissipation from machine affects the surrounding air by rising the air temperature. The same regions, where poor air quality was noticed during data measurements on site, exhibits poor thermal comfort as per ANSYS Fluent. The critical zones are situated near stenters where processing achieved temperature up to 150°C, see Figure 3(b).

Case 3 – Factory shutdown, With ventilation. Case 3 simulated the ventilation systems with objectives of understanding the air distribution and particle movements so that IEQ can be improved. The ideal system should provide fresh air in laminar flow, which is first directed towards occupants for comfort, then move further to machines taking heat and pollutants away. In practice, these ideal situation is difficult to obtain because machines act as an obstacle to air movement, resulting in flow disturbance, thus turbulence at some areas. However, Figure 3(c) shows that most particles have a low residence time in the factory, hence, this helps to reduce the accumulation of particles in the air.

Case 4 – Factory operation, With ventilation. On a normal working day, the ventilation system is able to maintain good IEQ inside the building. Fresh air is supplied to working area of the dyehouse, which contribute greatly to provide thermal comfort and better IAQ to employees. On hottest days, in the absence of ventilation systems, air temperature reached up 36.5°C (310 K). This represents high risks of SBS, such as heat stress, heat exhaustion and muscle cramps. With the implementation of ventilation systems, Figure 3(d) shows that the indoor air temperature is evenly distributed and should not exceed 30°C (303 K), which is considered acceptable when air velocity is provided at 2 m/s.

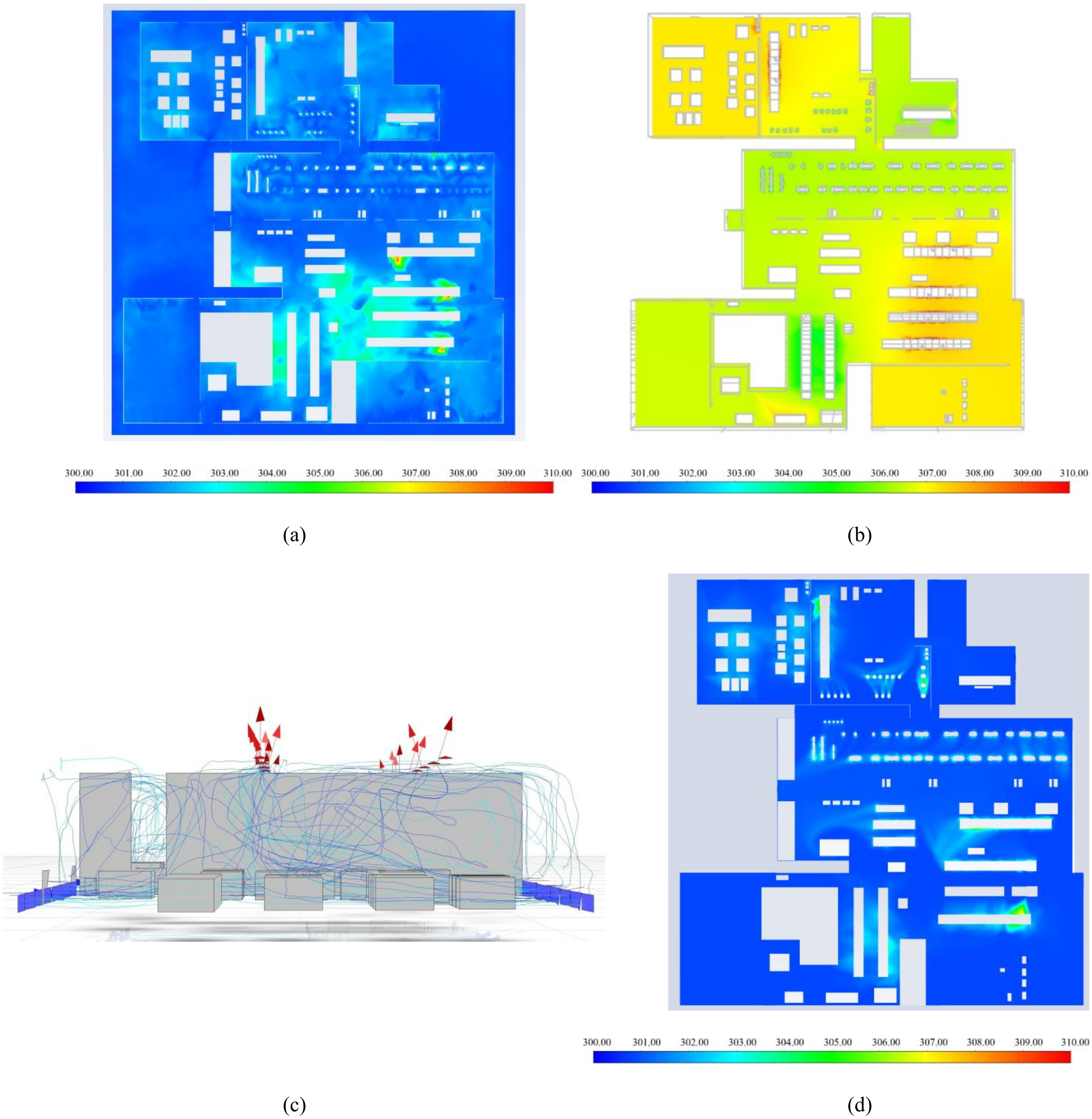


Figure 3 (a) Air temperature contours during shutdown (K), (b) Air temperature contours during operations (K), (c) Particles movement (Side view) and (d) Air temperature contours with ventilation system (K)

PROJECT COSTING

Cost estimation approximates the financial worth of project by considering cost of materials, equipment, labor, resources and contingency (Eby 2017). With galvanized steel as material of construction for its strength, durability and lower cost, fans, ducting and fittings contributes 74.2%, 22.1% and 3.7% respectively to material costs. OPEX is directly proportional to electricity, which adds extra expenses to the production and operations costs. However, the payback period cannot be estimated for ventilation system because production rate is affected by several factors, including raw materials supply chain and logistics, machine conditions and efficiency, production planning, machine breakdown and human performance. CAPEX was estimated to 1,029,408 USD and OPEX at 541,233 USD.

CONCLUSIONS

Emissions of heat and pollutant are serious issues in industrial sectors, leading to SBS. In most cases, employees are unaware of the dangers of poor IEQ. This study has formulated one solution to improve poor IEQ experienced in a dyehouse, situated n the north-western coastal region of Mauritius. The dilemma for project implementation is the extra operations cost while its benefits cannot be directly measured and related to increase in production. This can reduce the price competitiveness, but corporate social responsibility and environmental compliance can influence project approval phase.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the management of the dyehouse for providing access to the factory and the University of Mauritius for the support to complete this research.

NOMENCLATURE

BP	=	Breakpoint value of C_p	μg/	P	=	Pressure loss	Pa
C	=	Concentration	m^3	PM	=	Particulate Matter	ppm
HI	=	Heat index	μg/	RH	=	Relative Humidity	%
I	=	Index value	Dimensionless m^3 °C	v	=	Velocity	m/s
K	=	Fitting losses	Dimensionless				

Subscripts

d	=	Dynamic loss	p	=	Pollutant p
Hi	=	High breakpoint value of BP	v	=	Velocity pressure
Lo	=	Low breakpoint value of BP			

REFERENCES

Adewumi, B.A., Bolaji, B.O., Giwa, S.O., Layeni, A.T., Nwaokocha, C.N. and Waheed, M.A. 2020. Computational modelling and simulation of the feasibility of a novel dual purpose solar chimney for power generation and passive ventilation in buildings. *Scientific African*, 8, 298.

American Heart Association. 2010. "Scientific and Organizational Statements on the Adverse Effects of Leaf Blower-Related Air and Noise Pollution". Accessed 22 April 2020. http://lincolnrec.com/DocumentCenter/View/738/Statements-on-Pollution_consolidated?bidId=.

Arens, E., Meng, Q., Pasut, W., Zhai, Y., Zhang, H. and Zhang, Y. 2013. Comfort under personally controlled air movement in warm and humid environments. *Building and Environment*, 65, 109-117.

ASHRAE. 2001. *2001 ASHRAE Handbook*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. 2013. *ANSI/ASHRAE Standard 62.1-2013: Ventilation for Acceptable Indoor Air Quality*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1-58.

ASHRAE. 2016. *ASHRAE Handbook -- HVAC Systems and Equipment*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. 2017. *ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Bluyssen, Philomena M. 2009. *The Indoor Environment Handbook: How to Make Buildings Healthy and Comfortable.* 1st Edition. London: Earthscan.

Brightman, H.S., Cozen, M., Erdmann C.A., Girman, J.R., Lei-Gomez, Q., Mendell, M.J. and Womble, S.E. 2007. Indicators of Moisture and Ventilation System Contamination in U.S. Office Buildings as Risk Factors for Respiratory and Mucous Membrane Symptoms: Analyses of the EPA BASE Data. *Journal of Occupational and Environmental Hygiene*, 3 (5), 225-233.

Brumbaugh J.E. 2004. *Audel HVAC Fundamentals, Volume 3: Air Conditioning, Heat Pumps and Distribution Systems.* 4th Edition. United States of America: Wiley Publishing, Inc.

CIBSE. 2018. *CIBSE GUIDE A: Environmental Design*. London: CIBSE Publications.

Daisey, J.M., Deddens, J.A., Fisk, W.J., Goldman, L.R., Hodgson, A.T., Mendell, M.J., Seavey, W.G. and Smith, D.F. 1996. Elevated Symptom Prevalence Associated with Ventilation Type in Office Buildings. *Epidemiology*, 7 (6), 583-589.

Eby, K. 2017. "The Ultimate Guide to Project Cost Estimating". Accessed 15 October 2020. https://www.smartsheet.com/ultimate-guide-project-cost-estimating.

EPA. 1991. "Indoor Air Facts No. 4 – Sick Building Syndrome". Accessed 06 April 2020 https://www.epa.gov/sites/production/files/2014-08/documents/sick_ building_factsheet .pdf.

European Commission, 2003. Ventilation, Good Indoor Air Quality and Rational Use of Energy. *Urban Air Indoor Environment and Human Exposure*, 23, 1-95.

Fisk, W.J. and Seppanen, O.A. 2004. "Summary of human responses to ventilation". Accessed 07 April 2020. https://www.researchgate.net/publication/8381115_Summary _of_human_responses_to_ventilation.

Foldberg, P., Geuens, J. and Pauquay, S. 2015. Renovation of a single family house in a social housing garden city in Brussels as private-public collaboration: ambitious targets for energy, indoor climate and post-occupancy monitoring. In: M. LOOMANS AND M. TE KULVE ed. *Healthy Buildings Europe 2015*, 18-20 May 2015 Eindhoven. Virginia: International Society of Indoor Air Quality and Climate (ISIAQ), 94-99.

Gaisma. 2019. "Port Louis, Mauritius - Solar energy and surface meteorology". Accessed 18 September 2019. https://www.gaisma.com/en/location/port-louis.html.

Gulten, A. and Oztop, H.F. 2020. Analysis of the natural ventilation performance of residential areas considering different urban configurations in Elazığ, Turkey. *Urban Climate*, 34.

Gunay, H.B., Mahdavi, A., O'Brien, W. and Tahmasebi, F. 2016. A preliminary study of representing the inter-occupant diversity in occupant modelling. *Journal of Building Performance Simulation*, 10 (5), 509-526.

Hasanbeigi, A. 2010. "Energy-Efficiency Improvement Opportunities for the Textile Industry". Accessed 07 April 2020. https://www.osti.gov/servlets/purl/991751-BePVH5/.

HSE. N.D. "Thermal comfort checklist". Accessed 19 April 2020. https://www.hse.gov.uk/temperature/assets/docs/thermal-comfort-checklist.pdf.

Huh, J., Kim, Y., Kwak, Y. and Mun, S. 2019. A Comprehensive Thermal Comfort Analysis of the Cooling Effect of the Stand Fan Using Questionnaires and a Thermal Manikin. *Sustainability*, 11, 1-18.

ISO. 2004. *ISO 16000-1: Indoor air – Part 1: General aspects of sampling strategy*. 1st Edition. Switzerland: International Organization of Standardization.

ISO. 2018. *ISO 19011: Guidelines for auditing management systems*. 3rd Edition. Switzerland: International Standards Organization.

Jaakkola, J.J. and Miettinen, P. 1995. Ventilation rate in office buildings and sick building syndrome. *Occupational and Environmental Medicine*, 52 (11), 709-714.

Kamaruzzaman, S.N., Mahbob, N.S., Salleh, N. and Sulaiman, R. 2011. A Correlation Studies of Indoor Environmental Quality(IEQ) Towards Productive Workplace. In: IPCBEE, ed. 2011 *2nd International Conference on Environmental Science and Technology*, 26-28 February 2011. Singapore: IACSIT Press, 434-438.

Komfovent. 2018. "Ventilation equipment market trends". Accessed 05 April 2020. https://www.komfovent.com/en/news/ventilation-equipment-market-trends.

Leakair. N.D. "Air Changes Per Hour". Accessed 01 May 2020. https://www.lakeair.com/air-changes-per-hour/.

Mujeebu, M.A. 2019. "Introductory Chapter: Indoor Environmental Quality". Accessed 08 April 2020. https://www.intechopen.com/books/indoor-environmental-quality/introductory-chapter-indoor-environmental-quality. NIOSH. 2017. "Heat Index: When humidity makes it feel hotter". Accessed 14 April 2020. https://blogs.cdc.gov/niosh-science-blog/2017/06/05/heat-index/.

NOAA. 2018. "Heat Index Calculator". Accessed 21 April 2020. https://www.wpc.ncep.noaa.gov/html/heatindex.shtml.

Oxycom. 2017. “Air Changes Per Hour”. Accessed 01 May 2020. https://www.cci-dialog.de/branchen/branchenverzeichnis/oxycom/downloads/air_ changes_per_hour.pdf.

Popovici, C.G. 2017. HVAC System Functionality Simulation Using ANSYS-Fluent. *Energy Procedia*, 112, 360-365. Ronald, P.T. 1994. Relevant moisture properties of building construction materials. In: H.R. TRECHSEL, ed. *Moisture control in buildings*. Philadelphia: American Society for Testing and Materials, 35.

Sherman, M.H. 1990. Tracer-Gas Techniques For Measuring Ventilation in a Single Zone. *Building and Environment*, 25 (4), 365-374.

Srivajana. 2003. Effects of Air Velocity on Thermal Comfort in Hot and Humid Climates. *Thammasat International Journal of Science and Technology*, 8 (2), 45-54.

Statistics Mauritius. 2013. “Continuous Multi-Purpose Household Survey – 2013”. Accessed 06 April 2020. http://statsmauritius.govmu.org/English/Publications/Documents/2005/EI0505/ ESI%200505.pdf.

Statistics Mauritius. 2018. *Digest of Environment Statistics 2017*. Volume 16. Mauritius: Statistics Mauritius.

Temtop. 2019. “Temtop LKC-1000S+ Air Quality Detector Professional Formaldehyde Monitor Detector with HCHO/PM2.5/PM10/TVOC”. Accessed 11 April 2020. https://temtopus.com/products/temtop-lkc-1000s-air-quality-detector-professional-formaldehyde-monitor-detector-with-hcho-pm2-5-pm10-tvoc.

Toyinbo, O. 2019. Chapter 4 - Indoor Environmental Quality. In: V.W. TAM AND K.N. LE, ed. *Sustainable Construction Technologies*. Australia: Butterworth-Heinemann, 107-122.

USEPA. 2006. *Guidelines for the Reporting of Daily Air Quality – the Air Quality Index (AQI)*. North Carolina: U.S. Environmental Protection Agency.

USGBC. 2014. “Green Building 101: What is indoor environmental quality?”. Accessed 08 April 2020. https://www.usgbc.org/articles/green-building-101-what-indoor-environmental-quality.

Wang, S.K. 2001. *Handbook of air conditioning and refrigeration*. 2nd Edition. USA: The McGraw-Hill Companies, Inc.