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RESEARCH ARTICLE

INTERRELATION OF ATTRIBUTES OF OCCUPANT'S COMFORT, VENTILATION SYSTEM AND INDOOR AIR QUALITY IN RESIDENTIAL BUILDINGS

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ABSTRACT

Indoor environmental conditions, attributes of indoor air quality, their mutual correlation and SBS effect studied for non-air-conditioned residential areas of composite climate. As in residential areas like other buildings, toilets are most neglected areas as far as light and ventilation is concern. Author focused on this issue to improve IAQ and reduce SBS effect. 100 cases (50 directly ventilated and 50 indirectly ventilated cases) are taken as case studies/ sample studies and qualitative and quantitative data collected through resident's personal interview and physical survey of residences (information about temperature, humidity, air velocity, Carbon dioxide concentration and areas of toilets and their ventilator/window collected by using mechanical/digital instruments) respectively. For assessing the indoor air quality level CO_2 concentration is measured. Although CO_2 is not directly responsible for SBS effect or dangerous; but it is considered as a representative of air pollution and very easily measurable too. After detailed analysis, it is concluded that direct ventilation is preferable for maintaining desired level of air change and indoor air quality.

INTRODUCTION

Practical Implications: Considering the CO_2 concentration as representative of air pollution; CO_2 level in differently ventilated spaces measured and found that "AIR EXCHANGE" is the key factor for improving ventilation level and reduce SBS effect in indoor spaces. For desired/ recommended air exchange, air velocity difference in outdoor and indoor area plays a major role and floor-window area ratio cannot be a designing criterion for improving ventilation level. To achieve the goal passive as well as active design techniques shall be adopted in case of direct and indirect (majorly) ventilation system (ventilation through ducts in multi-storeyed buildings). People occupy a building to work or to reside in more comfortable andprotected manner, but sometimes buildings in itself becomes the cause of illness due to presence of few unwanted /inappropriate physical as well as social environmental features; such condition is described as SBS (Sick building syndrome). With the trend of modernisationandurbanisation this phenomenon is being more prevalent and this paper is focusing on this issue (especially in residential areas) only. This does not mean that author is against the modernisation and urbanisation; but seeking the attention of policy makers,stakeholders, researchers, medical practitioners and other governing bodies towards this burning issue and expect to practice an integratedapproach for getting out of wrong practices.

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Author finds that Dimensional and spatial features, Visual, Auditory and Tactilefeatures, Social indoor environmental features are the point of consideration for creating a healthy and safe environment for users.[1]. Amongst all environmental features, 'Indoor air quality' is the most prominent feature which affects all the users almost in a same manner. Various attributes of IAQ are temperature, humidity, air movement, presence of various harmful pollutants in indoor air. Their interdependence may also accelerate the process of IAQ quality declination and SBS effect stimulation.This paper is in special reference to IAQ of toilets of non- air conditioned or partially air-conditioned residential building (single and multistoried) of composite climate in Indian context. Looking the contextual aspect and future development prospects, "Moradabad" city is chosen a study area. It is a part of western Uttar Pradesh and a historical and industrial city in vicinity of Delhi. It is well known as "Brass city". Approach methodology is used for investigating various cases similar to the current context of research to assess the households' satisfaction levels against various attributes of well-being. These case studies will help to gauge the true condition of area/zone and to know that whichpart actually needs a critical attention. Various instruments were used for measuring attributes of occupant's comfort and personal interviews were conducted for collecting user's opinion.

Attributes of occupant's comfort:

Temperature: Thermal conditions in living and working environment play an important role in providing a comfort

level.It may affect the work efficiency and health of occupants. Higher temperature may cause heat stroke and dehydration and in lower temperature occupants feel chilling, shivering. Occupants feel severe discomfort.[2]As every individual has different metabolism and tolerance, it is difficult to satisfy all of them (physiologically and psychologically) at the same condition; it is needed to find a level where majority may feel satisfied and comfortable.[2]As per the recommendation of National building code 2005 occupants feel comfortable if temperature varies from 25 degree to 30 degree[3].Although outdoor temperature is major factor to controls the thermal conditions of indoor temperature, but some other factors like humidity level, air movement, fenestration design, building material etc may improve the conditions.

Relative Humidity

Relative humidity is *"the ratio of the partial pressure or density of the water vapour in the air to the saturated pressure or density respectively of water vapour at the same temperature."*[4]

RH uptoan extent of 65% does not cause discomfort. If RH is in the range of 80%+ then it evident that the grains of moisture in air are high.[5]Closer the proximity of moisture particles, greater is the heat retention because moisture grains absorb the convection and radiation heat. Furthermore, greater the density of moisture particles greater is the conductive heat. In such a condition, human beings cannot dissipate their body heat to the atmosphere and as a result sweat a lot. Sweating is an uncomfortable predicament. On the other hand very low humidity may cause dryness of skin and mucus membrane in the nose, throat and eyes.ASHRAE considers that the problem of humidity driven mould is a serious cause of Sick Building Syndrome.[5]National building code 2005 has given some specific recommendations for relative humidity. As per NBC standards RH between 40 to 70% is mostly acceptable.[6]

Air movement

Air movement in buildings can be achieved due to difference in pressures of two spaces (indoors to outdoors or indoor to indoor). It may be created either by natural forces (wind induced pressure difference and stack effect) or mechanical power (fan) because air moves from high pressure regions to lowpressureones. While air movement can be pleasant and provide comfort in some circumstances, it is sometimes unwanted and causes discomfort. In case of extreme winters, higher air movement is unwanted. It is very harmful for health conditions. In case of high humidity and high temperature air movement is highly desirable and in case of high humidity and low temperature air movement may be an unpleasant phenomenon for occupants. Air movement also helps in improving Air change (used air of indoor replaced by fresh air of outdoor), which is good for a healthy environmental conditions.National building code has given some specific recommendations for air change for various type of building.[7]
Carbon dioxide (CO_2) as representative of pollution levelCarbon dioxide is one of the major human metabolite (bioeffluent). As humans are the main indoor source of carbon dioxide in residential buildings; concentration of CO_2 in buildings is higherthan outdoors. The level of CO_2 that occurs indoors thus depends predominantly on humanoccupancy and the rate of air exchange with outdoor (naturally or mechanically).

The high level of Carbon dioxide may lead to drowsiness, reduced activity level and headache amongst the occupants but it is neither an indoor pollutant nor a direct health risk for occupants. Since it is relatively easier to measure CO_2 level compared to other pollutants, it is used as an indicator of ventilation efficiency[8]. The effects of CO_2 on adults at good health can be summarized to[9]:

350 - 450 ppm-Normal outdoor level
600 ppm- Acceptable levels
600 - 1000 ppm- Complaints of stiffness and odours
1000 ppm- ASHRAE, NIOSH and NBC standards
1000 - 2500 ppm- General drowsiness
2500 - 5000 ppm- Adverse health effects may be expected
5000 - 10000 ppm - Maximum allowed concentration within a 8 hour working period
30000 ppm- Maximum allowed concentration within a 15 minute working period
30000 - 40000 ppm- Slightly intoxicating, breathing and pulse rate increase, nausea
50000 ppm- Above plus headaches and sight impairment
100000 pp- Unconscious, further exposure death
*ppm - parts per million

The levels above are quite normal and maximum levels may occasionally happen from time to time. In general - ventilation rates should keep carbon dioxide concentrations below 1000 ppm to create indoor air quality conditions acceptable to most individuals.

MATERIALS AND METHODS

Physical Survey

The city under consideration was surveyed physically to get the perception of the integration of built environment and indoor air quality. Primary data is collected in form of Sample survey of households, Questionnaires, Observations and Informal Interviews.Sample Survey of Slum households Sample survey was done in different residential colonies of Moradabad to find out the key issues and occupants problem. After doing the sample survey, we were able to further limit the scope of this survey/research. Few outcomes were:

- Survey only pacca houses
- House of age should be between 01 to 15 years
- Toilets of the houses should be either directly or indirectly ventilated

(Direct ventilation means when window or ventilator is directly exposed to outside space/air and having no obstacle near-by and Indirect ventilation meanswhen window or ventilator is indirectly exposed to outside space/air due to presence of some physical obstruction, Example- ventilation through duct.)

A comprehensive list of well-being attributes was prepared compiling the attributes of well-being suggested by eminent researchers and research agencies. Survey format is developed using the formats given in guidelines provided by various research programs as a base, and research specific need. A representative sample size of the dwellings of city under consideration was taken for Primary survey. The size of the sample is constrained by the resources and time available.

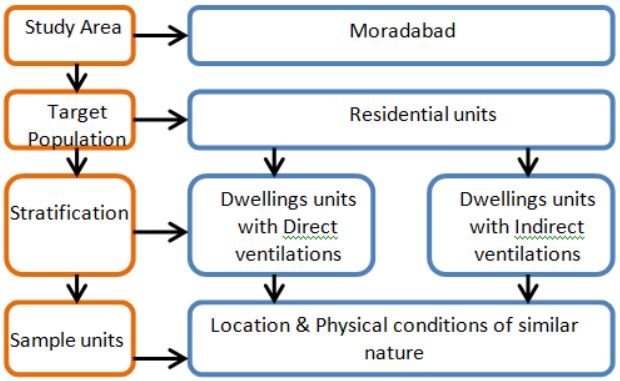


Figure 1. Sample selection Methodology; Source-Author

Case study approach is found suitable for limited resource availability. It also provides opportunities to compare various cases. However case study approach applies to particular contexts hence the inferences from case study cannot be applied universally but it helps in identifying most realistic solutions. Since the households/dwellings need to be dealt in their particular context (climatic conditions), case study approach is found to be most suitable for research. This research considers newly established (within 15 years) residential colonies of Moradabad City (part of western Uttar Pradesh) for household survey with a sample size of 150 households. Random selection of samples produces minimum error therefore attempts are made to randomize the sample selection process to reduce systematic biases. While selecting the samples, a special consideration was given on the type of ventilation systems of various spaces of those dwellings; so that a varied behaviour of ventilation system and their outcome (indoor air quality) will give the real scenario and genuine outcome.The secondary data specific to the cases considered for research is collected from various concerned standards, byelaws, findings of researchers. The recommended standards of atmospheric conditions are taken from National Building code (NBC), basics of SBS, their effects and causes are taken from findings of researchers, engineers and scientists.

Effect of Window-floor area ratio and its position on Temperature

Window-floor area ratio and its position play a major role in balancing indoor temperature and outdoor temperature.

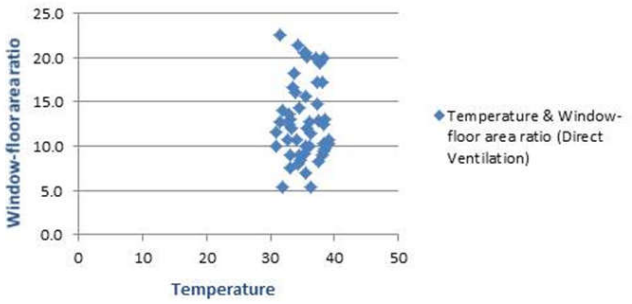
In case of direct ventilation (window opening directly in outdoor space), we found a better correlation between window-floor area ratio and indoor temperature rather than in indirect ventilation (ventilation through duct).

The graph (Figure-2) above indicates that in case of indirect ventilation, it is difficult to maintain desired indoor temperature even by achieving recommended standards of window-floor area ratio.

Effect of temperature on Relative humidity

Relative humidity is a measure of how much water vapour is in the air relative to how much water vapour the air is capable of holding. If the relative humidity is 50% the air is only holding half as much water vapour as it's capable of holding. How much water vapour air capable of holding is determined by its temperature.

Temperature & Window-floor area ratio (Direct Ventilation)



Temperature & Window-Floor area ratio (Indirect Ventilation)

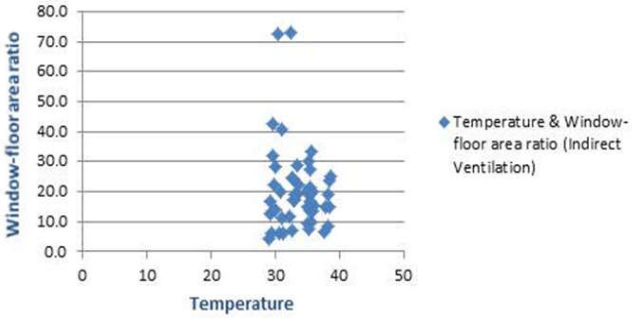
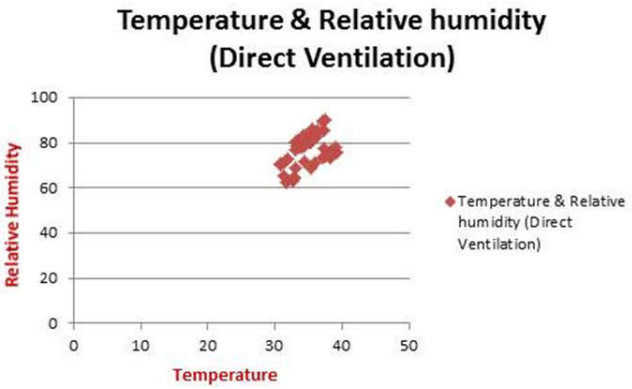


Figure 2. Graph showing corelation between Window-floor are ratio & indoor temperature, Source- Author



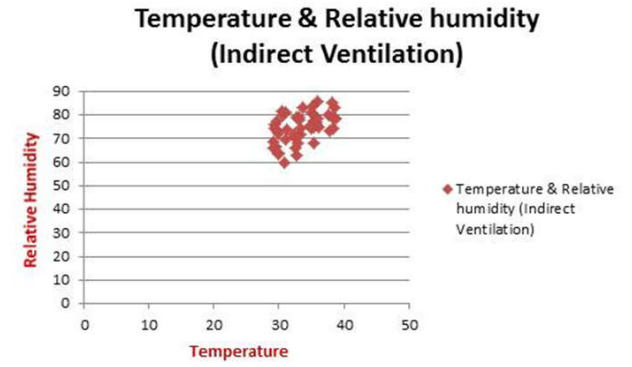


Figure 3. Graph showing corelation between indoor temperature & Relative Humidity, Source- Author

When air is warm, it expands and allows more room between the air molecules to hold water vapour; thus warm air can hold large volumes of water vapour. When air cools it contracts and allow for less room between air molecules. Thus, as temperature decreases, the relative humidity will increase, and likewise, as temperature increases, the relative humidity will decrease.

The graph (Figure-3) above indicates that we need to control indoor air temperature for maintaining desired level of humidity in all the cases (directly as well as indirectly ventilated rooms).Effect of Window-floor area ratio on rate of Air changeWindow floor area ratio is very important for air change. It was found that as the window floor area increases the rate of air change increases; and this corelation can be seen more constant in direct ventilation rather than indirect ventilation.

Method for calculation of Rate of air change[10]

Rate of Air change is defined as the amount of air volume added or removed from an enclosed space divided by the volume of space. Air change per hour (ACPH or ACH) is a measure of how many times the used/ indoor air is replaced by outdoor/fresh air.The actual rate of air change is depends on the many factors like air velocity, opening/duct sizes, methods used for ventilation. For achieving a stage of equilibrium, the amount of air leaving the space and entering the space must be the same.

ACH equation in Imperial units

$$N = \frac{60Q}{Vol}$$

Where:

- N = number of air changes per hour
- Q = Volumetric flow rate of air in cubic feet per minute (cfm)
- Vol = Space volume L × W × H, in cubic feet

For determining the rate of ventilation based on wind action the wind may be assumed to come from any direction within 45 degree of the direction of prevailing wind. Ventilation due to external wind is given by the following formula[11]:

Q = KAV

Where
Q = Rate of air flow in meter cube/hour
K = Coefficient of effectiveness, which may be taken as 0.6 for wind perpendicular to openings and 0.3 for wind at an angle less than 45 degree to the openings.
A = Free area of inlet openings in meter square
V = Wind speed in meter/hour

Ventilation rates are often expressed as a volume rate per person (CFM per person, L/s per person). The conversion between air changes per hour and ventilation rate per person is as follows[10]:

$$Rp = \frac{ACPH * D * h}{60}$$

Where:

R_p = ventilation rate per person (CFM per person, L/s per person)
ACPH = Air changes per hour
D = Occupant density (occupants per square foot, occupants per square meter)
h = Ceiling height (ft, meters)
Air change rates are often used as rules of thumb in ventilation design.

In graph (Figure 4) above clearly shows that in case of indirect ventilation rate of air change is less than the required in almost all the cases. This indicates that direct ventilation is preferable to get best advantage of provided opening for getting higher rate of air change and finally a better quality of Indoor air.

Effect of Air change on indoor pollution level

The issue about ventilation efficiency is getting more and more people's attention. Although there are number of ways to evaluate the ventilation performance of a space, but analysis of CO_2 concentration is a space is most popular and commonly acceptable to evaluate the specific aspects of IAQ. CO_2 is a common air constituent and major source of CO_2 are industries and fuel combustion.

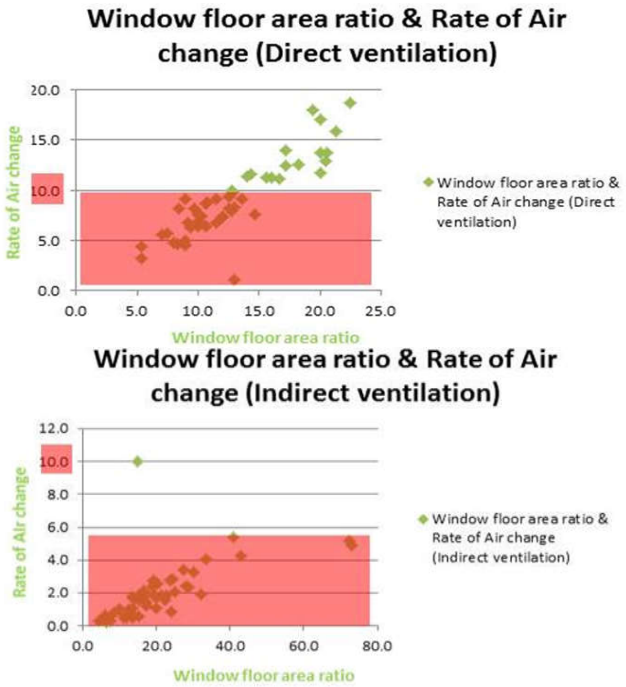


Figure 4 . Graph showing corelation between Window-floor are ratio & Rate of Air change, Source- Author

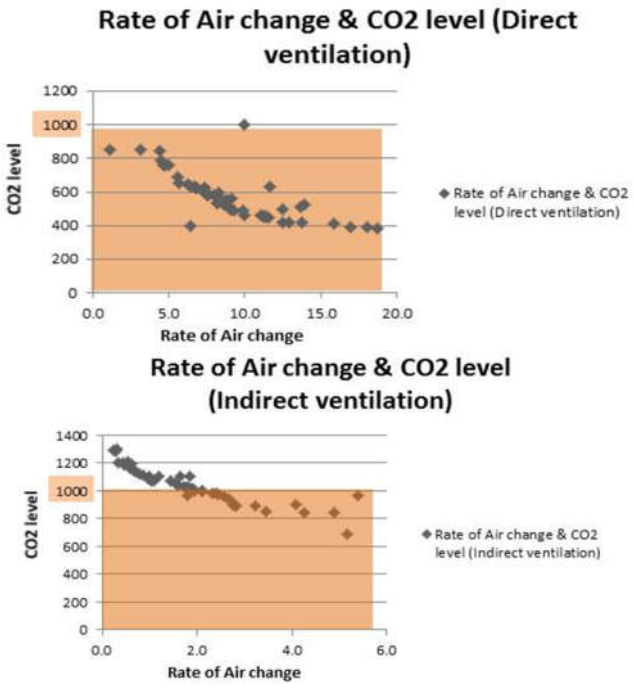


Figure 5. Graph showing corelation between CO_2 level & Rate of air change, Source- Author

In residential area (non-industrial areas) major source of CO_2 are the human beings (respiration system) only. Although it is not a dangerous or poisonous air but its higher concentrations may significantly affect the mucous membrane (dry eyes, sore throat, nose congestion, sneezing) and lower respiratory related symptoms (tight chest, short breath, cough and wheeze). Its higher levels may also cause headaches and affects the respiratory pattern. As occupants are the main source of indoor CO_2, its concentration levels in indoor air becomes a clear indicator of ventilationefficiency. In above graphs (Figure-5) can be seen that Co_2 concentration level and rate of Air change are inversely proportion to each other. Means the higher rate of air change will lead to lesser CO_2 concentration level and better and safer indoor air environment and this co-relation could be found better in case of direct ventilation rather than in indirect ventilation. This phenomenon is not always same, because it depends on the number of occupants and their living pattern too.It can also be seen that in case of indirect ventilation CO_2 concentration level is higher than the recommended level (1000ppm) in maximum cases.

Recommended design strategies for increasing ventilation to improve IAQ

This paper is focused for composite climate and in composite climate we face different weather conditions like (i) very low temperature (till 3 to 4 degrees) in winters with low humidity, (ii) very high temperature (upto 48 degrees) in summers with moderate humidity and the most challenging i.e. (iii) high temperature with high humidity in monsoons. As we discussed earlier, in case of high temperature and high relative humidity level the occupants feel a problem of sweating and exhaustive; we need to increase air movement for better indoor environmental conditions. Design solutions for all three conditions are as follows:

Provision of multiple openings with staggered positions

Higher window floor area ratio is preferable in composite climatic conditions, because in case of extreme winters and summers, the openings may get closed (fully or partially) in different parts of the day as per requirement and benefits of sunlight (heat and anti-bacterial property) can still be enjoyed by providing clear glass panes.

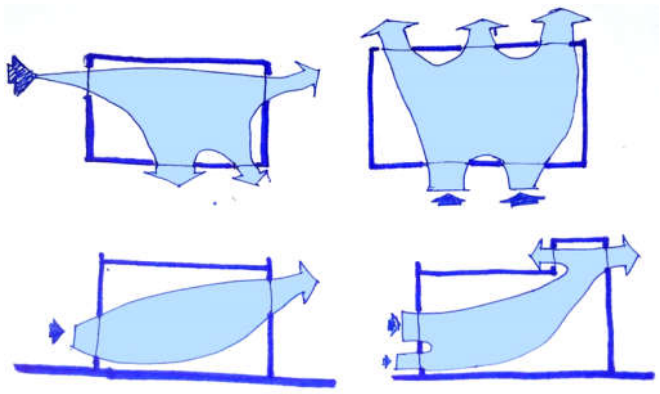


Figure 6. Staggered position of openings improves air movement, Source- Author

In monsoon season, these multiple windows helps in improving air movement/cross ventilation to improve indoor environmental conditions. In such case window/opening positions and area both play important roles.

Provision of shaft effect in multi-storied buildings

In multi-storied building, we generally provide shafts for ventilation of washrooms and kitchens. The cross section of these shafts is very less as compared to height. In such cases where we face difficulty in getting natural ventilation due less air pressure and less cross section of shaft, we need to give forced ventilation by providing exhaust fans at the top of the shaft. When these exhaust fans sucks the used (warm) air from indoor spaces via shaft, then due to pressure difference the fresh (cool) air get sucked from openings of the building from the lower level. Shaft effect is very effective and economical method for getting natural ventilation in multi-storied buildings.

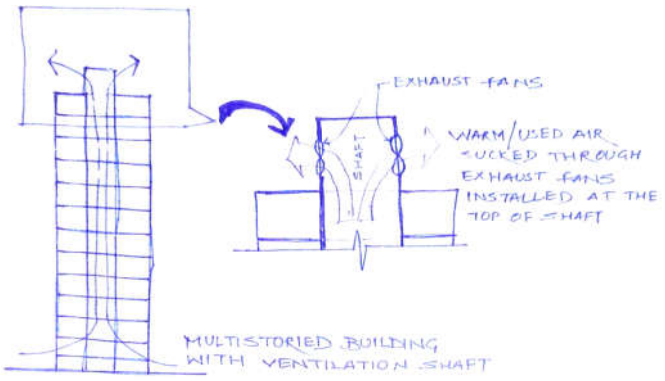


Figure 7. Shaft effect in multistoried building, Source- Author

Provision of Stack effect in building

Stack effect in building occurs due to Buoyancy effect. It is the movement of air into and out of buildings due to difference in indoor-to-outdoor air temperature. As the indoor used air gets warmer, its density reduces and the phenomena occurs. Stack effect or buoyancy effect accelerates with the thermal difference and the height of the structure. The stack effect is also known as the "chimney effect", and it helps in improving natural ventilationand infiltration.

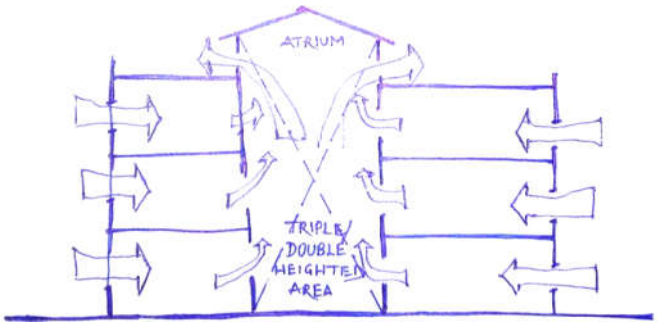


Figure 8.Stack effect in building through atrium/ double/triple heighted areas, Source- Author

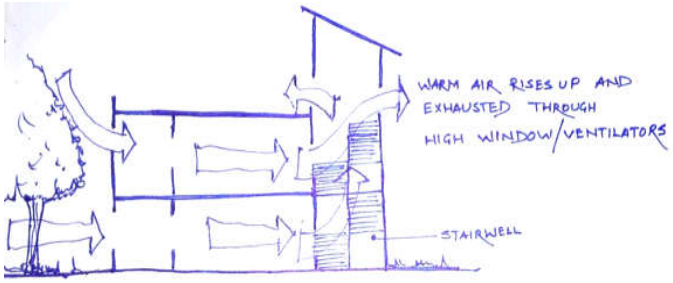


Figure 9. Stack effect in building through stairwell, Source- Author

In summer season seasons the warmer indoor air rises up and escapes at the top through intentionally designed opening or unintentionally left out openings. The rising air reduces the pressure at the base of the building, so the building starts sucking cold air through openings (door/ window/ other openings). In winter season seasons this effect is reversed, but is weaker due lesser pressure difference. In buildings stairwells, shafts, elevators, and the like, tend to contribute to the stack effect. (Note: Buoyancy (also known as the buoyant force) is the force exerted on an object that is wholly or partly immersed in a fluid.)

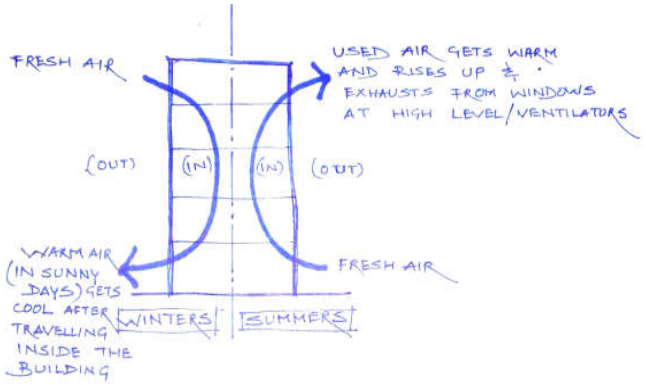


Figure 10. Air movement in building due to difference in temperature & air pressure, Source- Author

Conclusion

The main findings of this study can be divided in two sections. Section one is establishing some fact about correlation of major attributes of IAQ after doing an analytical study of interdependence of different attributes of comfort level like temperature, humidity, air velocity and CO_2 level and another section is about suggesting passive design strategies for improving IAQ level.

Recommendations

From all above discussions, it is concluded that in case of composite climate most important phenomenon is the "AIR VELOCITY" for achieving desired level of Air change andother attributes of comfort level (like temperature, humidity, CO_2 concentration) and satisfactory IAQ.

As in case of directly ventilated cases, it is easy to get air pressure difference between outdoor and indoor and air velocity as resultant, direct ventilation is preferable. In case of directly ventilated, but lesser air pressure in outdoor atmosphere and indirectly ventilated spaces; forced ventilation methods needs to be adopted to achieve recommended standards (NBC and ISHRAE) of air change and indoor pollution level to achieve acceptable comfort level and IAQ.

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