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THE EFFECTIVENESS OF VERNACULAR STACK VENTILATION WITH APPLICATION IN MODERN AND RETROFITTED BUILDINGS

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ABSTRACT: Ventilation is a vital aspect in an internal environment for every room occupant to achieve basic health requirements and acceptable thermal comfort. To achieve the required ventilation rate, mechanical ventilation is generally used in modern buildings. This comes at an energy cost required in operating the necessary equipment. In some cases, it makes sense to make use of natural ventilation depending on site conditions. Vernacular stack ventilation systems use vents to try to achieve modestly ventilated spaces. At the moment, there is little to no knowledge on their effectiveness and no quantification of the ventilation rates can be found from the addressed literature. This research aims at bridging this gap in knowledge. The ventilation flow rates resulting from vents are numerically assessed using a hypothetical test room as well as a case study. On the basis of this, new modifications are proposed and analysed. The purpose of this is to enhance the ventilation flow rates and compare them with established ventilation standards. The numerical approach used here is based on Computational Fluid Dynamics (CFD). The results obtained are promising, as the studied case was found to result in an air change rate of 3.2l/s or 0.13 ACH for a typical summer condition while the enhanced natural ventilation case produced a ventilation rate of 5.8 l/s or 0.23 ACH, with a significant improvement in comfort. Upon further research, such a vernacular ventilation system using vents could be an important yet simple and relatively maintenance free approach. This can aid in reaching nearly zero energy targets for buildings.

Keywords: Natural Stack Ventilation, Retrofitted Buildings, Energy Efficiency, Computational Fluid Dynamics (CFD)

1 INTRODUCTION

This study analyses the effectiveness of the natural stack effect generated by the vernacular ventilation systems (1960's) which make use of vents and how such systems can be best enhanced to implement in the modern buildings construction. Such system aims at improving comfort conditions to the occupants while reducing the reliance of mechanical ventilation to improve energy efficiency.

To the author's best knowledge there is very little information in literature specifically dealing with this kind of system. This is partly because of the vernacular character of this feature in building engineering design.

1.1 Aims

The aims of this work can be summarised as follows:

1. To define to what extent the stack ventilation in vernacular buildings are effective as a means of ventilation to control the indoor temperature and air quality.
2. To establish new and more effective passive ventilation strategies without affecting the vernacular character of the building.

2 LITERATURE REVIEW

2.1 Natural Ventilation

In order to understand well the requirements of natural ventilation, one must understand thermal comfort and air quality needs of occupants. Thermal loads from occupants can be divided into two main types including the latent and sensible heat. Latent heat (kJ/kg) is the amount of heat energy that will be absorbed in the change of state (solid, liquid and gas) without change in temperature. While sensible heat (kJ/kg) is the energy absorbed in its original state. [25]

The well-known energy balance on the human body is written hereunder:

$$S = M + W + R + C + K - E - RES$$

Where:

S is the heat storage in body – the total heat in the body
M is the metabolic rate – the rate of burning calories (convection)
W is mechanical work – activity done
R is the heat exchange by radiation – the energy in the form of waves or particles
C is the heat exchange by convection – movement of particles within a fluid (air, liquid, gas)
K is the heat exchange by conduction – direct transfer of heat from clothes
E is the evaporative heat loss – this is the sweat
RES is the heat loss by respiration – heat loss from breathing [9]

2.2 Vernacular Architecture

Vernacular architecture in Malta is still the dominant form of architecture today as this can be easily found in old town including Mdina, Valletta, Zejtun and other typical layouts. These towns have their urban planning designed in such way so as to enhance natural ventilation. The emphasis of this literature review is placed on the typical ventilation system used in the 1960s including stack ventilation. However, one should note the importance of urban planning design as a means of enhancing natural ventilation. The actual ventilation system alone without good urban planning design will not give satisfactory natural ventilation performance.

2.3 Natural Ventilation in Modern Buildings in Malta

Stack ventilation strategies in architectural context have been used for centuries in order to aid human comfort in the internal environment. In modern buildings, stack ventilation should also be given importance at design stage. Modern buildings have good potential for stack ventilation since most of them have multiple floors. Also cross ventilation potential is many times not possible in highly dense urban settings.

Considering that this design strategy requires the temperature differential from the indoor to the outdoor, one can find various types of stack ventilation and some of them have been developed to enhance this strategy in modern buildings. [9]

On the other hand, nowadays considering hotter climates and denser built environment, cross ventilation might not be ideal. This is due to the fact that the requirements of modern buildings include a more compact layout of planning which leads to limited openings for cross airflow. Therefore, for such modern buildings the most efficient natural ventilation method will be an outlet at the highest point of the building in order to increase vertical air movement.

3 METHODOLOGY

3.1 General approach

This study was based on a purely numerical approach. First the performance of a simple room geometry is modelled with a single occupant represented as a block. Secondly a typical vernacular stack system was identified as a case study. Both cases are analysed using an advanced computational fluid dynamics (CFD) approach in 2D for more efficient computation. Given that the scope is limited to establishing first hand estimates of the performance of the system, the 2D approximation is considered to be adequate at this stage.

3.2 Basic Room Geometries

The following are the vernacular ventilation detail geometry and the rooms geometries used for this study. These rooms include a typical room and an open plan office as a case study.

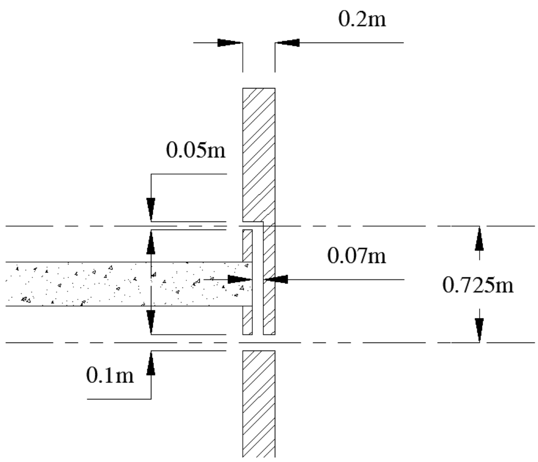

Figure 1: Vernacular Ventilation Detail (NTS)

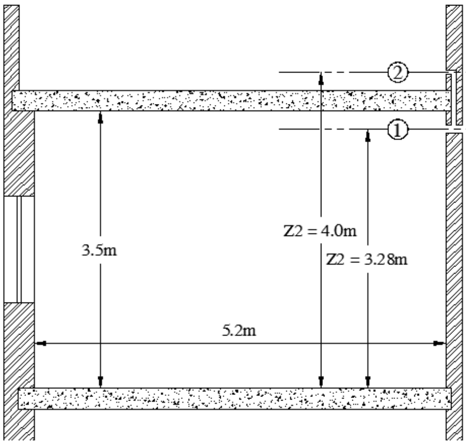

Figure 2: Typical Room used for Analytical Approach (NTS)

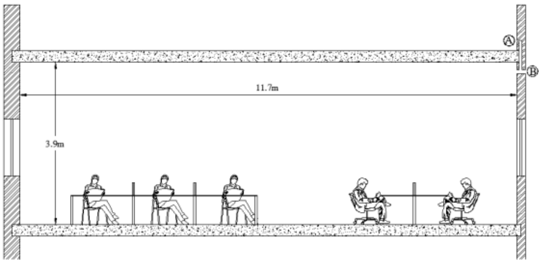

Figure 3: Case Study - Open Plan Office

3.3 Sample Investigation – Cases Considered

The following cases were considered in this study. These include modifications in the same design, additional features and a case study of an open plan office.

Table 1: Cases Considered

Case	*Description*	*Vent A*	*Vent B*	*Airtight Closed Windows*	*Window C*	*Air leakage from Windows*
1	The vernacular ventilation system with airtight closed windows	☑	☑	☑		
2	Vernacular system with the traditional vent closed and airtight closed windows	☑		☑		
3	The vernacular ventilation system with left side window open	☑	☑		☑	
4	Vernacular system with the traditional vent closed and left side window open	☑			☑	
5	Traditional vent open and airtight closed windows		☑			
6	The vernacular ventilation system and air leakage from windows	☑	☑			☑
7	Vernacular system with the traditional vent closed and leakage from both windows	☑				☑
8	Traditional vent open and leakage windows		☑			☑
9	New design with vernacular ventilation system and air leakage from windows	☑	☑			☑
10	New design with closed traditional vent and air leakage from windows	☑				☑
11	New design with traditional vent only and air leakage from windows		☑			☑
12	Case study with vernacular ventilation system and air leakage from windows	☑	☑			☑
13	Case study with closed traditional vent and air leakage from windows	☑				☑
14	Case study with traditional vent only and air leakage from windows		☑			☑

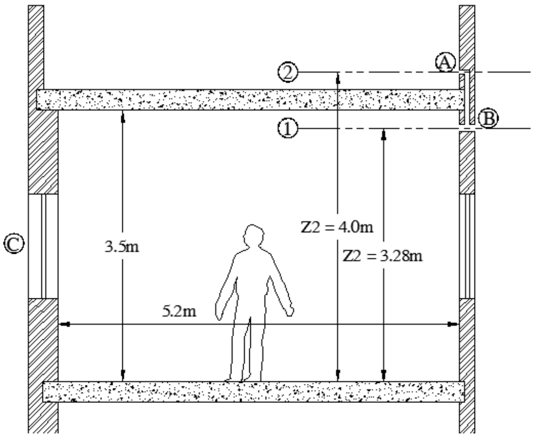

Figure 4: Typical Room used for CFD Approach

These include different combinations of the ventilation system, windows and air leakages.

3.4 Computational Fluid Dynamics (CFD) Approach

It is important to note that this study is based on convection heat released (assuming 70W/m² metabolic rate for a person sedentary/working in an office environment [9]) only, therefore the following criteria that are part of the energy balance equation for the human body were not considered:

- Radiation
- Evaporation
- Respiration
- Conduction

3.4.1 Geometry and meshing

The geometries of both test cases as shown in Figure 2 – Basic Room Geometries were constructed. These were then meshed using an unstructured grid avoiding excessive cell distortion. Mesh independence studies were also carried out successfully.

3.4.2 Meshing

Once the geometric model was completed, the next step was to mesh the model. This step is very important as it is the main structure of CFD. It is therefore important to be done as smooth as possible, as an inappropriate mesh can lead to longer computational time, non-physical behaviour, un-converged solutions and misleading results. There are three main classifications of meshes as follows: the structured, unstructured and the hybrid. In this case the mesh must be structured.

Structured grids include quadrilateral cells and have several advantages including faster and easier convergence, accurate results and more efficient in terms of cells. On the other hand, an unstructured grid is the other way round that means slower convergence and inaccurate results. While the hybrid mesh is a combination of both [24]

3.4.3 Boundary Conditions

The boundary conditions that were named in the meshing part were selected one by one to configure the appropriate properties including the type of boundary. In this study, the following types were required to be used: wall, pressure-outlet and velocity-inlet. Apart from the type, the temperature of 296K equivalent to 23℃ (standard internal temperature) was used. Walls were assumed to have no slip and a roughness constant of 0.5 was chosen along with zero roughness height. For the pressure-outlet, the backflow total temperature was set at 299K equivalent to 26℃ (average external temperature in summer). Finally the velocity-inlet was set to a magnitude of 0.3m/s that was changed to 0.01m/s for different cases by the working the air infiltration from windows and also with the same external temperature. Such properties were set as shown in table 2.

Table 2 – Boundary Conditions Properties

Case	Inlet C – Right Side Window	Outlet A – Upper Vent	Outlet B – Lower Vent
1	Wall 23˚C	Pressure outlet 23˚C	Pressure outlet 23˚C
2	Wall 23˚C	Pressure outlet 23˚C	Wall 23˚C
3	Velocity inlet 26˚C and 0.3m/s velocity	Pressure outlet 23˚C	Pressure outlet 23˚C
4	Velocity inlet 26˚C	Pressure outlet 23˚C	Wall 23˚C
5	Wall 23˚C	Wall 23˚C	Pressure outlet 23˚C
6	Velocity inlet 26˚C and 0.01m/s velocity	Pressure outlet 23˚C	Pressure outlet 23˚C
7	Velocity inlet 26˚C and 0.01m/s velocity	Pressure outlet 23˚C	Wall 23˚C
8	Velocity inlet 26˚C and 0.01m/s velocity	Wall 23˚C	Pressure outlet 23˚C
9	Velocity inlet 26˚C and 0.01m/s velocity	Pressure outlet 23˚C	Pressure outlet 23˚C
10	Velocity inlet 26˚C and 0.01m/s velocity	Pressure outlet 23˚C	Wall 23˚C
11	Velocity inlet 26˚C and 0.01m/s velocity	Wall 23˚C	Pressure outlet 23˚C
12	Velocity inlet 26˚C and 0.01m/s velocity	Pressure outlet 23˚C	Pressure outlet 23˚C
13	Velocity inlet 26˚C and 0.01m/s velocity	Pressure outlet 23˚C	Wall 23˚C
14	Velocity inlet 26˚C and 0.01m/s velocity	Wall 23˚C	Pressure outlet 23˚C

3.5 Solution Methodology

The setup for the calculations parameters were set as follows:

3.5.1 Time discretisation

At first, the simulation was set to steady for 10,000 iterations and then changed to transient for 240 time steps for 1 minute (60/0.25) with a size of 0.01s. This was repeated till the calculation converged.

3.5.2 Models

The energy equation was used for this study. For turbulence modelling, the SST k-ω was used due to the fact that various literature references make use of this model for internal flows. Also, modelling of turbulence in the case of natural convection is known to be well predicted using the SST k-ω model [8,11,13].

3.5.3 Materials

Fluid chosen was air having a density of 1.225kg/m^3 which varies according to the ideal gas equation. The viscosity was set to1.7894×10^{-5}.

3.6 Verification

In order to verify the model calculation, both the residual and monitor convergence were required. Velocities were assessed at various locations in the model including around the human body and the vent. These were created to verify the calculation of the scaled residuals including the continuity, x and y velocities, energy, k, and omega. Temperature monitoring points were also used. The convergence history of the residuals and monitors was applied for all cases. It was ensured that both monitors and residuals showed convergence. All residuals reduced below 10^{-5}.

4 RESULTS & DISCUSSION

4.1 Hermetically sealed case

Considering the first case of a single room, it is noticed that the effect of the vernacular ventilation system is not enough. This contour image shows that the upper area has some high temperatures as it reaches above 35℃. In addition if one considers the temperature at the level of the human body, it is roughly above 30℃, which temperature is generally considered not comfortable for summer particularly in days of high humidity.

Comparing the first case with case 2 (refer to figure 4), where the traditional vent is closed (lower vent), a noticeable difference in the temperature distribution can be observed. It can be seen that the upper part of the room will have the temperature lowered by approximately 2℃. This means that while the upper vent provides a reduction in the resulting temperature, opening the lower vent does not seem to produce improvements in the resulting temperature distribution.

To confirm this hypothesis, case 2 (figure 5) was compared with case 5 (refer to figure 4) where only the traditional vent is open. Case 5 shows a much higher temperature distribution above the human body as can be shown by the dark orange area in figure 4. This means that having the upper vent open achieves better results than the traditional vent or utilising both. Also, having both vents open, the traditional vent will act as an outlet and the upper as an inlet, therefore the fresh air going into the room will be lost immediately from the traditional vent. One could also notice, that case 2 is the typical stack ventilation system, which is the most effective.

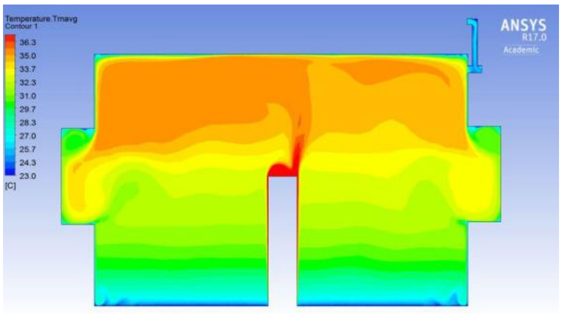

Figure 4: Sample 1 of Results (vernacular ventilation system open with airtight closed window)

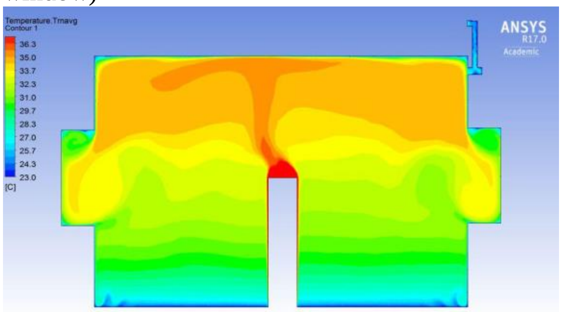

Figure 5: Sample 2 of Results (traditional vent closed with airtight closed window)

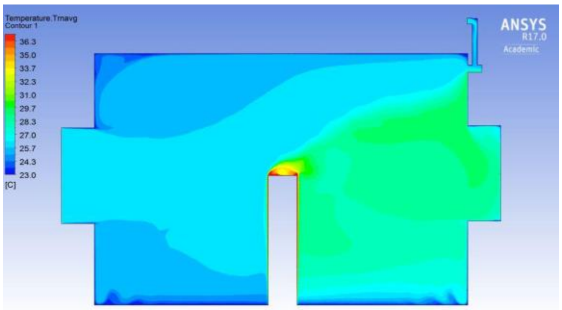

Figure 6: Sample 3 of Results (vernacular ventilation system open with left side window open considering a wind velocity of 0.3m/s)

From the sample case above, one can immediately notice that the resulting temperatures are much lower than the first three cases. Considering case 1 (figure 4) compared with case 6 (figure 6) the temperature immediately shows that the upper part of the contours changed from the high temperature to the lower temperature and the area in the level of the human body turned from yellow/green to light blue. This means that the temperatures decreases by roughly 6℃ which is very substantial in thermal comfort terms. At the level of the human body, from a temperature of 32℃ it decrease to 26℃, which is within the EN 15251 comfort temperature limits for Summer. (EN-15251, 2007)

4.2 Modified design with air leakage from windows case

To enhance this system, some modifications in the model were done. These includes having a false ceiling and the opening of the vent to be directly on the human body to have more control on the direction of the thermal plume released from the body.

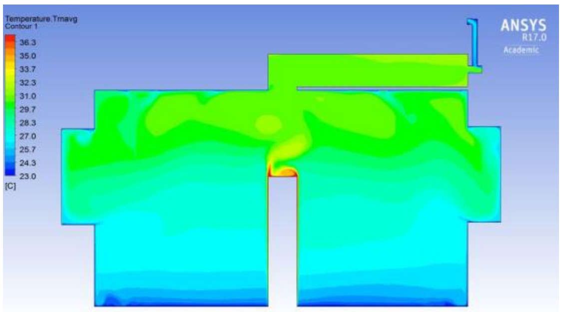

Figure 7: Sample 4 of Results (new design vernacular ventilation system open with air leakage windows)

4.3 Case study of an open plan office with air leakage from windows

In this case study, it is well indicated that overheating occurs in the lower parts having temperatures reaching 47℃ and an overall temperature of approximately 43℃ which is also relatively high. This happened because of three main reasons being the internal gains from people, the height of the ceiling and the sectional area of the open plan. Both the height and the area are much more than the typical case of the room. In order to minimize this problem, one could open the window and also increase the amount of vents according to the amount of people. The modified design should also be applied here on every person in the room.

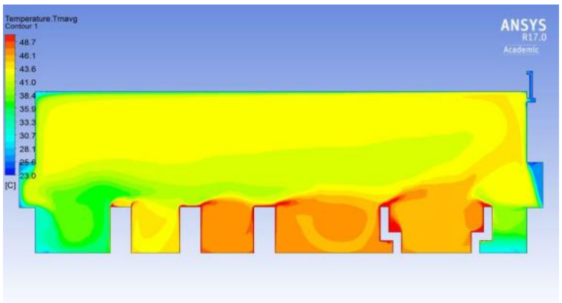

Figure 8: Sample 5 of Results (case study with vernacular ventilation system open with air leakage windows)

4.4 Discussion

4.4.1 Flow Rates

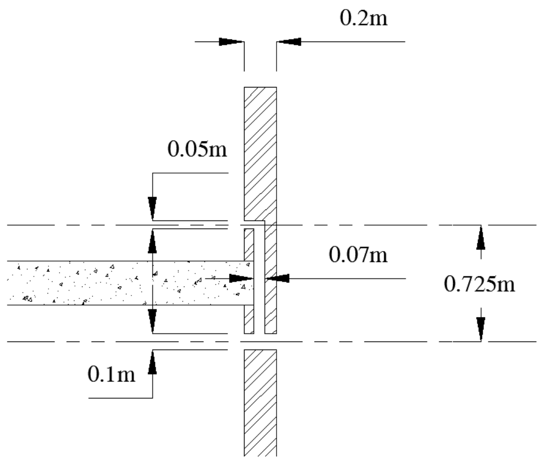

Figure 9: Vent Detail

In order to find the following flow rate, the equation below was used:

$$Q = \bar{v} \times A$$

Where:
Q is the flow rate
$\bar{v}$ is the average velocity
A is the vent area

The flow rate was converted to litres/second/person by multiplying the result by 1000. This was also converted to air changes per hour (ACH), the equation below was used:

$$ACH = \frac{Q(L/s) \times 3600}{V\ (m^2) \times 1000}$$

$$Example: ACH = \frac{3.2\ \times 3600}{91 \times 1000} = 0.1266\ ACH$$

Assuming 5m depth for the typical room and 12m depth for the case study (open plan office)

$Volume = L \times B \times H$

$Example: V = 5.2 \times 5 \times 3.5 = 91 m^3$

Group A

		Outlet A (0.01m²)		Outlet B (0.01m²)		Inlet C (0.02m²)		
Case	Description	$\bar{v}$ m/s	Q1 m³/s	$\bar{v}$ m/s	Q2 m³/s	Q3 m³/s	L/s	ACH
1	The vernacular ventilation system with airtight closed windows	0.23	0.0023	-0.19	-0.0038	0.0015	1.5	0.0593
2	Vernacular system with the traditional vent closed and airtight closed windows	0.001	0.000011			-1.1E-05	-0.01	-0.0004
5	Traditional vent open only and airtight closed windows			-0.002	-3.8E-05	0.000038	0.038	0.0015

Group B

		Outlet A (0.01m²)		Outlet B (0.01m²)		Inlet C (0.02m²)		
Case	Description	$\bar{v}$ m/s	Q1 m³/s	$\bar{v}$ m/s	Q2 m³/s	Q3 m³/s	L/s	ACH
3	The vernacular ventilation system with left side window open	0.29	0.0029	-4.24	-0.0848	0.0819	81.9	3.2400
4	Vernacular system with the traditional vent closed and left side window open	-4.77	-0.0477			0.0477	47.7	1.8870

Group C

		Outlet A (0.01m²)		Outlet B (0.01m²)		Inlet C (0.02m²)		
Case	Description	$\bar{v}$ m/s	Q1 m³/s	$\bar{v}$ m/s	Q2 m³/s	Q3 m³/s	L/s	ACH
6	The vernacular ventilation system and air leakage from windows	0.10	0.001	0.35	0.007	-0.008	-8	-0.3165
7	Vernacular system with the traditional vent closed and leakage from windows	-0.32	-0.0032			0.0032	3.2	0.1266
8	Traditional vent open and leakage from windows			0.27	0.0054	-0.0054	-5.4	-0.2136

Group D

		Outlet A (0.01m²)		Outlet B (0.01m²)		Inlet C (0.02m²)		
Case	Description	$\bar{v}$ m/s	Q1 m³/s	$\bar{v}$ m/s	Q2 m³/s	Q3 m³/s	L/s	ACH
9	New design with vernacular ventilation system and air leakage from windows	0.14	0.0014	0.30	0.006	-0.0074	-7.4	-0.2927
10	New design with closed traditional vent and air leakage from windows	-0.58	-0.0058			0.0058	5.8	0.2295
11	New design with traditional vent only and air leakage from windows			0.25	0.005	-0.005	-5	-0.0329

Group E

		Outlet A (0.01m²)		Outlet B (0.01m²)		Inlet C (0.02m²)		
Case	Description	$\bar{v}$ m/s	Q1 m³/s	$\bar{v}$ m/s	Q2 m³/s	Q3 m³/s	L/s	ACH
12	Case study with vernacular ventilation system and air leakage from windows	0.38	0.0038	0.24	0.0048	-0.0086	-8.6	-0.0565
13	Case study with closed traditional vent and air leakage from windows	-0.26	-0.0026			0.0026	2.6	0.0171
14	Case study with traditional vent only and air leakage from windows			0.2	0.004	-0.004	-4	-0.0263
15	Case study with vernacular ventilation system and left side window open	0.21	0.0021	-0.07	-0.0014	-0.0007	-0.7	-0.0046

From these cases, it is noted that when the upper vent only is opened, the inlet is effective. On the other hand, the inlet is working as an outlet when both vents are open working as an inlet, except for the cases where no air leakage is present and the case where the window is open. In group B, one could notice the extremely high flow rates due to open window.

Considering these results for the both vents open cases, the ventilation rates are quite sufficient, except the air tight case that is not a typical environment, this ventilation system is quite effective. Therefore the greater the number of room occupants and area of the room, the size of these vents needs to be modified accordingly. Considering the typical room area with an average flow rate of 7l/s is quite enough.

In cases with only the upper vent open the system extracts air from the room. In the new design case higher ventilation flow rates are observed. Therefore having an inlet (window) this system will works more efficient with the upper vent only.

5 CONCLUSION

5.1 Conclusions

From the results and discussion, one could conclude that the vernacular architecture ventilation system produced satisfactory results to improve thermal comfort conditions, at least for the conditions assumed in this study. This improvement resulted due to an adequate ventilation rate inside the room. Although the model in this study includes two vents to the external environment, as this was the set up that was still found to be existing, it is worthy to note that these vents were generally used between two rooms, which increases the requirement on stack ventilation to satisfy the required air changes. Given that the upper vent was found to be the most effective due to stack pressure effect, this continues to confirm that the usefulness of the vent to improve thermal comfort conditions. It was found that the vent produces satisfactory results with an air change rate of 3.2l/s (0.13 ACH) using the upper vent only.

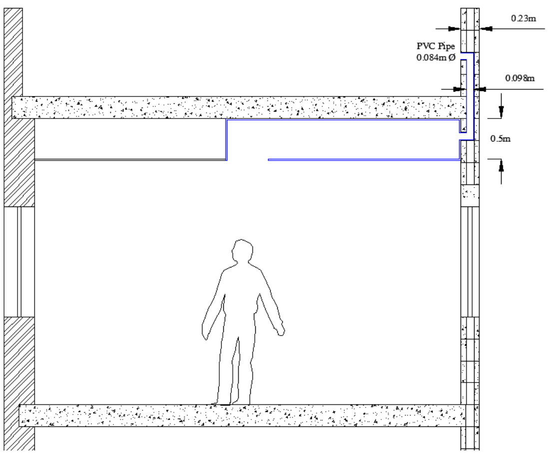

Figure 10: Proposed ventilation system

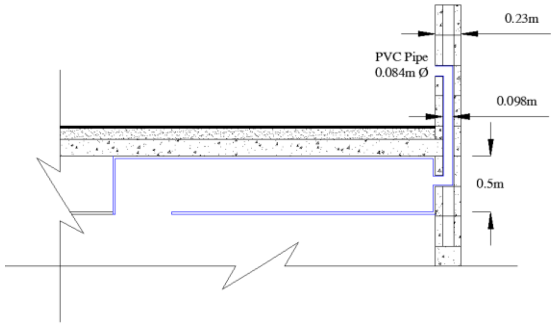

Figure 11: Detail of the proposed system

5.2 Limitations

The main limitation in this study is that not all the factors in the energy balance of the human body were considered. The reason for this was the limited time. The model however gives a good quantification of the ventilation rates. The second major shortcoming is the lack of validation data for this model.

5.3 Recommendations for Future Research

For future research one could consider taking all factors that are included in the energy balance equation mentioned in the methodology. Apart from this, to understand well the full effects on the human body, experimental testing is recommended. The study can also be modelled using a fully 3D approach.

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