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Effect of Duct Width in Ducted Photovoltaic Facades

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Biography

Dr. Abdel Rahman is an experienced consultant on sustainable Architectural design majoring solar electricity producing cells (i.e., Photovoltaics) and wind operated turbines ways and means of their integration into buildings. He has published over three papers in this field in over four international conferences. His research work in sustainable design spans from undergraduates since 1989 to his recent PhD 2007. He was involved with the design of some residential high-rise buildings of excess of 17 storeys in china in 2006. He participated as a design tutor for third year architecture students at University of Nottingham, UK during his PhD studies.
Dr. Abdel Rahman involvement with high rise buildings goes back to 1995 were he was involved with an international competition for the design of Sudanese Airways headquarters in Khartoum, which he won together with a team of eight Architects including him self. The design became a reality as the airliner decided to go a head with its construction.

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Abstract

This paper presents an investigation into the integration of a ducted photovoltaic (PV) system in an architectural facade. The aim is to optimise the design of the ducted system in a real life façade design scenario. Computational fluid dynamics (CFD) has been applied as a tool to estimate temperatures of the ducted PV system and to evaluate between different studied parameters. Miscellaneous design conditions are considered together with high rise building integration.

The combined effect of PV panel configuration and the addition of vents into a ducted PV system would result in an optimum depth of the duct for cooling PV within 90cm. Ducted PV systems provide cooling prospects of up to 60% better than PV integration without it. A ducted PV system can benefit from the height of a high rise building due to the build up effect of buoyancy.

Keywords: Photovoltaic, Ducted PV, CFD, Architectural facades, high-rise Buildings.

Introduction

Designing buildings with PV presents a challenge to the designer to meet the demands for the physical form, environmental system, orientation, footprint and aesthetics of buildings. Among these challenges is the problem of overheating of PV panels when subjected to prolonged periods of solar radiation that reduces efficiency. Many approaches have been adopted to utilize this heat, such as hybrid systems, (i.e. combined generation of heat and electricity). From the architectural point of view, approaches that involve passive cooling through buoyancy would be valuable. The physical phenomena underlining the buoyancy effect rely on the density of air being reduced by heating, causing the warm (i.e., low density) air to rise and be replaced by cooler dense air from below. Wind induced pressure difference gives rise to a second force acting on the air near the PV panel. Forces that resist the flow are friction and end losses at both ends of the gap between the PV panel and wall or panel behind. The PV panel is heated by radiation and heat is transferred to the air gap by convection and radiation.

2. Methodology

To investigate the effect of duct width in a ducted PV system a typical design was chosen with regards to the PV panel configuration as well as the possibility to incorporate a ducted system Figure 1. A similar façade configuration was employed in the computer and science building of Northumberland University, the first PV integrated building in the UK figure 2. However, it was not equipped with a ducting system. The façade has been modified here to incorporate a ducting system with the ability to adjust the width of the duct in 30cm intervals as can be seen in Figure 1. The façade was used for two storey height (7.82m) however; the principles can be applied for high rise buildings.

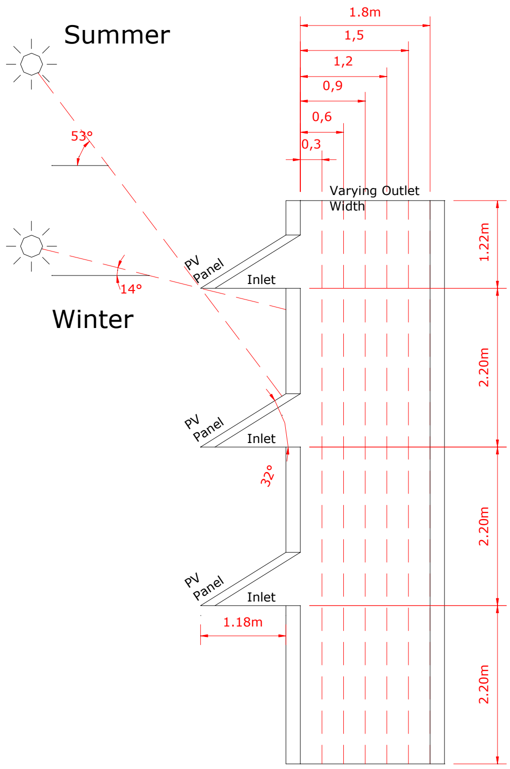

Figure 1, schematic section of a ducted PV façade.

3. Previous Work

In the pursuit for effective integration of Photovoltaic systems into the building fabric, there has been extensive investigation into window design versus day lighting and thermal performance of buildings[1'3]. Facades acquire an additional function of electricity production when they are integrated with photovoltaic[4], or windows integrated with the technology of semi-transparent photovoltaic, and glass integrated photovoltaic modules applied to glass facades or skylights[5]. Sandberg and Moshfeg[6] have undertaken theoretical and experimental investigation on ventilated solar roof and façade airflow and heat transfer with varying duct widths. In their study, they have varied the width of the duct from 10-90cm in an attempt to establish a relationship with air velocity. They have concluded that the relationship between the total heat input (q) and the flow rate (Q) in the air gap is a power law relation ($Q \sim q^{ø}$) where ø equals to ½ in laminar flow and 1/3 in turbulent flow. Brinkworth[7] has undertaken a similar investigation into the optimum depth for PV cooling ducts. He suggested that for a given length (L) and width (W) of the duct there would be a variable depth (H), the optimum location of which will be dependant upon the Hydraulic depth of the duct (D), where D is defined as $D = 2WH/(W+H)$. He suggested that the optimum depth of the duct is achieved when the ratio of L/D is around 20. What is new about this investigation is that it has taken the lessons learned from the effect of the shape of the PV design on the panel temperatures by Elbakheit et al[8] where he introduced PV panels in three different shapes figure (3), and quantified how PV operating temperature would be affected according to its selected architectural shape, as well as maintaining a series of inlets between the PV panels into consideration. The process adopted CFD as a tool to inform the design solution.

Figure 2, Northumberland building, PV rain screen block at the University of Newcastle. The installation provides 32,000kwh/y

4. DUCTED RAIN SCREEN SYSTEM

This study adopted a small façade design for a two storey house Figure 4. The design has three-inclined PV arrays with an air inlet opening below each array. A band of horizontal windows is located below each array. The inlets are connected to a duct that runs along all the façade. An outlet is positioned at the very top end of the duct (Figures 1 and 4). A number of duct widths are selected to examine the effect of the duct width on the PV cooling and flow behind PV panels both evaluated using CFD. Architecturally, the ducts can be positioned on a cantilevered façade allowing for more flexibility of duct depth as well as being independent form inner space use. It can also accommodate any relevant services lines.

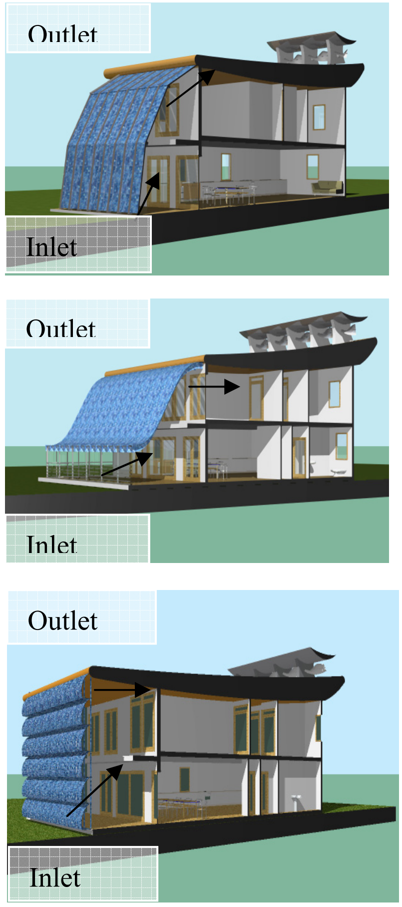

Figure 3, the three design options considered by Elbakheit et al for enhanced cooling of ducted PV panels.

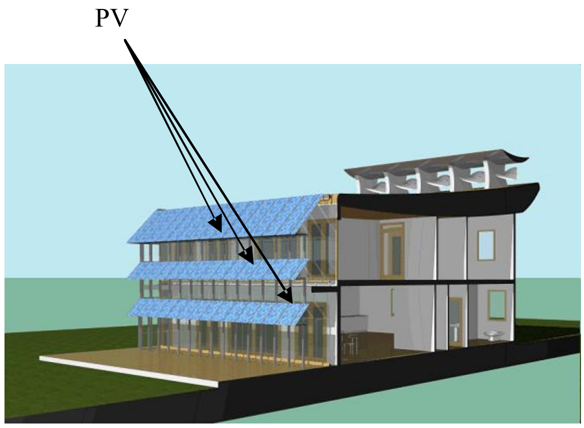

Figure 4, velocity vectors for a room space behind the PV

5. CFD SIMULATION

Computational fluid dynamics (CFD) is used to assess the effect of the gap width behind a PV panel in the above depicted design solution. A two dimensional unstructured grid of full scale is employed, representing the cross section of the building behind the PV façade.

The dimensions of the mesh are up to 3.00m deep and 7.82m high. The mesh has been tested according to ERCOFTAC[9] Guides and found complying. The mesh is refined close to the PV panel surface up to 10cm away from the panel. A total of 100 grid lines are specified for the area of 10cm immediately behind the PV position. The mesh is gradually enlarged for the whole area below the panel along bands of 12cm width retaining a proportion of 0.1% enlargement of the cells in each successive band.

Table 1, Y Plus values for the studied cases.

Duct Width cm	Y Plus value
30	32.00
60	15.00
90	16.74
120	14.46
150	24.00
180	33.94

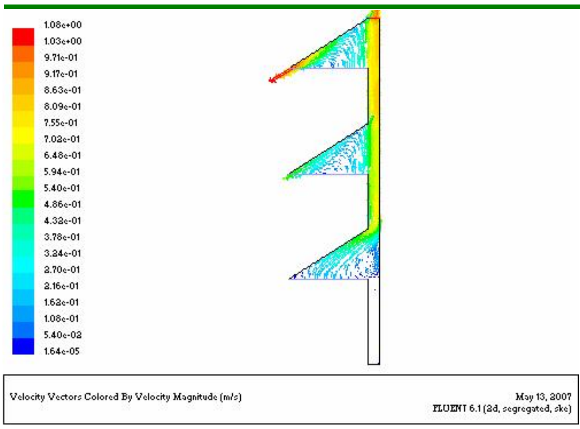

Figure 5, velocity vectors for duct of 30 cm width.

This produced the Y Plus values for each studied duct size as shown in Table 1. These values of Y plus are in the safe range of (11-100) specified by ERCOFTAC. The main influencing factor on the PV performance here is the heat flux through the panel, which is assumed to be 360W/m^2 that is the condition prevailing in a wall mounted PV module based on clear sky radiation data for London[10] at noon on June 21. The ambient air temperature is assumed 293K (20degrees C) under atmospheric pressure.

5.1 RESULTS AND DISCUSSION

5.1.1 Velocity profile (all cases):

In the entire examined duct widths (i.e., 0.30, 0.60, 0.90, 1.20, 1.50 and 1.80m) upward flow is observed through out the different studied duct widths from bottom to top. However, the air mass flow rates increasing from upper inlets to lower ones (i.e., in the opposite direction Table 3.

At the bottom of the two upper PV inclined surfaces (i.e., top and middle panels, Figure 5) some reversed air flow exists side by side with upward flow. At the bottom panel most of the air flow is upward going, Figure 5. Table 3, below shows that the mass flow rate of air increasing with duct width.

Table 3, Effect of Duct width on predicted Mass flow rate at different inlets.

Case	Mass Flow, Kg/s at Middle PV	Mass Flow, Kg/s at Middle PV	Mass Flow, Kg/ at Upper PV	Outlet air Velocity m/s
Duct width 30 cm	0.19	0.10	0.05	0.95
Duct width 60 cm	0.22	0.10	0.06	0.58
Duct width 90 cm	0.49	0.18	0.10	0.80
Duct width 120 cm	0.78	0.29	0.11	0.80
Duct width 150 cm	0.84	0.30	0.10	0.70
Duct width 180 cm	1.53	1.11	0.77	1.74

The reason why the lower inlets have higher mass flow rates than the upper ones can be perceived from equation 1. The mass flow rate (Q) or velocity at inlets can therefore be calculated. The (H) component is the height or distance of the inlet from the outlet position. The larger this distance, the larger the resulting mass flow rate.

$$Qstack = CdA\sqrt{\frac{2Hg(Ti-To)}{Ti}} \quad \text{.......................1}$$

Where, Qstack = volume of ventilation rate m^3/s, Cd =0.65, a discharge coefficient, A= free area of outlet opening. m^2, g = gravitational acceleration. 9.8m/s^2, H = vertical distance between inlet and furthest outlet. m, Ti= average indoor temperature K, To= average outdoor temperature

5.1.2 Temperature profile (all cases)

The temperature variations on the three PV panels due to the increase in duct width are presented in Figure 6. The Figure presents the graphs of the three PV panels temperature (i.e., lower, middle and top panels) from left to right, for the 6 duct widths investigated in this analysis. The predicted temperatures range between 304K to 316K for each of the ducts. The graphs show higher temperatures for the lower duct widths such as 30 and 60cm width and cooler temperatures for large duct width such as 150 and 180 cm. Duct widths of 90 and 120 cm lay in the middle of these two boundaries.

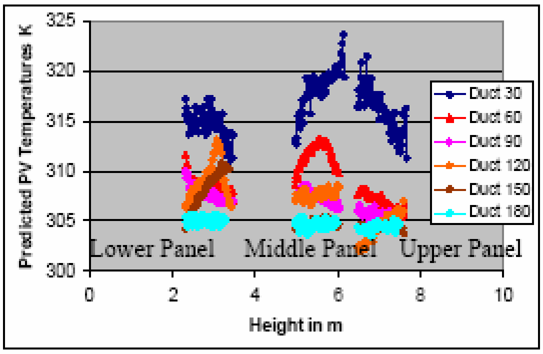

Figure 6, Predicted PV temperatures for the 6 Duct widths studied on lowest, middle and upper PV installations

5.1.3 Comparison of duct's performance

From the above investigation, we can conclude that with an increase in duct width we can increase the PV cooling. It also shows that the lower PV panel has the coolest resulting temperatures followed by the middle and Upper panels figure 7. The figure also shows that the Upper panel might have lower temperatures than the middle panel in ducts 30 and 60cm. This might be because of the restriction of the duct width in these two cases, which results in higher air velocities at the outlet. However, the selection of the most suitable duct size may be dependant upon other requirements of the space behind it as well. In terms of PV integration for this façade design, the duct width of 90cm appears to be the optimum choice.

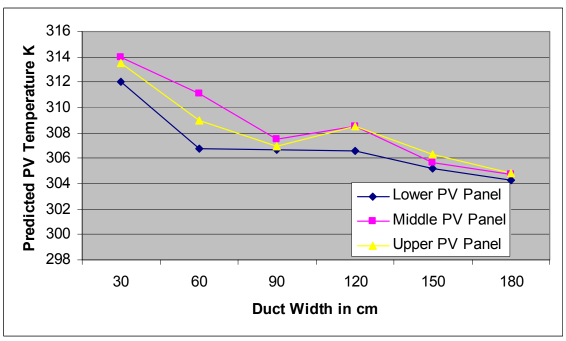

Figure 7, Comparison between cooling effects by different duct widths.

6. MISCELLANEOUS SCENARIOS

When closing the openings below each of the PV panels whilst leaving the outlet open (Figures 1 or 8), a double height room of 4m deep is introduced in lieu of the ducts behind the facade. A door way is also opening with 2m height at the bottom right corner opposite PV façade figure 9. The velocity vectors of the air movement can be seen in Figure 9, while the mean predicted temperatures of the three PV panels behind the PV seen in Figure 9 and Table 4, which is higher than the temperatures obtained by all the ducted systems above.

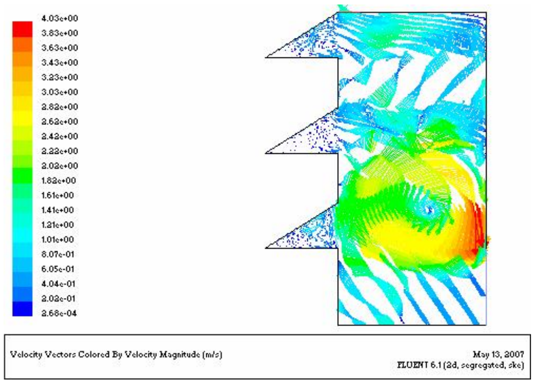

Figure 8, Velocity Vectors by Velocity Magnitude for a room space behind the PV façade case.

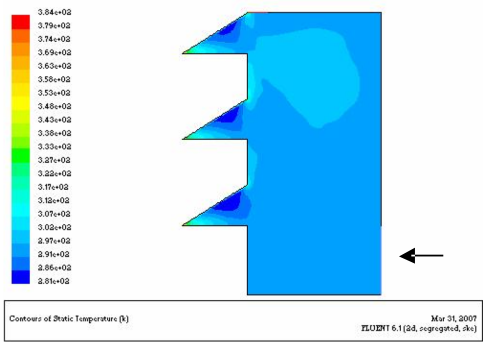

Figure 9, Temperature contours for a room space behind the PV façade case.

The velocity resulting in these cases varies considerably as Figures 5 and 9 reveal. This suggests that when removing the inlets below the PV panels, this has lead to the whole of the space behind the PV façade to be under turbulence, with lesser air mass flow due to the restriction of the inlet/outlet position and therefore less heat removed. Hence, the ducted system option would be more suited for both cooling the PV and the provision for natural ventilation. Therefore, the cooling expected from a ducted system can be up to 60% better than the un-ducted scenario as revealed from the results of the middle PV panel's temperatures in both systems.

Table 4 summer scenario temperature results

PV Panel	Upper	Middle	Lower	Mean interior
Mean Temperature	320	323	320	294

7. HIGH RISE BUILDING SCENARIO

The benefits of integrating ducted PV systems in high rise buildings are tremendous. In these buildings, the stretch of the height of the building will always be the dominant useful dimension. This is particularly useful for newly planned buildings as this can be incorporated in the vertical circulation strategies as well as the anticipated environmental solutions. High rise buildings can provide a long stretch of the vertical duct or space behind the PV. This would increase the pressure difference between the inlet and outlet of the panel and therefore increase the flow rate as well as the PV cooling potential.

The term $\frac{w}{A}\int_0^H \tau_w dy$

In the momentum equation (2) below, which is the integration of the shear stress to the derivative dy along the height of the building, will therefore increase considerably giving more force upward to the buoyancy

$$g\frac{\Delta m}{A}=\left(\frac{\dot{m}}{A}\right)^2\left(\frac{1}{\rho_{out}}-\frac{1}{\rho_{in}}\right)+\frac{w}{A}\int_0^H\tau_w dy+\frac{1}{2}\left(\frac{\dot{m}}{A}\right)^2\left[\frac{1}{\rho_{in}}(1+k_{in})\left(\frac{A}{A_{in}}\right)^2+\left(\frac{A}{A_{out}}\right)^2\right]$$

effect.

…………………………………………………………2

The ducted system proposed for high-rise buildings, however, can be designed in separate vertical shafts or ducts of one metre depth and one to two metres wide. The reason behind choosing these dimensions is taken from the proceeding study of optimizing duct width above. While the width of the duct was to minimize loss of momentum due to large turbulent flows occurring horizontally, the radiation and air temperatures can vary considerably in the horizontal planes due to diverse exposure to the sun, especially in circular or elliptical shaped buildings plans figure 10.

7.1 Ducted PV system in high rise buildings miscellaneous cases:

Due to the high wind pressure on tall buildings a flat ducted PV system (i.e., free from protrusions or cantilevers) with a depth of 1m is used to study the effect of the ducted PV system in this scenario. The system is of 40m height and is integrated within an atrium in a tall office in London. Width of the duct is 2m. The atrium stretches all the height of the PV system with a depth behind the duct of 1m. The main parameters used were the variation of the fluxed heat through the PV as a result of incident solar radiation, the use of the ducted system with and without air vents. It is worthwhile to mention here that a ducted system can be easily integrated in any basic form of plan. (i.e., square, circular or elliptical), figure 10.

7.2 CFD Simulation of Ducted PV system in high rise buildings:

A CFD simulation is undertaken for the high rise ducted PV system during a daily solar variation. Figure 11 depicts the resulting mean PV temperatures along the height of the PV panel for each mean heat flux value. Obviously, solar radiation peaks and is symmetrical at about noon time. The peak resulting PV temperature noon time is 337K. The Figure reveals that the first ten metres would have rising temperatures. However, from 10m height onwards the temperatures become steady in all studied heat fluxes. The reason why this happens can be seen from the velocity vectors through a section of the duct in Figure 13 below, which shows high air velocity of up to 4m built up of the buoyancy effect as explained in equation 1 and 2 above.

7.3 Effect of the addition of vents between the PV panels:

A series of vents/openings are introduced at each floor level of the proposed PV facade section. Each inlet is 20cm in height. Figure 14, below shows the plotted mean PV temperatures after adding the series of vents for the heat flux of 360W/m2 case.

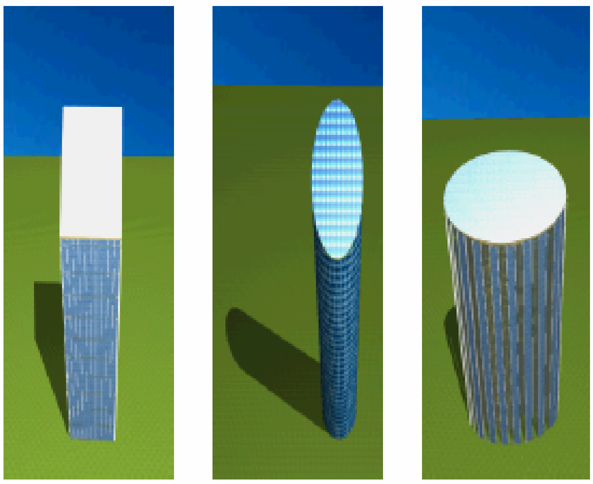

Figure 10, proposed ducted PV systems on three different high rise plans.

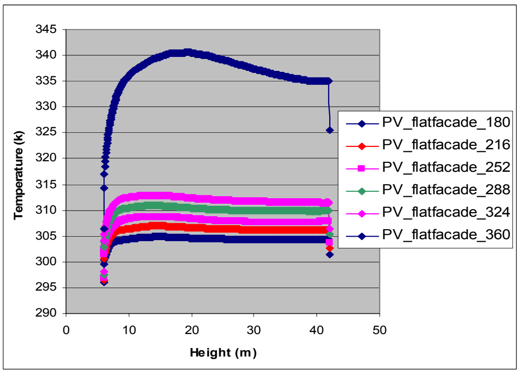

Figure 11, PV mean temperature under daily solar radiation in high rise ducted PV system (No Vents).

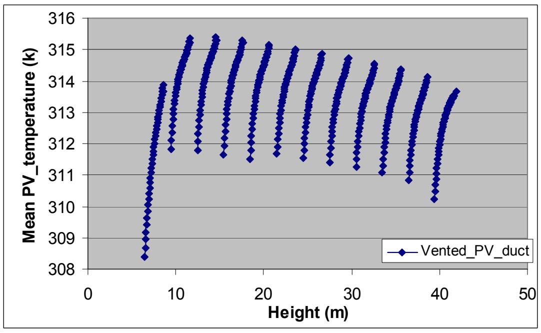

Figure 12, PV mean temperature in high rise ducted PV system. (With vents).

If we compare the resulting graphs of mean PV temperatures in the case with and without vents (i.e., Figures 11 and 12 above) we can see that the overall

Maximum mean PV temperature has been reduced from 337k to 312K that is a 25K cooling effect. Theoretically, this could provide up to 12% higher PV efficiency in the case with vents over the un-vented case.

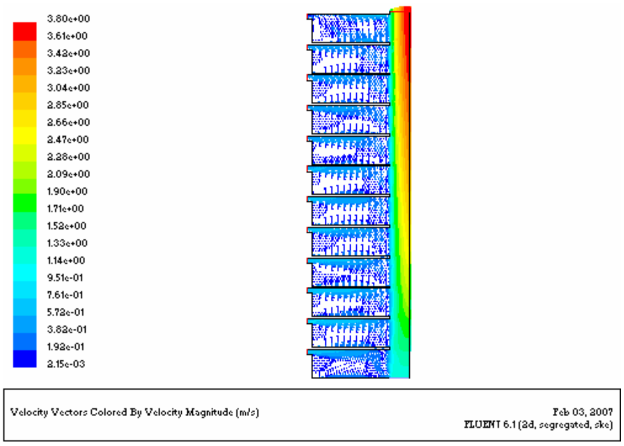

Figure 13, velocity vectors of a section through a high rise ducted PV system (without Vents).

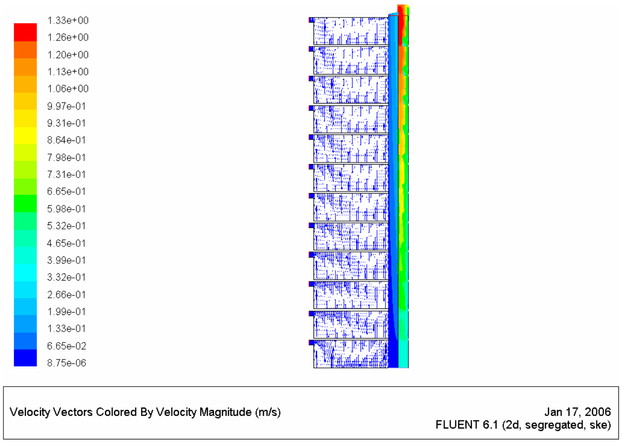

Figure 14, velocity vectors of a section through a high rise ducted PV system (with Vents).

8. CONCLUSIONS

The combined effect of PV panel configuration and the addition of vents into a ducted PV system would result in an optimum depth of the duct for cooling PV within 90cm. Ducted PV systems provide cooling Prospects of up to 60% better than PV integration without it. A ducted PV system can benefit from the height of a high rise building due to the build up effect of buoyancy.

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