# MECHANICAL COOLING ENERGY REDUCTION FOR COMMERCIAL BUILDINGS IN HOT CLIMATES: EFFECTIVENESS OF COMBINED PASSIVE SYSTEMS

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## ABSTRACT

The aim of this work is to quantify the ability of passive systems combinations to reduce the mechanical cooling load in a case study commercial building in a hot climate. Results show that combination of double ventilated facade, external solar shading and rain screen facade is the most effective for Portugal and Kenya climates offering an annual cooling energy reduction of 35% and 21% respectively. For individual passive systems in hot climates, external solar shading is the most effective individual passive system providing a cooling potential 26% in Portugal and 14% in Kenya. As part of the passive system selection process, it is identified that direct solar radiation, external air temperature and mass flow rates of external air are major criterion for system selection.

## INTRODUCTION

Building energy reduction using low carbon/passive methods is highly desirable and designers are encouraged to incorporate natural ventilation and passive system strategies. If not practical, fresh air delivery and space cooling uses various existing methods of mechanical ventilation systems such as Variable Air Volume (VAV) and Constant Air Volume (CAV), each using energy saving control methods i.e. close control via building energy management systems (BEMS). Efficient refrigerant based cooling systems are adopted, such as variable refrigerant volume (VRV), in order to maintain supply air temperatures. These are used to maintain indoor thermal comfort when external air temperature begins to exceed 26$^{o}$C (78.8$^{o}$F). In large scale buildings, centralised plant such as VAV with cooling coils (VRV) provides large potential cooling capacities (Iqbal & Al.Homoud, 2007).

To improve energy efficiency, hybrid buildings are becoming more common incorporating rain screen facades, double ventilated facades and solar shading. Following previous studies completed by Marinoscia et al (2011), Lieb (2001) and Brittle et al (2013), these systems each provide specific levels of passive cooling with complex boundary conditions and limitations which include integration in building geometry, construction practicalities, input energy efficiency and budget. The selection of these systems is influenced by the clients design team and case studies i.e. solar shading has aesthetic implications to facades. Practical installation of these systems requires significant planning and design. An example is external solar shading which more common with fewer complexes (structural) compared with natural ventilation as this has major impacts on internal building geometry, structural stability and room configuration (low resistance passage of supply air).

A significant amount of research has been completed for individual passive system performance but there appears to be very little on exploring the impacts of combining multiple passive systems in order to reduce cooling energy. The aim of this work is to quantify the ability of passive systems combinations to reduce the mechanical cooling load in a case study commercial building in a hot climate. Comprehensive analysis is completed for selected individual passive systems and combined thereof for a theoretical commercial office building, in terms of mechanical cooling energy reduction.

The aim is realised by the following four objectives:

- Calculate cooling potentials for external solar shading, rain screen facades and double ventilated facades using existing simulation/analytical techniques.
- Create and dynamically simulate a theoretical single storey office space located in two different hot climates.
- Determine most effective passive system combination for annual performance.
- Determine annual effects on input energy associated with mechanical cooling systems simulating passive system and combinations thereof.

## METHODOLOGY

In order to determine total reduction on mechanical cooling systems, we first must analyse and determine monthly cooling potentials for each selected passive system. As dynamic thermal simulation (DTS) packages are limited with regards to the simulation of double ventilated facades and rain screen facades, with only solar shading being available, research was completed to determine fundamental equations and developed accordingly to suit the particular passive system. The process also shows development of a base case model using dynamic thermal simulation software (DTS) where results are generated for sensible & latent heat gains (kW) and annual cooling energy consumption (kWh). The passive cooling systems selected for this analysis are as follows:

- External Solar Shading (SS)
- Double Ventilated facades (DVF)
- Rain Screen Facades (RSF)

For each passive system, these values are generated and deducted from the base case model to determine effective reduction of cooling load and monthly energy consumption. These systems are analysed individually and then combined with other passive systems. The base case model shows mechanical cooling loads for normal operation without passive systems. Figure 1 below shows the process to this paper and how cooling capacities are determined.

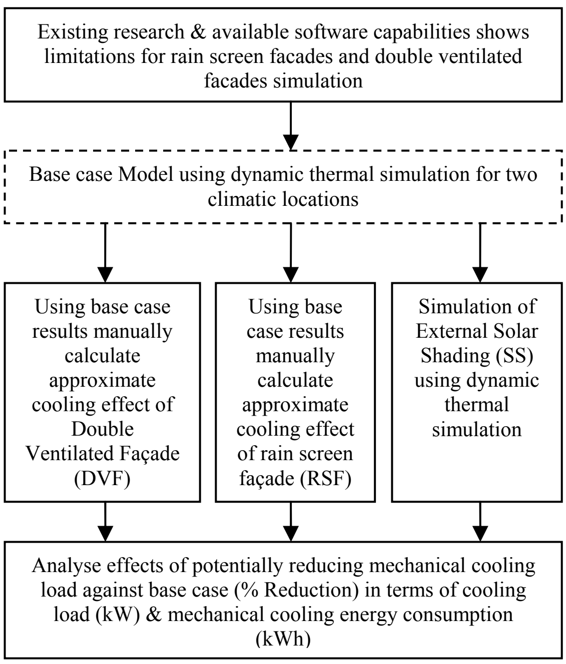


*Figure 1- Mechanical Cooling Reduction Using Passive Systems Methodology Flow Diagram*

For DVF and RSF, steady state passive system models are used to adjust the results from a dynamic simulation program applied to base case models as DTS excludes these technologies. Simple summation rules are used to obtain a maximum possible cooling reduction for combined passive system. Note that when considering natural ventilation, solar chimneys, sub-terrain earth ducts, passive down draught evaporative cooling, phase changing materials, radiant cooling, radiant barrier, available simulation software is limited and does not have specific passive system design applications available; therefore these system are not considered in this study. Furthermore these systems require computational fluid dynamic (CFD) calculation to obtain accurate thermal behaviour and air flow dynamics.

## Base Case Office Building

A theoretical commercial building model was created for different combinations of passive ventilation and cooling strategies. Building simulations were completed to determine the effects on room cooling load (kW) and input energy reduction for mechanical cooling systems (kWh). Initial analysis is completed for passive systems highlighted in figure 1 which require analytical assessment for cooling potential. The second part analyses annual input energy reduction for the space highlighting ideal combinations for this type of climate, ranking them accordingly. The selected building locations selected is Portugal & Kenya.

*Table 1*
*Climate Data for Hot Countries*

| Location | Height Above Sea Level(m) | Max.Tem (°C)/(°F) | Min. Temp. (°C) /(°F) |
|---|---|---|---|
| Lisbon, Portugal | 95 | 27.9/82.22 | 8.2/46.76 |
| Nairobi, Kenya | 1,676.40 | 25.6/78.08 | 11/51.8 |

Table 1 above shows maximum temperature, minimum temperatures and height above sea level (World Meteorological Organisation, 2014a & 2014b). Climate data used is design summer year (DSY) in the building simulations (DTS).

The metrics used (SI Units) in this analysis are mechanical cooling input energy consumption (kWh), sensible cooling load (kW) and Latent Heat Gains (kW). Sensible and latent heat gains are combined to determine annual mechanical cooling energy. The building is simulated using Design builder software version 3.0.0.105 incorporating DB Sim v1.0.2.1 as this enables dynamic thermal building simulations for mechanical cooling loads and input energy required for the cooling system operation over monthly and annual periods. A solution algorithm of finite differencing and adaptive convection algorithms are used for interior convection including McAdams algorithm used for exterior convection. Within the simulation air velocities for comfort are 0.1370 m/s.

A single height open office plan (theoretical model) has been created 20m (L) x 10 (W) x 3m (H). The south façade consists of a full height window 3m (H) x 19m (W). The East and West walls contain 3No. 2m (W) x 1.5m (h) and North wall contains double doors which are 2m (H) x 1.9m (W) and 2No. windows 6m (W) x 2m (H). The graphic generated by the software is shown in figure 2 below which shows the South facade view. Figure 3 indicate the building without the flat roof show highlighting the interior.

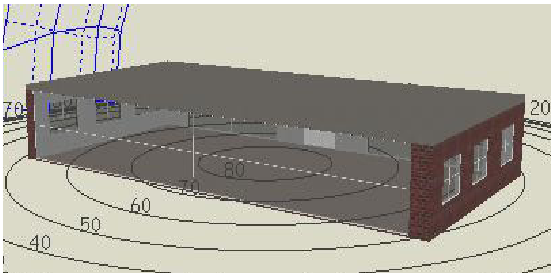


*Figure 2-South View of Office Building (Graphic)*

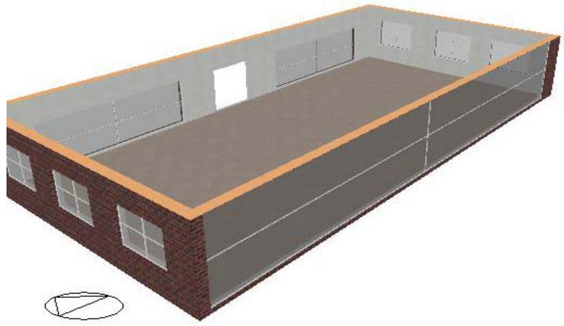

*Figure 3- South South West View of Office Building illustrating interior (Graphic)*

The building also has a flat roof. The test building is based upon a generic building design identified by 1 North Bank, Sheffield, Yorkshire (e-architect, 2014) and Modern Small Office Buildings Verkerk Group in Netherland (Zeospot, 2014).

*Table 2*
*Building Parameters*

| Type | Description |
|---|---|
| External Walls | Brickwork, Outer Leaf (105mm), XPS Extruded Polystyrene (118mm), Medium Concrete Block (100mm) & Gypsum Plastering - U value of 0.25W/m$^2$ K |
| Roof (Flat) | Asphalt (10mm), MW Glass Wool (200mm), Air Gap (200mm), Plasterboard 13mm- U Value of 0.186W/m$^2$ K |
| Floor | Urea Formaldehyde Foam (200mm), Cast Concrete (100mm), Floor Screed (70mm) & Timber Flooring (30mm) - U Value of 0.176 W/m$^2$ K |
| Glazing | Pilkington North America Solar-E Arctic Blue (7.9mm), 12mm Argon Filled Gap & Pilkington North America Eclipse Advantage Clear (5.91mm)- U Value of 1.685W/m$^2$ K |
| Doors | Metal Framed Doors with Infill to match glazing- Pilkington North America Solar-E Artic Blue (7.9mm), 12mm Argon Filled Gap & Pilkington North America Eclipse Advantage Clear- U Value of 1.685W/m$^2$ K |
| Air Permeability | 0.25 Air Changes Per Hour |
| Ventilation | Normal Operation (Base Case)- 10 litres/second per person<br>Supply Air condition 12$^o$C<br>Supply Air Humidity Ratio (g/g)- 0.08<br>Vents for Natural Ventilation- Large Grille (Dark Slates)- 0.5 Co-efficient of Discharge |
| Indoor Environmental Conditions (Summer Time Cooling) | Nominal Cooling-24$^o$C<br>Cooling Set Back- 26$^o$C |
| Internal heat gains are based on occupancy and lighting heat gains only | Lighting – 12W/m$^2$<br>Occupancy Density- 10m$^2$/Person<br>Activity- Light Office Work/Standing/Walking<br>Computers 25W/m$^2$<br>Other Equipment- 0W/m$^2$ (Non Selected) |
| Occupancy Pattern | Weekdays Summer Design Day- 0700- 0% Occupancy, 0800 Hours- 25% Occupancy, 0900 Hours- 50% Occupancy, 1200 Hours- 100% Occupancy, 1400 Hours- 75% Occupancy, 1800 Hours- 50% Occupancy, 1900 Hours- 25% Occupancy, 2400 Hours- 0% Occupancy |
| Mechanical Cooling Fuel Source | Electrical |

Building design criterion is taken from United Kingdom Building Regulations (HM Government, 2010a, b & c), British Standards, British Standards (1991), CIBSE (2006) and BSRIA Guidelines (BSRIA 14, 2003) relevant to multi-use office space. These standards are world leading improving upon Portuguese/African Building Codes with regards to improved U-values and air infiltration (higher or minimum values), providing a solid bench mark for future building performance analysis. Prior to dynamic simulation of various systems, modelling of various mechanical systems had been completed to determine ideal system for the base case. This is to ensure the most efficient cooling system was used as part of this analysis. Ideal mechanical ventilation and cooling system for this simulation is split cooling (Direct expanding) with separate extract ventilation as systems energy consumption only vary by <1% when comparing against VAV with Heat Recovery (Mixed Mode) and VAV with Outside Air Reset.

For office building model in each climate, simulations were completed to determine annual cooling load performance and annual cooling energy performance. Figure 4 shows sensible and latent DTS heat gains and plotted for each month. The graph shows that Portugal has higher sensible heat gains from March to November where Kenya has constant temperature due to location being higher above sea level. Latent heat gain as similar with Portugal indicating a slightly higher level June and October.

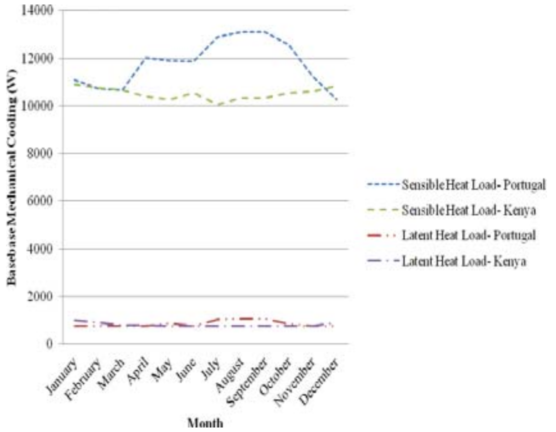


*Figure 4- Base Case cooling loads for both climates*

Figure 5 shows annual energy performance for cooling associated with each climate with Kenya climate indicating a greater value of 6.4%.

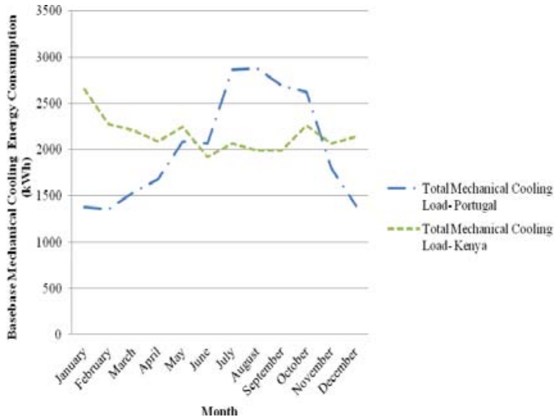


*Figure 5- Base Case mechanical cooling energy consumption over Annual Period*

**WEATHER DATA ANALYSIS**

Weather data extracted from Designbuilder software used for steady state analysis using monthly average dry bulb temperatures (maximum) and maximum monthly solar irradiance ($W/m^2$) in order to determine maximum effectiveness of façade systems. The negative effects is averages used are not as accurate as measured average data hence an error is introduced. As an example of this, figure 6 below shows inter-comparison of Designbuilder temperatures (max/min) and measure WMO data (World Meteorological Organisation, 2014a, 2014b).

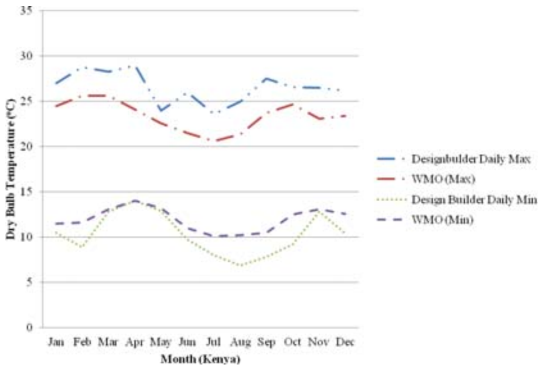


*Figure 6- Inter-comparison of Average Dry Bulb Weather Data from Designbuilder and WMO*

Analysis indicates that Designbuilder data over predicts monthly average dry bulb temperatures by 14.45% (minimum) and 11.79% (maximum) per annum. The same is encountered for Portugal is 36.14% higher values for minimum dry bulb temperatures and 19.15% higher value for maximum dry bulb temperatures per annum.

**PASSIVE SYSTEM ASSESSMENT**

1. **EXTERNAL SOLAR SHADING**

External Solar Shading (SS) consists of fixed multiple angled slate shading devices are used on main windows at an angle of $45^o$ (Lieb, 2001). These shading slats are space at 300mm apart for East, South & West windows.

2. **DOUBLE VENTILATED FACADE**

Double Ventilated Facade (DVF) is designed as 0.3m deep with low and high level external grills 18.92m (L) x 0.1m (W) for the complete length and height of the South facade. For heat energy transfer within the double ventilated façade space (1) which is adapted from CIBSE (2006) and CIBSE (1999):

$$Q_{DVF} = \sum Ag\ ø_s\ eff_{gg} + h_c\ M_a\ A_{fw} \quad (1)$$

Where: Ag is area of external facade glazing ($m^2$); $ø_S$ is external solar radiation ($w/m^2$); $U_g$ is U value of glazing; $h_c$ is heat transfer co-efficient of air (natural); Ma is mass flow rate of air (kg/s) and $A_{FW}$ is area of facade wall. For cavity air temperature ($T_{CA1}$):

$$T_{CA1} = T_o - \left\{ \frac{Q_{DVF}}{C_{pa}\ M_a} \right\} \quad (2)$$

Where: $T_o$ is outside air temperature ($^oC$); $C_{pa}$ is specific heat capacity of air (1.2kJ/kg). For effective opening area of DVF ($A_{eff}$) (British Standards, 1991):

$$A_{eff} = (A_1 + A_2)\ \frac{\varepsilon \sqrt{2}}{(1+\varepsilon)\,(1+\varepsilon^2)^{1/2}} \quad (3)$$

Where: $A_1$ is area of lower grill (Free area); $A_2$ is area of higher grill (Free area) and $\varepsilon$ is $A_1/A_2$. For mass flow rate of air (Ma) (British Standards, 1991):

$$Q = C_d A \left( \frac{2\Delta P}{\rho} \right)^{1/2} \tag{4}$$

Where: Q is flow rate of air calculated as 14.89 l/s; P is pressure drop (Pa) and ρ is air density. For Resultant Heat gain through façade glazing using the corrected external air temperature ($Q_{FG}$) CIBSE (1999):

$$Q_{FG} = \sum U_g A (T_{CA1} - Ti) \tag{5}$$

In order to make a comparison, a standard facade glazing calculation is completed, as show below:

$$Q_g = \sum U_g A (T_0 - Ti) \tag{6}$$

These values are inter-compared to determine total reduction heat loss $Q_{TR1}$:

$$Q_{TR1} = Q_g - Q_{FG} \tag{7}$$

The parameters used to calculate heat gains and reduction are detailed in table 3 below. For external air temperatures and direct solar radiation, data was extracted from Designbuilder software.

*Table 3*
*Double Ventilated Facade Core Parametres*

| P | $h_c$ | $A_1$ ($m^2$) | $A_2$ ($m^2$) | Ma (kg/s) | (Cd) | $eff_{gg}$ |
|---|---|---|---|---|---|---|
| 100 | 25 | 1.89 | 1.89 | 0.0183 | 0.61 | 0.8 |

Figures 7 and 8 below show the resultant outputs for both climates. As the main variable are external dry bulb temperature and direct radiation, figure 7 shows this system is most effective between months of March to November. The highest heat gain is shown to be in August and lowest direct comparable heat gain in April.

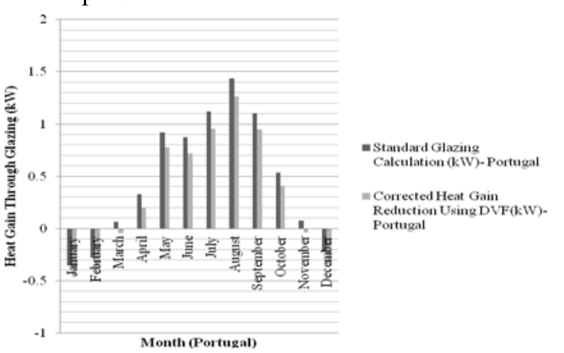


*Figure 7- Heat Gain Analysis comparing DVF against Standard glazed external wall in Portugal*

Figure 8 provides a similar pattern to Portugal climate and shows a consistent reduction in heat gains into the space. The most significant reduction, where external air temperature exceeds internal air temperature, is between February and April.

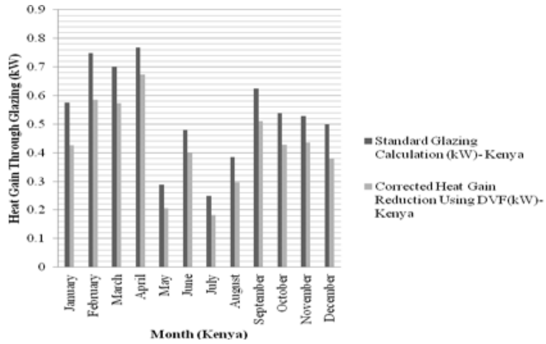


*Figure 8- Heat Gain Analysis comparing DVF against Standard glazed external wall in Kenya*

To summerise, double ventilated facade has an effective impact on reducing heat gains which is dependent on direct solar radiation levels to South facade. The cooling load reduction is detailed in table 4 below.

*Table 4*
*Calculated Reduction for DVF against Standard Glazing*

| Month | % Reduction Against Base Case for DVF (Portugal) | % Reduction Against Base Case for DVF (Kenya) |
|---|---|---|
| January | -30.48 | 25.83 |
| February | -38.70 | 21.84 |
| March | 164.88 | 18.06 |
| April | 39.44 | 12.34 |
| May | 15.98 | 28.45 |
| June | 17.89 | 16.84 |
| July | 15.06 | 26.65 |
| August | 12.32 | 23.03 |
| September | 13.91 | 18.07 |
| October | 24.08 | 20.26 |
| November | 148.83 | 17.26 |
| December | -50.34 | 24.03 |

## 3. RAIN SCREEN FACADE

Rain Screen Facade (RSF) is designed for North, East, West & South elevations. The primary aim of a RSF is to protect the external wall from rain and secondary to reduce solar heat gains into the fabric. The facade consists of 13mm weatherboard and 200mm Air Gap (combined U value- 2.258W/$m^2$ K). The façade weather board are 1.995m (L) x 0.995m (w) panels allowing a 0.01m air gap between each panel. U value for the external weather board only is 3.804w/$m^2$ k.

To calculate steady state heat gain into the facade cavity incorporating rain screen facades ($Q_{RSF}$), the basic heat loss equation from CIBSE (2006) and CIBSE (1999) has been adapted below:

$$Q_{RSF1} = \sum A_{rsf}\, ø_s\, eff_{gRSF} + h_c\, m_a\, A_{rsf} \tag{8}$$

Where: Arsf is surface area of rain screen facade (m2); $ø_S$ is external solar radiation (w/m$^2$); $U_{rsf}$ is thermal conductivity of rain screen facade (w/m$^2$ k); $h_c$ is heat transfer co-efficient of air (natural) and Ma is mass flow rate of air (l/s). To calculate cavity air temperature:

$$T_{CA2} = T_o - \left\{ \frac{Q_{RSF}}{C_{pa}\, M_a} \right\} \quad (9)$$

Where: $T_o$ is outside air temperature ($^o$C); $C_{pa}$ is specific heat capacity of air (1.2kJ/kg). For total fabric heat loss/gain ($Q_{RSF2}$):

$$Q_{RSF2} = \sum UA\,(T_{CA2} - Ti) \quad (10)$$

Where: U is thermal conductivity of wall (w/m$^2$ k); A is area of wall (m$^2$); $T_{CA2}$ is cavity air Temperature ($^o$C) and Ti is internal air temperature ($^o$C). In order to make a comparison, a standard wall calculation is completed, as show below:

$$Q_f = \sum U\,A\,(T_o - T_i) \quad (11)$$

These values are inter-compared to determine total reduction heat loss $Q_{TR2}$:

$$Q_{TR2} = Q_f - Q_{RSF2} \quad (12)$$

The parameters used to calculate heat gains and reduction are detailed in table 5 below. For external air temperatures and direct solar radiation, similar to method used in DVF.

*Table 5*
*Rain Screen Facade Core Parametres*

| Heat Transfer Co-efficient of Air | Air Flow Rate (l/s) | Ma (kg/s) | Effective g value of weather board | U value of wall |
|---|---|---|---|---|
| 25 | 100 | 0.12 | 0.6 | 0.25 |

As shown in figures 9 and 10, RSF is particularly effective in reducing conductive thermal heat gains through walls.


*Figure 9- Wall Heat Gain Analysis comparing RSF against Standard wall in Portugal*

For the months of July (Summer), RSF provides a maximum cooling load reduction of 568.16% for Portugal and 1,016.19% for Kenya as shown below in table 6. The large percentages show a significant reduction in solar heat transmittance through the wall for each month (building fabric only).

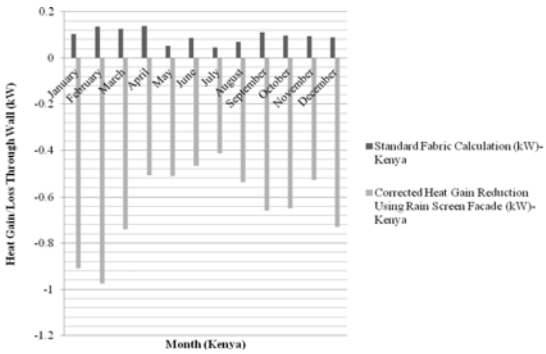


*Figure 10- Wall Heat Gain Analysis comparing RSF against Standard wall in Kenya*

*Table 6*
*Calculated Heat Gain Reduction for RSF against Standard Wall*

| Month | % Reduction Against Base Case for RSF (Portugal) | % Reduction Against Base Case for RSF (Kenya) |
|---|---|---|
| January | -1,154.21 | 973.08 |
| February | -1,479.72 | 822.04 |
| March | 6,273.55 | 683.33 |
| April | 1,493.89 | 466.26 |
| May | 601.32 | 1,081.54 |
| June | 673.95 | 639.22 |
| July | 568.16 | 1,016.19 |
| August | 465.47 | 874.78 |
| September | 525.88 | 683.94 |
| October | 909.47 | 768.28 |
| November | 5,625.18 | 655.45 |
| December | -1,906.77 | 909.53 |

## Cooling Energy Results

Further to the analysis completed for individual passive systems, annual cooling energy consumption (kWh/annum) is determined by completing an assessment DTS base case for full mechanical cooling operation and impact of passive system monthly cooling potentials based upon working days only and hours of operation. For DVF (South facing), 12 hours (daylight) are used and 5 hours for RSF due to changes in solar azimuth. For DVF/RSF, cooling energy reduction is determined by deducting RSF/DVF steady state model from a standard wall model. Using heat gain difference (kW), calculated steady state heat gains (kW) are multiplied by hours of operation (kWh/Working Day/Occupied Time). This is then deducted from the monthly base case cooling energy (mechanical) value to determine maximum energy reduction (kWh/Annum). Maximum cooling energy reduction (kWh/Annum) and percentage energy saving potential are shown in tables 7 and 8 for individual and combined passive systems.

*Table 7 Annual Cooling Energy & Percentage Reduction for Portugal*

| Passive System | kWh (Portugal) | % Reduction (Portugal) |
|---|---|---|
| Base case | 24,372 | - |
| RSF | 22,693 | 7 |
| DVF | 23,782 | 2 |
| SS | 17,924 | 26 |
| DVF+SS | 17,678 | 28 |
| RSF+SS | 16,245 | 33 |
| DVF+SS+RSF | 15,999 | 35 |

Identical analysis is completed below in table 8 for kenya.

*Table 8*
*Annual Cooling Energy Reduction & Percentage Reduction for Kenya*

| Passive System | kWh (Kenya) | % Reduction (Kenya) |
|---|---|---|
| Base Case | 25,901 | - |
| RSF | 24,570 | 5 |
| DVF | 25,434 | 2 |
| SS | 22,200 | 14 |
| DVF+SS | 22,006 | 16 |
| RSF+SS | 20,869 | 19 |
| DVF+SS+RSF | 20,675 | 21 |

The results obtained are validated accordingly:

- SS- A study completed by Brittle et al (2013) determined that a mechanical cooling energy saving of 25% for Aswan, Egypt.
- DVF- Energy performance analysis of DVF 5 storey Biomedical laboratory of University of Michigan Ann Arbor, USA by Azarbayjani (2013) discovered that a 2% reduction in electrical energy for heating and cooling was achieved. Although these buildings are different similar effects of cooling reduction are observed.
- RSF- Marinoscia (2011) completed a study on simulated test buildings for Bologna, Rome and Palermo, where the energy demand for cooling when compared to non ventilated solution where 6-8%.

## Discussion

The results identify high levels of cooling reduction available to mechanical cooling systems. For each climate type, passive systems are ranked accordingly in terms of their effectiveness where 1 is the most effect (table 9).

*Table 9*
*Passive system order of effectiveness*

| Passive System | Rank (Portugal) | Rank (Kenya) |
|---|---|---|
| DVF+SS+RSF | 1 | 1 |
| RSF+SS | 2 | 2 |
| DVF+SS | 3 | 3 |
| SS | 4 | 4 |
| RSF | 5 | 5 |
| DVF | 6 | 6 |

Annual cooling energy performance is plotted for each of the individual passive systems and combined systems. In each climate case, as shown in figure 11 and 12, profiles for each passive system highlight a reduction against the base case model.

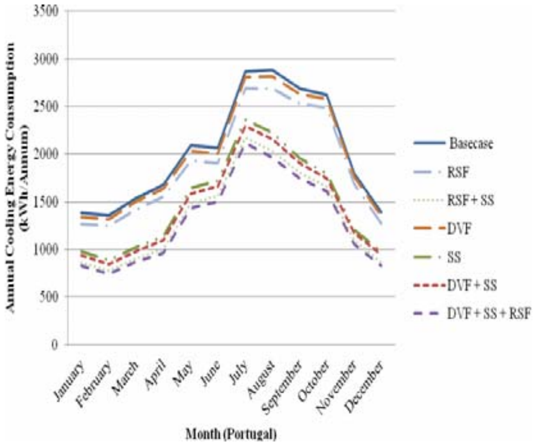


*Figure 11- Annual cooling energy performance for Portugal*

Upon analysis of the building performance in Kenya, as shown in figure 12; the graph shows a similar performance pattern to figure 11. This also indicates close levels of passive system performance, in particular between May and September.

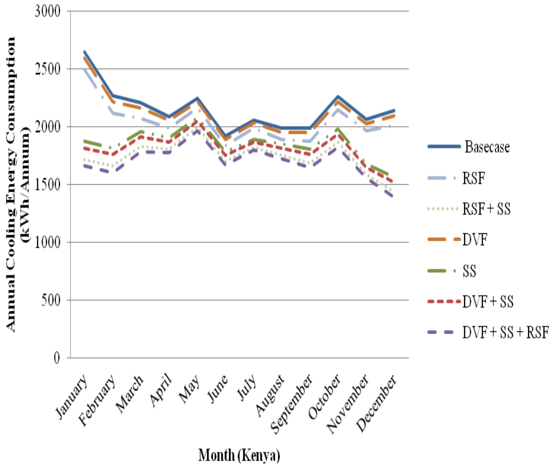


*Figure 12- Annual cooling energy performance for Kenya*

Summarising, differences between the two graphs (Figures 11 and 12), both graphs show similar cooling energy performance trends and similar levels of cooling energy reduction with all combined systems providing maximum amount of available cooling reduction.

## CONCLUSION

This work has been completed in order to determine the effectiveness of combined passive systems for a theoretical commercial office building in terms of mechanical cooling energy reduction. The results enabled analysis to form the following conclusions:

1) Combination of double ventilated facade, external solar shading and rain screen facade is the most effective for Portugal and Kenya climates offering an annual cooling energy reduction of 35% and 21% respectively.
2) For individual passive systems in hot climates, external solar shading is the most effective in both climates where cooling potential offers 26% in Portugal and 14% in Kenya
3) There is an error identified with regards accuracy of dry bulb data within computer simulation software over estimates values between 11.79% and 19.15%. This over estimates heat gains via building fabric and passive systems.

## FURTHER WORKS

Possible future research could be implemented for the following:

- Clearly this work applies to a bespoke building configuration and can benefit from assessing the impact of the above being applied to various other types of buildings in different global location (tropical climate).

## ACKNOWLEDGEMENTS

The authors would like to thank their families for their support. This research required significant time and work.

## NAMENCLATURE

$SS$ Solar Shading
DVF Double Ventilated Façade
RSF Rain Screen Facade
$Q_{DVF}$ Rate of heat gain into DVF cavity
$Q_{RSF1}$ Rate of heat gain into RSF cavity
$Q_{RSF2}$ Rate of heat gain into space using RSF
$T_i$ Internal air temperature (Dry bulb)
$T_o$ External air temperature (Dry bulb)
$A_{fw}$ Area of facade wall (DVF)
$A_g$ Area of Glazing
$ø_s$ External Solar Radiation
$U_g$ Thermal conductivity of glazing
$h_c$ Heat transfer co-efficient of air (natural)
$M_a$ Mass flow rate of air
$T_{CA1}$ Air temperature of cavity (DVF)
$T_{CA2}$ Air temperature of cavity (RSF)
$C_{pa}$ Specific heat capacity of air
$A_{eff}$ Effective opening area
$A_1$ Free area of lower ventilation gill
$A_2$ Free area of higher ventilation grill
$\varepsilon$ Ratio of opening area
$Q_{TR1}$ Total heat reduction (DVF)
$Q_{TR2}$ Total heat reduction (RSF)
$Q_g$ Rate of heat gain through standard glazing
$Q_f$ Rate of heat gain through standard wall
$Q_{FG}$ Rate of heat gain through DVF glazing
$A$ Area of facade/Wall (DVF/RSF)
$A_{rsf}$ Area of rain screen facade weatherboard
$U_{RSF}$ Thermal conductivity of external weather board
$Q$ Flow rate of air
$P$ Pressure drop
$\rho$ Air density
$eff_{gRSF}$ Effective g value of RSF weatherboard
$eff_{gg}$ Effective g value of DVF Outer glazing

## REFERENCES


Brittle, J. P, Eftekhari, M.M & Firth, S.F (2013) *'Mechanical cooling energy reduction for commercial buildings in hot climates: Effective use of external solar shading incorporating effects on daylight contribution.'* 13th Conference of International Building Performance Simulation Association, France.

British Standards (1991) *'Code of practice for ventilation principles and designing for natural ventilation'.* BS 5925 Incorporating amendment No.1. UK.

CIBSE (1999) *'Guide A: Environmental Design.'* London, England

CIBSE (2006) *Technical Memorandum 37: Design for Improved Solar Shading Control.* London, UK

HM Government (2010a) *'Approved Document F: Means of Ventilation.'* The Building Regulations. England, UK.

HM Government (2010b) *'Amendments to Approved Document and Compliance Guide. Non-Domestic Building Services Compliance Guide.The Building Regula.ions.'* England, UK.

HM Government (2010c) *Approved Document L2A: Conservation of Fuel and Power in New Buildings other than Dwellings.* The Building Regulations. England, UK.

Iqbal, I & Al.Homoud, M (2007) *'Parametric Analysis of alternative energy conservation measures in an office building in hot and humid climates'.* Elsevier.King Fahd University, Dhahran, Saudi Arabia.

Lieb, R-D (2001) *'Double Skin Facades'.* PretelVerlag, Stutgard, Germany.

Marinoscia, C. Strachanb, P.A. Semprinia, G. Morinia G.L. (2011) *'Empirical validation and modelling of a naturally ventilated rainscreen façade building'.* UniversitàdegliStudi di Bologna, Italy & University of Strathclyde, Glasgow, Scotland, UK

World Meteorological Organisation (2014a) *Nairobi, Kenya, Africa Weather Statistics.* Available From: http://worldweather.wmo.int/071/c00251.htm [accessed: 3 November 2013]

World Meteorological Organisation (2014b) *Lisbon, Portugal Weather Statistics.* Available From: http://worldweather.wmo.int/003/c00002.htm [accessed: 3 November 2013]

Azarbayjani, M (2013) 'Comparative Performance Evaluation of a Multistory Double Skin Façade Building in Humid Continental Climate'. University of North Carolina. Available From: www.arcc-journal.org/index.php/repository/article/download/.../148 [accessed: 26 January 2014]

Marinoscia, C (2011) 'Dynamic Thermal Performance of Building Components and Application to the Experimental and Theoretical Analysis of a Ventilated Facade.' Universita di Bologna. Available From: amsdottorato.unibo.it/3556/1/PhD_thesis_C_Marinosci.pdf [accessed: 26 January 2014]

e-architect (2014) *'1 North Bank – Sheffield Architecture, Yorkshire, England.'* Available From: http://www.e-architect.co.uk/leeds/sheffield-office-building [accessed: 26 March 2014]

Zeospot (2014) *'Modern Small Office Buildings Verkerk Group in Netherland.'* Available From:http://zeospot.com/modern-small-office-buildings-verkerk-group-in-netherland/modern-small-office-buildings-night-photo/ [accessed: 26 March 2014]